Environmental flows for English rivers: a focus on modified catchments

Neachell, E.

Environmental flows for English rivers: a focus on modified catchments

Emma Neachell

A thesis submitted in partial fulfilment of the requirements of
the University of Westminster for the degree of Doctor of
Philosophy

October 2015

Abstract

Increased human demands upon water resources and growing uncertainty surrounding climate change have focused attention on the need to determine environmental flows (*e-flows*) to protect and sustain river ecosystems. Internationally there have been several advances but within England an anthropocentric approach to water resources management has led to polices that set minimum flows founded in fear of water shortage. By exploring the history of flow management in England and its influence on current practice, and by introducing the concept of 'ecological drought' as a basis for managing future flows, this thesis makes two valuable contributions to the *e-flows* debate. It also explores the influence of George Baxter who more than 50 years ago proposed that compensation flows below dams could be varied to meet the seasonal ecological requirements without reducing water supplies.

In this thesis, hydrological assessments are made of watercourses spanning the 'natural – heavily modified' continuum located across the River Trent and Great Ouse catchments of central England, using a dataset of 48 stations and approximately 1000 station-years. Analyses highlight a variety of 'ecological drought' responses, in magnitude, timing and duration, with extreme low flows being rarely observed on all watercourses in the same year. This suggests *e-flow* determinations at the local, sub-catchment, scale would have benefits for environmental protection and water supply. A variety of potential *e-flow* metrics are examined and Baxter's hypothesis tested. It is shown that supporting flows during the key ecological periods of spring and autumn, while sustaining current levels of abstraction, would risk degradation of the rivers through the increased frequency and duration of extreme low flows. Finally, the thesis examines practical issues impacting on any future *e-flows* policies relating to climate change and hydrometry.

Table of Contents

List of Figures

List of Tables

List of Plates

List of Acronyms and Abbreviations

The following table lists the various acronyms and abbreviations used throughout the thesis. The page on which each one is defined or first used is also provided.

Abbreviation	**Meaning**	**Page**
ADF	Average Daily Flow	58
AEF	Adequate Ecological Flow	102
BFI	Base Flow Index	59
CAMS	Catchment Abstraction Management Strategy	29
CMF	Channel Maintenance Flow	103
DEF	Desirable Ecological Flow	104
DWF	Dry Weather Flow	33
EAFR	Ecologically Acceptable Flow Regime	101
EFC	Environmental Flow Components	95
EFI	Environmental Flow Indicator	34
ELOHA	Ecological Limits of Hydrological Alteration	97
EMF	Ecological Minimum Flow	101
ERFO	Ecological River Flow Objective	34
GEP	Good Ecological Potential	33
GES	Good Ecological Status	33
HEP	Hydroelectric power	238
HMF	Habitat Maintenance Flow	103
HOF	Hands-off flow	33
IFIM	Instream Flow Incremental Methodology	74
IHA	Indicators of Hydrologic Alteration	94
IQR	Interquartile range	149
MAD	Minimum Acceptable Discharge	71
MAF	Minimum Acceptable Flow	71
MAM	Mean Annual Minimum	33
NRFA	National River Flow Archive	38
OEF	Optimum Ecological Flow	102
PCA	Principal Component Analysis	59
PHABSIM	Physical Habitat Simulation	30
RAM	Resource Assessment and Management	78
RVA	Range of Variability Approach	94

Abbreviation	Meaning	Page
SWALP	Surface Water Abstraction Licensing Procedure	77
TEF	Threshold Ecological Flow	102
WFD	Water Framework Directive	29
WTW	Water Treatment Works	46

Glossary of Terms

The following table lists the various specialist terms used throughout the thesis. The page on which each term is defined or first used is also provided.

Term	Meaning	Page
Abstraction Sensitivity Band	There are three Abstraction Sensitivity Bands assigned to each waterbody; ASB1–low sensitivity; ASB2–moderate sensitivity and ASB3–high sensitivity. Each ASB has a different EFI associated with it allowing slightly less abstraction in highly sensitive sites and more in sites with lower sensitivity. Each of these sensitivity bands was developed from assessment of (1) physical typology; (2) macroinvertebrate typology and (3) fish typology. Scores and confidence ratings from each component were combined for the overall ASB for the waterbody..	81
Anti-Drought	Flows in regulated rivers are often artificially increased above natural flow conditions during dry periods and during times of peak demand, resulting in the elimination of natural periods of low flows during the summer, and in the creation of anti-drought conditions...	44
Artificial Drought	The creation of prolonged periods of artificial low-flows and droughts by the abstraction of surface water from unregulated watercourses..	45
Artificial Influences	Anthropogenic influences on the flow regime of a river including surface and groundwater abstraction, discharges, impoundments and inter-basin transfers.....	51
CAMS Cycle	The first CAMS cycle ran between 2001 and 2008 with each individual CAMS consisting of five elements; (1) resource assessment and resource availability; (2) sustainability appraisal; (3) consultation; (4) publication of CAMS documents and (5) implementation. The CAMS process has now moved away from a cyclic review process..	34

Term	Meaning	Page
Compensation Flow	Denotes a flow that is required to remain in a river when a dam is constructed. Historically intended to protect the rights of existing millowners downstream of new reservoirs. The term has become adopted for all constant low flow releases for other purposes such as protection of the river ecosystem and navigation...........	33
Critical Ecological Period	Across England the two critical ecological periods may be defined as Spring (the months of April to June inclusive) and Autumn (the months of October and November). During these months riverine biota have higher minimum flow requirements than during the summer or winter...	106
Discharge-rich	Discharges from mine drainage, industrial water and sewage treatment works may significantly increase low flows, such discharge-rich watercourses with artificially augmented baseflows and low flows are not uncommon in modified catchments...............................	36
Ecological Drought	A rare, prolonged period of low-flow that is severe in magnitude and/or duration and adversely impacts on key ecological functions in ways that are manifest by delayed recovery...	29
Ecological River Flow Objectives	The minimum river flows (or water levels) required to protect ecological objectives..	80
(Ecosystem) Resilience	The measure of the capacity of an ecosystem to respond to a disturbance or perturbation, of its ability to absorb changes and still exist and to recover from a disturbance...	132
Effluent Discharge	Liquid waste from industrial, agricultural or sewage plants...	44
Environmental Flow Indicator	The river flow indicator threshold currently used in CAMS to screen river flows to identify where flows may not be sufficient to support Good Ecological Status and to indicate where abstraction pressures may be starting to have an undesirable impact on river habitats and riverine ecology..	80

Term	Meaning	Page
Environmental Weighting Band	An assessment of a river's sensitivity to abstraction based on physical characteristics, fisheries, macrophyte and macroinvertebrates for a catchment or sub-catchment. Once scores for each element had been determined, rivers were then categorised into one of five Environmental Weighting bands: Band A (most sensitive), Band B, Band C, Band D and Band E (least sensitive to abstraction)..	79
Hands-off flow	A condition attached to an abstraction licence which states that if the flow falls below the level specified on the licence, the abstractor will be required to reduce or stop the abstraction...	33
Heavily Developed Catchment	Catchments containing rivers whose hydrology has been influenced by long-term anthropogenic interference and therefore bear little, or in extreme cases, no resemblance to the hydrologic character of unmodified catchments. By definition a heavily developed catchment may no longer be able to achieve natural conditions...	44
Julian Date	Julian Dates represent calendar dates with integer values, which start with 1 on January 1 and ends with 366 on December 31. Although the number of calendar days varies slightly in each year, depending on whether or not it is a leap year, the starting and ending Julian dates in each year are always 1 and 366...	58
Naturalised flows	Flows in the absence of artificial influences including effluent discharges, surface abstractions, groundwater abstractions and compensation releases from reservoirs..	56
Process Stationarity	The idea that natural systems fluctuate within an unchanging envelope of variability. It implies that any variable for example annual streamflow has a time-invariant probability density function, whose properties can be estimated from the instrument record................	32

Term	Meaning	Page
RAM Framework	A technical framework for resource assessment (for the definition and reporting of CAMS) and subsequent resource management (including abstraction licensing)..	78

List of Appendices

Acknowledgments

I am grateful to the National River Flow Archive and the Environment Agency for providing river flow data and to Wallingford HydroSolutions for providing natural flow estimates.

I am also grateful to Sheena Recaldin for assisting with my Chinese visa application and flight arrangements.

Finally I would like to express my sincere gratitude to my Director of Studies Professor Geoff Petts for his substantial and continued advice, patience, encouragement and support. Without Geoff's guidance and expertise this PhD would not have been possible.

Author’s Declaration

I declare that the present work was undertaken in accordance with the Guidelines and Regulations of the University of Westminster. The work is original except where indicated by special reference in the text.

The submission as a whole or part is not substantially the same as any that I previously or am currently making, whether in published or unpublished form, for a degree, diploma or similar qualification at any university or similar institution.

Any views expressed in this work are those of the author and in no way represent those of the University of Westminster.

Signed: E A. Neachell Date: 26/10/2015

CHAPTER 1: RIVERS AND THEIR WATER NEEDS

1.1 INTRODUCTION

Increased human demands upon water resources combined with growing concerns about environmental change have focused attention on the need to determine, and then protect, flows to sustain river ecosystems (Petts *et al*., 1999). There is now wide recognition and acceptance that a dynamic, variable water regime is required to maintain the native biodiversity and ecological processes characteristic of every river and wetland ecosystem (Poff *et al*., 1997; Lytle and Poff, 2004). Translating this natural flow regime into environmental flow (*e-flow*) targets however, remains a challenge (Arthington *et al*., 2010), particularly in heavily regulated river systems. Indeed, in highly modified and regulated rivers where a return to natural conditions may no longer be feasible, the "designer" approach proposed by Acreman *et al*. (2014a) may be more appropriate. A number of *e-flow* methodologies are in use, each aiming to quantify the water requirements of individual species, communities or rivers as ecosystems (Tharme, 2003; Richter *et al*., 2006). Although there have been a number of advances within the field of *e-flows*, the question "how much water does a river ecosystem need?" (Petts, 1996; Richter *et al*., 1997) still remains challenging (Petts, 2009), especially in developed economies where rivers and their catchments have been modified over hundreds of years.

This thesis seeks to advance an approach to managing *e-flows* in the future, focussing on the rivers of modified landscapes within central England. It presents a critique of the management of low flows in England including a detailed review of the evolution of *e-flow* practice and a review of the Catchment Abstraction Management Strategy (CAMS) process from its launch in 2001 up to its current links with the EU Water Framework Directive (WFD). The thesis also reviews evidence for the ecological impacts/benefits of different low-flow management strategies and presents an empirical assessment of the hydrological effects of both current and historic water resource management practices. In order to advance the development of a new perspective on *e-flows*, this thesis also introduces the concept of ecological drought defined as:

> *"A rare, prolonged period of low-flow that is severe in magnitude and/or duration and adversely impacts on key ecological functions in ways that are manifest by delayed recovery".*

Previous definitions have focused on a measure of drought impact, i.e. terrestrial productivity; this definition is innovative as it introduces the concept of recovery post impact and the impact of drought stress on recovery processes in lotic environments.

1.2 BACKGROUND

The flow regime is regarded by many ecologists to be the key driver of river and floodplain wetland ecosystems (Bunn and Arthington, 2002) and scientists have developed a solid conceptual understanding of the importance of natural flows for river ecosystems (Poff *et al*., 1997; 2003). The Natural Flow Regime paradigm (Richter *et al*., 1996; Poff *et al*., 1997) postulates that five critical components of the flow regime; flow magnitude, frequency, duration, timing and rate of change of high and low-flow events regulate ecological processes in rivers. However, human activities and water resource developments have modified the flow regimes of many rivers. As river flows are depleted or otherwise altered, ecological degradation may result and society loses benefits provided by healthy, functioning ecosystems (Postel and Richter, 2003). Postel and Richter (2003) identify balancing human water demands with the needs of rivers themselves as one of the key challenges for 21st century river management.

There is now broad acceptance that it is in society's best interests to consider rivers as legitimate users of freshwater (Naiman *et al*., 2002; Arthington *et al*., 2006). *E-flows* are defined as flows that:

> *"...describe the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon the ecosystem"*

Brisbane Declaration (2007); page 1.

The recognition that rivers need adequate water of good quality to sustain ecological integrity is not new, and methods recognising the need to establish the extent to which the flow regime can be altered accelerated development of the science of *e-flows* (Tharme, 2003). Several authors have carried out detailed reviews of recent research on *e-flows* (e.g Poff and Zimmerman 2010; Tonkin *et al*., 2014). These emphasise the application of two contrasting *e-flow* methodologies: (1) hydraulic methodologies with much research centred on Physical Habitat Simulation (PHABSIM) and the principle that physical habitat attributes provide an index of suitability for biota (Petts, 2009) and (2) hydrological methodologies that are based on the premise that natural biota and ecological processes are adapted to the natural flow regime. Several reviews identify the limitations of *e-flows* science and highlight the persistent gaps in understanding of flow-ecology relationships. The different *e-flow* methodologies are summarised in Table 1.1.

Table 1.1: Summary of *e-flow* approaches

Category	General Purpose	Key Methods	Scale	Strengths	Weaknesses	References
Hydrological	Examination of historic river flow data to determine safe thresholds for flow abstraction	Baxter Tennant Q_{95} MAM7 Range of Variability Approach (RVA) Ecological Limits of Hydrologic Alteration (ELOHA)	Whole rivers, applicable for regional assessments	Cheap to apply Does not require extensive data collection Easy to apply	Non-stationarity Need long flow records Lack of any explicit consideration of actual habitat requirements	Baxter (1961; 1963) Tennant (1976) Richter *et al.* (1997) Poff *et al.* (2010)
Hydraulic rating	Examination of change in a hydraulic variable as a function of discharge, the change in variable is taken as a proxy for general quantity of habitat in a river	Wetted Perimeter	Study site/river segment scale upscaling to the whole river based on the assumption of representative reaches. River specific	Simple to use Does not require detailed species/habitat data	Selection of the critical breakpoint on the discharge-wetted perimeter curve can be problematic Should only be used in conjunction with other methods	Reiser *et al.* (1989) Gippel and Stewardson (1998)
Habitat simulation	Examination of change in the amount of physical habitat for a selected set of target species as a function of discharge	Physical HABitat SIMulation (PHABSIM)	Study site/river segment scale upscaling to the whole river based on the assumption of representative reaches.	Considered by some as the most scientifically and legally defensible *e-flow* approach	Expensive to apply	Bovee (1982; 1986) Nestler *et al.* (1989) Jowett (1997)
Holistic	Examination of flows in an expert opinion workshop leading to recommendation of flows for all components of the river ecosystem	Building Block Method (BBM) Downstream Response to Imposed Flow Transformation (DRIFT)	Whole rivers, applicable for regional or river specific scales	Address the flow needs of entire river ecosystems Not data intensive	Expensive Subjective and based on expert opinion. Probably not applicable outside of areas developed for	Arthington (1998) Arthington *et al.* (2003) Brown and Joubert (2003) Hughes and Hannart (2003) King and Brown (2006)

Adapted from Linnansaari *et al.* (2013).

A selection of 26 papers published between 2011 and 2015, were categorised into (a) review papers; (b) studies that aimed to determine flow-ecology linkages; (c) studies that either applied existing *e-flow* methodologies or examined *e-flows*; and (d) papers that proposed new classification approaches or frameworks to aid in the selection of *e-flow* methodologies (Appendix 1.1). This review demonstrated that in recent years emphasis has begun to focus on the practical implementation of *e-flows* in a world of modified rivers and uncertain climatic futures rather than to develop further novel *e-flow* methodologies.

Shenton *et al*. (2012) highlight a number of assumptions that undermine the capacity of *e-flow* methodologies; these include:

1. The use of habitat suitability as a proxy for population status.
2. The use of historical time series to forecast future conditions.
3. The inability of some *e-flow* methodologies to handle the extreme flow events associated with climate variability.
4. The assumption of process stationarity.

The high data requirements of some *e-flow* methodologies (e.g. Dunbar *et al*., 2012) and the inherent uncertainty in *e-flow* science (e.g. Acreman *et al*., 2014b) are also identified as issues that may limit the successful implementation of *e-flows*. The limited availability of integrated hydrological and ecological datasets continues to be an issue in many countries. Limitations in data availability are likely to hinder the successful and meaningful application of the majority of *e-flow* methodologies. In the majority of studies, *e-flows* are developed using historical hydrological data, however, in a context of rapid global change, the assumption of process stationarity may no longer be valid (e.g. Milly *et al*., 2008).

Most recently, the focus of international research appears to have shifted towards flow regime classification approaches to support the determination of regional *e-flows*. One justification for the use of a regional *e-flow* methodology is the limited availability of long-term hydrological and ecological datasets. Indeed, data limitations led to the development of holistic *e-flow* methodologies in South Africa and their subsequent application in Australia. In the majority of catchments located in England, flow data is readily available. In addition, following the introduction of the CAMS process in April 2001, routine ecological monitoring and assessment has increased. Issues experienced in many countries originating from the limited availability of hydrological and ecological data should, therefore, not be encountered in England. In addition, the widespread availability of data should enable the determination of *e-flows* at the local/site-specific scale rather than at the regional/catchment scale.

1.3 WATER RESOURCE MANAGEMENT IN ENGLAND

Within England the Environment Agency is responsible for ensuring that the needs of water users are met whilst safeguarding the environment (Environment Agency, 2002a). Indeed, it is now widely accepted that human water demands must be balanced with the needs of rivers (Petts, 2009). The legislative framework for water resources in England stretches back over two centuries (Barker and Kirmond, 1998), however, it was not until the 1963 Water Resources Act that general provision for controlling the use of water was introduced. The Water Resources Act 1963 required the River Authorities to set “minimum acceptable flows” and since then all new abstraction licences have contained conditions to protect the aquatic environment where necessary (Petts, 1996; 2007).

Within England non-statutory hydrological objectives have been used when required to try to protect aquatic life as well as downstream water rights, and these objectives have been implemented as ‘hands-off’ flow (HOF) conditions. HOF conditions require abstraction to cease when flows fall below a specified level. Historically within England an index of natural low-flow has been used to determine a single HOF at abstractions or compensation flow below dams. Two measures of the dry weather flow (DWF); the Q_{95} flow; the flow that is exceeded for 95 per cent of the time, and the mean annual minimum (MAM) 7-day flow frequency statistic have been used most commonly to determine HOFs (Petts and Maddock, 1996).

1.3.1 The Catchment Abstraction Management Strategy approach

The CAMS process was launched in 2001 with the aim of providing a consistent and structured approach to local water resources management, recognising both abstractors’ reasonable needs for water and environmental needs (Environment Agency, 2002a). The first cycle of CAMS was completed in March 2008 providing information on the availability of water resources for the first time.

The European WFD into force in December 2000. Member States are obliged to maintain or restore all surface waterbodies to Good Ecological Status (GES) by 2015. The exceptions to this are heavily modified waterbodies which must achieve Good Ecological Potential (GEP) by 2015. Member States have to balance abstraction against the need to maintain the integrity of river ecosystems. Although the WFD has placed ecology at the centre of *e-flow* definition, the WFD itself does not specify the measures required to restore or maintain GES. Each Member State was left with the task of defining environmental standards such as maximum abstraction rates and flow releases from dams (Acreman and Ferguson, 2010).

In the United Kingdom *e-flow* standards to inform the WFD resource assessments were primarily determined through two projects; WFD 48 (Acreman *et al*., 2006; Acreman *et al*., 2008a) and WFD 82 (Acreman, 2007; Acreman *et al*., 2009). Work in both projects was limited to defining *e-flow* requirements using existing science and data (Acreman and Ferguson, 2010); this included the CAMS process.

1.3.2 The current Catchment Abstraction Management Strategy approach

In the first cycle of CAMS recent actual and fully licensed scenario flows were assessed against Ecological River Flow Objectives (ERFOs). Environmental Flow Indicators (EFIs) have replaced ERFOs. According to the Environment Agency (2013) the difference between the fully licensed scenario flow and the EFI determines the volume of water available for abstraction and also when that water is available.

1.3.3 The status of English rivers

It is worth considering the status of the water environment across England. Such an assessment may help to determine whether the existing hydrological *e-flow* methodology that is centred on the annual Q_{95} has adequately protected the water environment. The Environment Agency identified that historically, in some areas water abstraction licences have been issued that may be harming the ecological health of catchments (Environment Agency, 2011). The WFD requires Member States to aim to achieve GES and good groundwater qualitative status by 2015. The Environment Agency considers that river flows in up to 1075 waterbodies in England (11 per cent of the total) are at risk of not supporting GES (Office of Water Services and Environment Agency, 2011). Although it is not clear if these figures include regulated sites, it is evident that the current system of abstraction management is maintaining ecological health in the majority of surface water waterbodies. In addition, in a review undertaken by the Environment Agency of the impacts of the environmental standards defined in the first CAMS cycle (based on the Q_{95}), very few examples of degraded river ecosystems that could be attributed to inappropriate abstraction limits were identified (Acreman *et al*., 2008a).

In the majority of surface water waterbodies across England, *e-flows* that were historically calculated using hydrological methodologies appear to be adequately protecting the water environment. Hydrological data is readily available across England, with the majority of flow records commencing in the mid to late 1960s in response to requirements for improved hydrometric monitoring that were stipulated in the 1963 Water Resources Act. Many of the more complex and data intensive *e-flow* methodologies are undermined by a number of assumptions, some relating to our current incomplete understanding of flow-ecology relationships. Until some of the research gaps identified by Shenton *et al*. (2012) are addressed, the case for the use of hydrological *e-flow* methodologies is compelling. Indeed, in England there is seemingly little to be gained from the use of more complex and data intensive *e-flow* methodologies.

Although the principle of including ecological issues in regulating river flows has been embedded in legislation for many years (Petts, 2007), it could be argued that advances in linking hydrology and ecology in England have fallen behind those made in countries such as the USA, South Africa and Australia. Arguably, the proposals (Acreman *et al*., 2008a) suggest that knowledge has advanced little over the past three decades since the publication of guidelines by Baxter (1961) and Tennant (1976).

1.4 RESEARCH AIMS

This thesis aims to explore a new approach to setting *e-flows* in a future of intensifying demands for river abstractions. It analyses the history of flow management in England to assess constraints on developing new approaches and elaborates the concept of ecological drought in advancing opportunities for flow management.

1.4.1 Objectives

1. To review the development of flow protection policies in England; this will include a critical appraisal of the CAMS process. The thesis will build on the paper *Water Allocation to Protect River Ecosystems* by Petts (1996) by carrying out a detailed literature review and by drawing on first-hand experience of low-flow management and the CAMS process gained from working at the Environment Agency.

2. To illustrate the potential ecological significance of low-flow variability across the two major river basins of central England, the Trent and Great Ouse. The thesis will carry out an empirical assessment of the effects of current and historic practices including

hands-off flows and compensation flows on rivers with contrasting flow regimes, including tributaries that span the ‘natural – heavily modified’ continuum.

3. To produce a set of management recommendations for the setting of *e-flows* for river protection under future water resources development. Assessments of alternative flow management recommendations aim to determine the applicability of seasonally variable *e-flow* policies and their application at the regional or catchment scale. Consideration is given to (a) how much water could be given to increase abstraction for irrigation in the summer growing season, and (b) whether it would be possible to reallocate water to the river to support the critical spring and autumn ecological periods.

4. Although the focus of research over the past 30 years has been on water abstraction and the need to maintain *e-flows*, this thesis also addresses the reality of discharge-rich watercourses, most of which have had low flows sustained by river regulating dams or by treatment effluent returns for three decades or more.

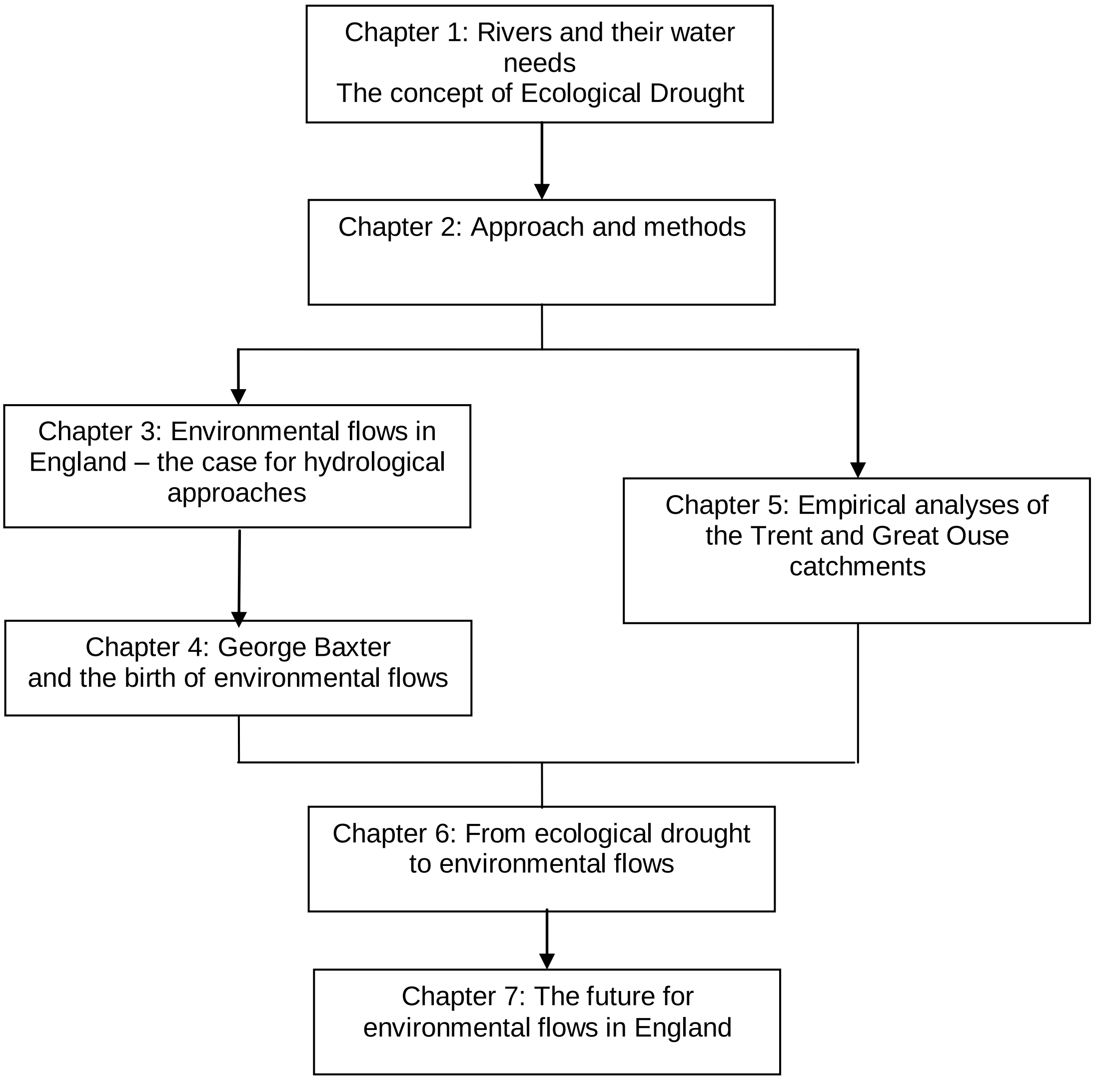
1.5 THESIS STRUCTURE

This thesis is formed of seven Chapters (Figure 1.1), which are described below, and comprises two major elements. The first is literature based and the second is an empirical study of daily river flow data. These two strands are brought together in Chapters 6 and 7 to advance a new approach to *e-flows*. Chapter 2 details the research methodology employed in order to achieve the aims and objectives set out in Sections 1.4 and 1.4.1 respectively.

Chapter 3 comprises a critical literature review. This initially focuses on the evolution of *e-flow* practice in England and is developed through several key stages (1) early approaches including (i) early rainfall-based approaches, (ii) compensation water linked to rainfall, losses, character for stream flow and the user factor and (iii) early streamflow approaches; (2) providing flows for migratory fish; (3) minimum acceptable discharge; (4) measures of the DWF including the annual Q_{95} and the mean annual minimum 7-day flow, (5) PHABSIM; (6) classification approaches; and (7) the CAMS approach and links with the European WFD. Chapter 3 then considers selected literature on the ecological principles underpinning *e-flows*. This includes: (a) the Natural Flow Regime paradigm, (b) the ecological principles for the sustainable management of water resources and (c) drought and ecology. Selected hydrological *e-*

flow approaches are evaluated and the case for employing hydrological approaches to determine *e-flows* within England is made. Chapter 3 concludes with a review of applications of hydrological approaches in England and of the determination of environmental objectives.

Figure 1.1: Thesis structure



The literature search revealed the work of one individual, the significance of which previously had been overlooked. Chapter 4 explores the impact of George Baxter, an influential Scottish Water Engineer who in the early 1960s had proposed that from a biological perspective, the practice of fixed rate compensation flows had little to commend it and that in most cases compensation flows could be varied to meet the seasonal requirements of fish. The principles established by Baxter as the basis of his hydrological approach to setting compensation flows are then explored in Chapters 5 and 6.

Chapter 5 uses flow datasets from the National River Flow Archive (NRFA) across a range of contrasting watercourses located within the two major river basins of central England, the heavily developed River Trent and the highly regulated lowland River Great Ouse, to determine the ecological significance of low-flow variability. Throughout the flow assessments the aim was to identify a range of hydrological indicators of drought severity that might be used to derive *e-flow* management approaches for use in heavily developed and highly regulated watercourses.

Chapter 6 focuses on the hydrological approach to setting *e-flows* and aimed to initially explore the utility of Baxter's (Chapter 4) approach to managing low flows and ecological drought across the Trent and Great Ouse catchments. The applicability of seasonally variable *e-flow* approaches was assessed and consideration given to (a) the allocation of water to increase abstraction for irrigation during the summer growing season and (b) the potential for the reallocation of water to the river during the critical spring and autumn ecological periods.

Finally, Chapter 7 summarises the main findings of this thesis, the recommended approach to *e-flows* and suggests areas for further work.

CHAPTER 2: APPROACH AND METHODS

This thesis aims to explore a new hydrological approach to determining *e-flows* in a future of increasing abstraction pressures and hydrological uncertainty. In order to achieve the aims and objectives set out in Sections 1.4 and 1.4.1 respectively, the following research methodology was employed.

2.1 LITERATURE REVIEW

Prior to performing any empirical assessments a detailed literature review was undertaken focusing on the following areas; (1) the science of *e-flows*, (2) the history of the determination of *e-flows* in England, (3) the application of *e-flows* internationally, (4) linking hydrology and ecology, (5) drought and ecology, and finally (6) a review of the most recent *e-flow* research. The literature review aimed to identify potential areas for research, to identify similar work done within the area, to identify any potential knowledge gaps, and to ensure my understanding of the subject area was both thorough and up to date.

2.1.1 Literature Review: sources used

During the initial stage of the literature review key *e-flow* papers were identified using the Web of Science (http://wok.mimas.ac.uk/). A search for papers containing the keyword "environmental flow(s)" identified relevant papers which were subsequently ranked by the number of citations (highest to lowest) in order to identify the most influential papers published within the field of *e-flows*. During this initial stage a number of key researchers were also identified.

Due to limitations in the Web of Science (the database only includes resources from 1950 onwards) a different approach was used to identify the pre-1950 papers and reports required to review the history of the determination of *e-flows* within England. Sheail (1984, 1985 and 1987) reviewed the historical development of the setting of compensation flows; these publications provided an important source of information on key contemporary legislation, conferences, reports and papers. A number of the most frequently cited references were subsequently obtained from the Institution of Civil Engineers, University of Birmingham and British Libraries.

The review of relevant reports and conference proceedings published during the 1960s highlighted the work of George Baxter, an influential Scottish Water Engineer. The proposals of Baxter were explored in detail in Chapter 4 with the Chapter comprising both a new synthesis of original sources and an assessment of Baxter's work and contemporary debates.

2.2 THE STUDY CATCHMENTS

In this thesis the potential ecological significance of low-flow variability is explored by focusing on two major river basins with contrasting flow regimes; the heavily developed River Trent and the highly regulated, lowland River Great Ouse. Information on the solid geology, catchment characteristics, distribution of rainfall and on the main artificial disturbances that influence low-flows across the River Trent and River Great Ouse basins is provided in Sections 2.2.1 and 2.2.2 respectively.

2.2.1 The River Trent

The Trent catchment covers an area of approximately 10,500 km^2. With a length of 274 km, the River Trent is the third longest watercourse in England, and is the second largest in terms of the flow of annual discharge (Environment Agency, 2003). The River Trent rises on Biddulph Moor near Stoke-on-Trent at an altitude of 290 m AOD (Law *et al*., 1997) and flows eastwards for 274 km to form the River Humber (Humber Estuary) at its confluence with the Yorkshire Ouse (Jarvie *et al*., 2000). The last 85 km is tidal (Edwards *et al*., 1997). The River Trent has a number of major tributaries including the Rivers Sow, Blithe, Tame, Dove, Derbyshire Derwent, Soar, Devon, Idle, Erewash, Greet, Leen and Torne (see Figure 2.1).

The solid geology of the Trent catchment is dominated by sedimentary rocks of Carboniferous, Permo-Triassic and Jurassic ages. Outcrops of igneous and metamorphic rocks are confined to small areas in the Peak District and Charnwood Forest (Pirt, 1983). Surface deposits of recent and Pleistocene ages are found in all areas of the catchment. Large tracks of the less elevated parts of the catchment were covered by a mantle of Pleistocene deposits however; subsequent erosion has largely dissected this mantle. The products of this erosional period are partly preserved in the terrace gravels and alluvial deposits lying in the main valleys. Four main types of surface deposit can be identified; peat, valley deposits, boulder clay, and sand and gravel (Downing *et al*., 1970).

Average annual rainfall across the Trent catchment is 700 mm (standard period 1961 – 1990) compared to an average for England and Wales of 897 mm (Environment Agency, 2003). Rainfall varies from less than 600 mm pa at Trent Falls to over 1600 mm pa in parts of the Pennines and Peak District, and according to Law *et al*. (1997) there is generally less rainfall in the east of the catchment than the west due to the prevailing wind. Greenwood *et al*. (2006) described the River Trent as forming a natural divide between the uplands of the north and west and lowlands of the south and east, with its location rendering the Trent unique among major English rivers giving it both an upland and lowland system along its course.

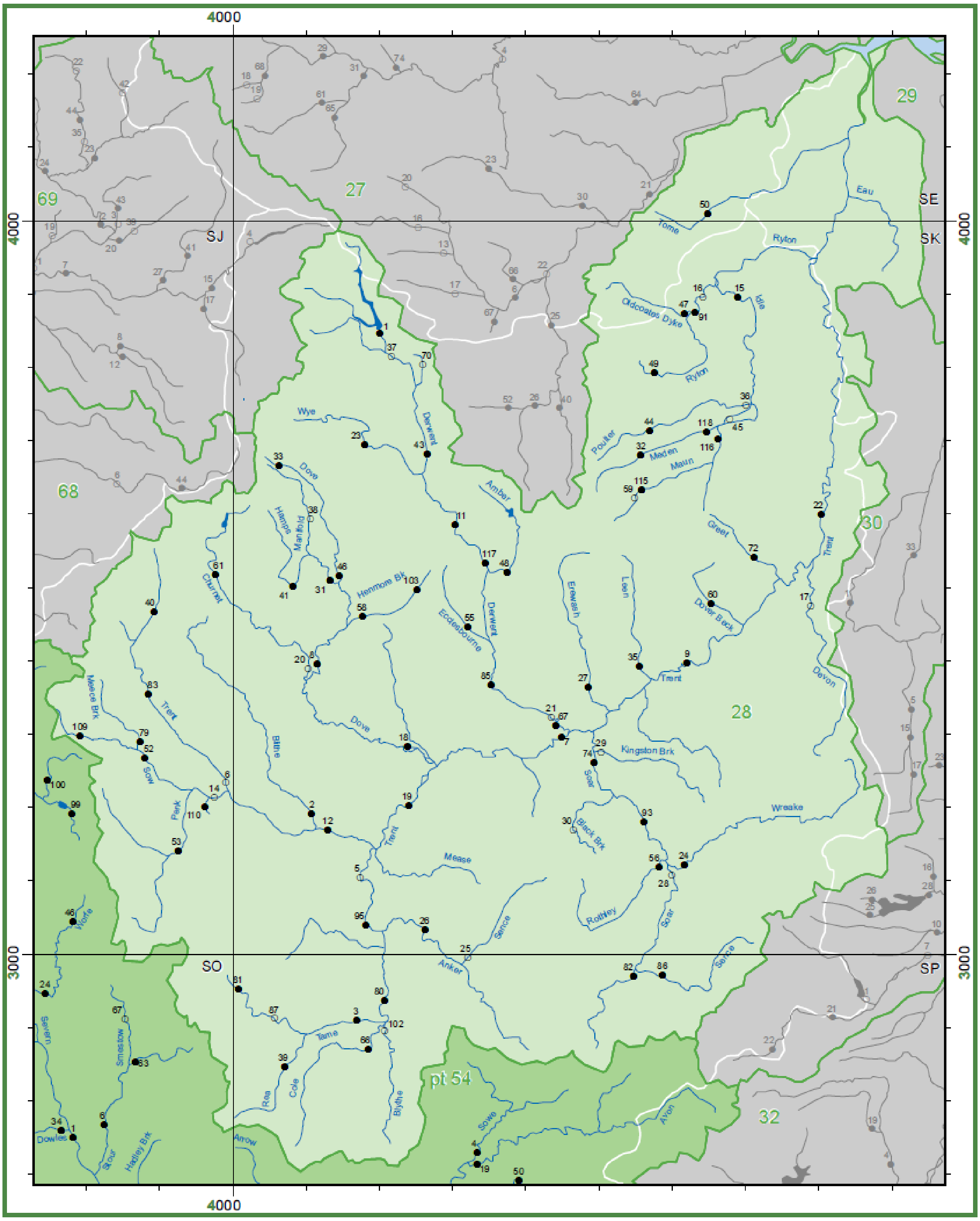
From the perspective of low flows, Pirt (1983) identified four discrete regions within the Trent catchment:

(1) **The Uplands of the South Pennines.** This area centred on the Peak District, is drained by the Rivers Dove, Manifold, Wye and Derwent.
(2) **The Trent Valley and associated terraces.** This area covers a wide arc of low lying ground between Stafford and Scunthorpe. Near Nottingham the lowland extends eastwards into the Vale of Belvoir. This latter area is drained by the River Devon and its tributaries.
(3) **The Uplands to the south of the Trent.** This arc of undulating country includes The Potteries, Cannock Chase, the Birmingham Plateau, the hills of Warwickshire and Leicestershire and Charnwood Forest. The area is drained by the Rivers Penk, Sow, Tame, Soar, Sence and Wreake
(4) **The Dukeries and Sherwood Forest.** This upland country to the north and west of the River Trent has a westerly facing scarp and easterly facing dip slopes. The area is drained by the River Idle and its tributaries.

2.2.1.1 River regulation and historical pollution

The River Trent has a long history of regulation, with early regulation in the form of small-scale work for powering mills, later becoming extensive to aid navigation (Large and Petts, 1996). Historically, the River Trent and some of its main tributaries have suffered major pollution from sewage and industrial effluents. Turing (1947a) carried out a survey of pollution within the catchment of the River Trent, identifying that until well into the third quarter of the 19th century the Trent was a salmon river with spawning grounds in the River Dove between Tutbury and Sudbury. However, industrial development between the 1880s and the First World War had reduced the condition of the main river and its Staffordshire tributaries to little better than an open sewer (Turing, 1947a). Since the early 1960s, however, there have been major improvements in water quality (Harkness, 1982; Jarvie *et al*., 2000) and it is now considered viable to use treated Trent water for potable water supply (Environment Agency, 2003).

Figure 2.1: Main watercourses and gauging stations located across the Trent catchment. Gauging stations used in this thesis are listed in Table 2.1



Map reproduced with permission from the Natural Environment Research Council

Today, the River Trent receives substantial discharges of effluent with the largest via the River Tame from Minworth Sewage Treatment Works. The resulting effluents have artificially enhanced low flows in the River Trent below the River Tame confluence; as a result 56 per cent of the dry weather flow at Nottingham is treated sewage and industrial effluent (Martin, 1994). In addition the Trent and its tributaries provide an important supply of water to a large number of licensed abstractions.

Anthropogenic disturbances within heavily developed catchments such as the Trent catchment may alter ecologically relevant attributes of the flow regime. Many watercourses have been degraded by loss of habitat and changes in flow regime and in regulated watercourses, the resilience of riverine biota to drought may be greatly reduced (Lake, 2003). Rolls *et al*. (2012a) identified six major anthropogenic induced threats to low-flow hydrology; (1) flow regulation, (2) surface-water abstraction, (3) interbasin transfers, (4) groundwater abstraction, (5) land use change, and (6) climate change and variability. Here the potential impacts of flow regulation, groundwater and surface-water abstraction and an additional major anthropogenic induced threat to low-flow hydrology prevalent across large areas of the Trent catchment; the augmentation of low flows by effluent discharge are considered.

2.2.1.2 Flow regulation

The regulation of flows alters the low-flow hydrology of watercourses. Flows in regulated rivers are often artificially elevated above natural conditions during dry periods and times of peak demand, resulting in the elimination of natural periods of low flows during the summer, and the creation of ‘anti-droughts’ (Bunn *et al*., 2006). The seasonality of flows are also often altered despite little change to the total annual discharge, and in some cases may be reversed (Humphries *et al*., 2008) so that the low-flow period no longer co-occurs with the usual seasonal cues for biotic responses and ecosystem processes (Rolls *et al*., 2012a). In extreme cases, watercourses below impoundments may be locked into permanent drought (Lake, 2003) or anti-droughts (McMahon and Finlayson, 2003).

Across the heavily developed Trent catchment, the variable effect of the regulation of watercourses is striking. No low-flow impacts due to flow regulation are evident, for example within the River Dove at Izaak Walton. Conversely, the highly regulated River Derwent below Ladybower Reservoir shows the complete loss of natural low-flow variability and flow seasonality.

2.2.1.3 Surface-water and groundwater abstractions

Surface-water and groundwater abstractions impact the flow regimes of the majority of rivers across the catchment. The abstraction of surface water from unregulated watercourses may produce artificial drought (Boulton, 2003), with reduced magnitude and increased frequency and duration of low-flow events (Rolls *et al*., 2012a).

Small tributary streams located below abstractions may dry out; these watercourses are remote from gauging stations, and therefore the occurrence of these artificial droughts may not be identified. Flows within the Rivers Alport, Ashop and Noe (all headwater tributaries of the River Derwent) are known to be impacted by abstraction; however, the effects are localised (G. Petts *pers.comm*). Plate 2.1 illustrates the River Alport, a tributary of the River Ashop during a period of artificial drought.

Plate 2.1: Artificial Drought conditions: River Alport (photograph provided by G. Petts)

According to Rolls *et al*. (2012a), surface-water abstraction may also alter the amount of natural variation in the flow regimes of rivers characterised by low flows. However, in discharge-rich watercourses such as the River Trent and River Tame, although surface-water abstraction will cause a reduction in low-flow magnitude, the variability and timing of low flows may be unaltered.

2.2.1.4 Flow augmentation by effluent discharge

The augmentation of flows from mine drainage, industrial water and sewage treatment works can significantly increase low flows. Along the main river, with catchment areas greater than approximately 3000 km^2, the River Trent has dry weather flows that are more than double the natural flow (G. Petts *pers.comm,* 2012). Such ‘discharge-rich’ systems, with artificially augmented baseflows and low flows are not uncommon, for example in France the Archeres water treatment works (WTW) increases baseflows in the River Seine by up to 40 per cent during low flows (Paul and Meyer, 2001).

Plate 2.2: Anti-Drought conditions: River Tame upstream of the Trent confluence March 2012

Plate 2.2 shows the River Tame upstream of its confluence with the River Trent. The photograph was taken in March 2012 when due to drought conditions persisting across East Anglia, the Midlands and southern England, there were concerns for water

resources. The River Tame at this location, however, was not experiencing low flows, with the discharge of effluents appearing to be creating anti-drought (McMahon and Finlayson, 2003) conditions. Indeed, during the summer, 80 per cent of the flow of the River Tame may be made up of treated sewage effluent, and downstream of the River Tame confluence, effluent discharges have more than doubled the dry weather flow of the main River Trent (Petts *et al*., 2002).

We currently have a poor understanding of the ecological ramifications of ‘anti-drought’ flows (Bond *et al*., 2008) that tend to elevate low flows in discharge-rich watercourses such as the Rivers Tame and Trent. The loss of low flows and droughts, both of which are important components of the natural flow regime, combined with the creation of more stable hydraulic conditions (Bond *et al*., 2008) may have a negative impact on riverine biota.

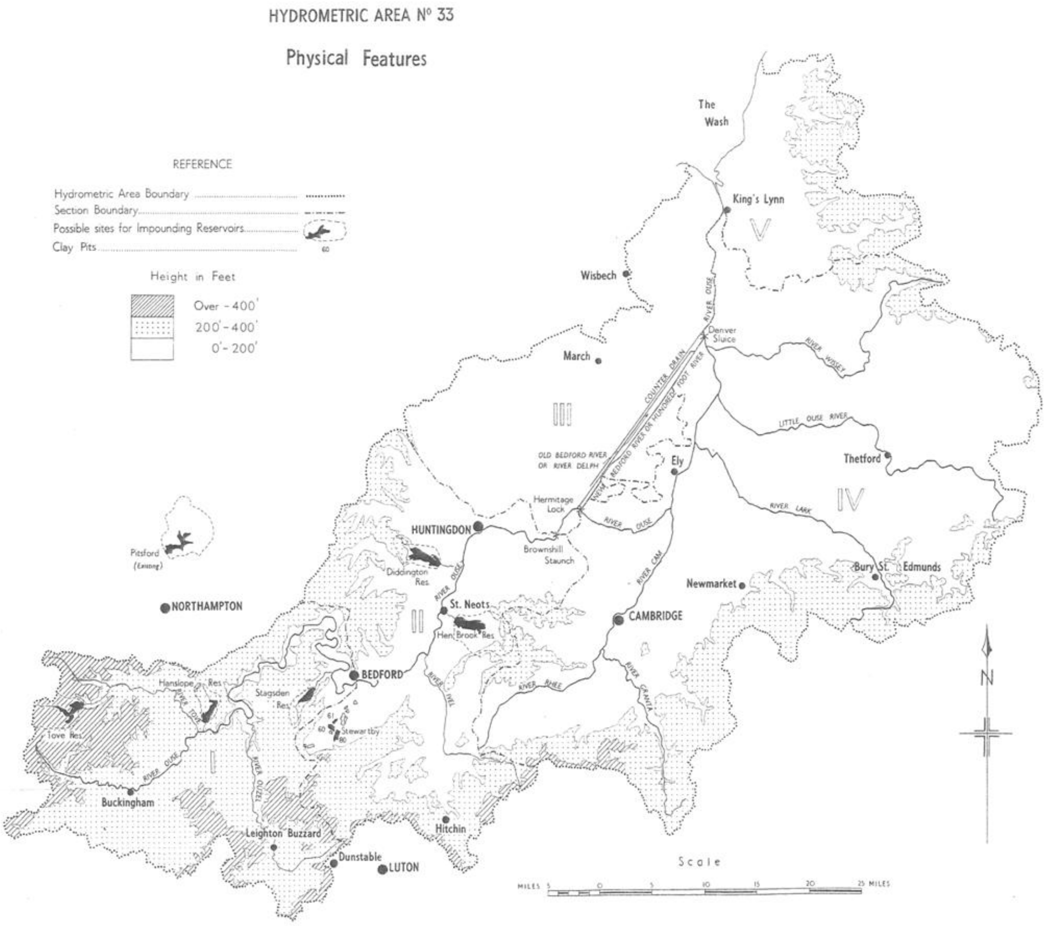
2.2.2 The River Great Ouse

The River Great Ouse catchment (Figure 2.2) covers an area of approximately 8600 km^2 (Pinder *et al*., 1997) and the main river is approximately 165 km in length (Mann, 1997); somewhat smaller than the River Trent. The source of the River Great Ouse is located at an altitude of approximately 250 m AOD (Environment Agency, 2010a). From there the river flows east through relatively steep terrain towards Buckington before changing direction to flow northeast towards Bedford and then in a north easterly direction towards Huntingdon and the Fens before eventually entering the North Sea at King’s Lynn. The River Great Ouse has a number of major tributaries including the Rivers Tove, Ouzel, Cam, Lark, Little Ouse River and Wissey. A large area of the catchment lies below sea level and consists of artificially drained fenland, with water being pumped into the main watercourses.

According to the Environment Agency (2010a) the catchment may be considered as consisting of seven main hydrological units defined by their topography and hydrological similarities: (1) The Upper Bedford Ouse containing the River Great Ouse from its source to Kempston Weir near Bedford and also including the Rivers Tove and Ouzel; (2) The Lower Bedford Ouse containing the navigable River Great Ouse from Kempston Weir to the tidal limit and also including tributaries such as the Rivers Ivel, Kym and Alconbury Brook; (3) The River Cam catchment containing the Rivers Rhee, Granta and the Bourn Brook; (4) the Fens – Middle Level containing the major drains of the Hundred Foot Drain (Old Bedford River) and the River Delph (New Bedford River); (5) the Fens – South Level containing the Ely Ouse/Ten Mile River; (6) Eastern

Rivers containing the upstream reaches of the Rivers Lark, Little Ouse, Wissey and their tributaries; and (7) North West Norfolk containing the Rivers Nar and Gaywood which drain into the tidal River Great Ouse at King's Lynn and the Rivers Heacham, Ingol and Babingley which drain directly into the Wash.

Figure 2.2: Physical features of the Great Ouse catchment



Ministry of Housing and Local Government (1960b); page 3.

The underlying solid geology crosses the Great Ouse catchment in bands running approximately north east to south west (Environment Agency, 2010a). Chalk dominates the southeast area of the catchment; mudstone becomes dominant in the northwest area, and limestone dominates the extreme western end of the catchment. In addition, limestone can be found in the most westerly areas of the catchment around the upper reaches of the River Tove. This solid geology is overlain by more recent drift deposits. At the upstream end of the catchment, the mudstone and limestone are overlain by gravelly clays, whilst in the lower section of the catchment, particularly in the Fens, thick deposits of peat or mud overlay the mudstone.

The majority of the Great Ouse catchment lies within one of the driest areas of the United Kingdom, with East Anglia receiving 624.0 mm pa rainfall on average according to Met Office 1981-2010 long-term data. By comparison, the average annual rainfall across the Midlands district, which incorporates the Trent catchment is 798.3 mm pa (1981-2010). The UK Hydrometric Register (Marsh and Hannaford, 2008) provides an indication of the mean annual rainfall over sub-catchments located within the Great Ouse catchment that have a gauged flow record. This data indicates that the three sub-catchments receiving the lowest annual rainfall are the Guilden Brook at Fowlmere Two (554 mm pa), Quy Water at Lode (563 mm pa), and the River Shep at Fowlmere One (563 mm pa). Indeed, according to the Environment Agency (2010a), much of the central part of the Great Ouse catchment receives less than 600 mm pa. Conversely, the northeast of the catchment receives more than 685 mm pa including the River Nar at Marham (693 mm pa), the River Heacham at Heacham (691 mm pa) and the River Babingley at Castle Rising (688 mm pa).

Land use across the Great Ouse catchment is varied, with agricultural and urban areas comprising approximately 65 and 7 per cent of the total catchment area respectively (Environment Agency, 2010a). Grassland comprises approximately 19 per cent and woodland 9 per cent of the catchment. The Fens area is dominated by arable land, the surrounding areas, however, have a more varied land use. The area to the north of Bury St Edmunds in the east of the catchment has a high density of woodland as well as large areas of natural grassland. Although the catchment is predominantly rural, several large urban developments including Milton Keynes, St Neots, Ely, Bedford and Kings Lynn are located along the River Great Ouse. Other urban areas including Towcester (River Tove), Bury St Edmunds (River Lark), Cambridge (River Cam) and Thetford (River Little Ouse) lie on the tributaries of the River Great Ouse.

The River Great Ouse has a long history of modification and regulation, and papers by Mann (1997) and Pinder *et al*. (1997) provide information on anthropogenic influences within the catchment from medieval times up to the present day. In recent years concerns have centred on the abstraction of water for spray irrigation. Indeed, according to the Environment Agency (2008b) abstraction for spray irrigation in East Anglia can average over 20 per cent of the total for all uses over a typical summer, with more water used on a hot dry day for spray irrigation than for public water supply. Section 2.2.2.1 provides an overview of the development of spray irrigation within the Great Ouse catchment and evaluates whether concerns initially raised in the late 1950s and early 1960s were justified.

2.2.2.1 Spray irrigation within the Great Ouse catchment

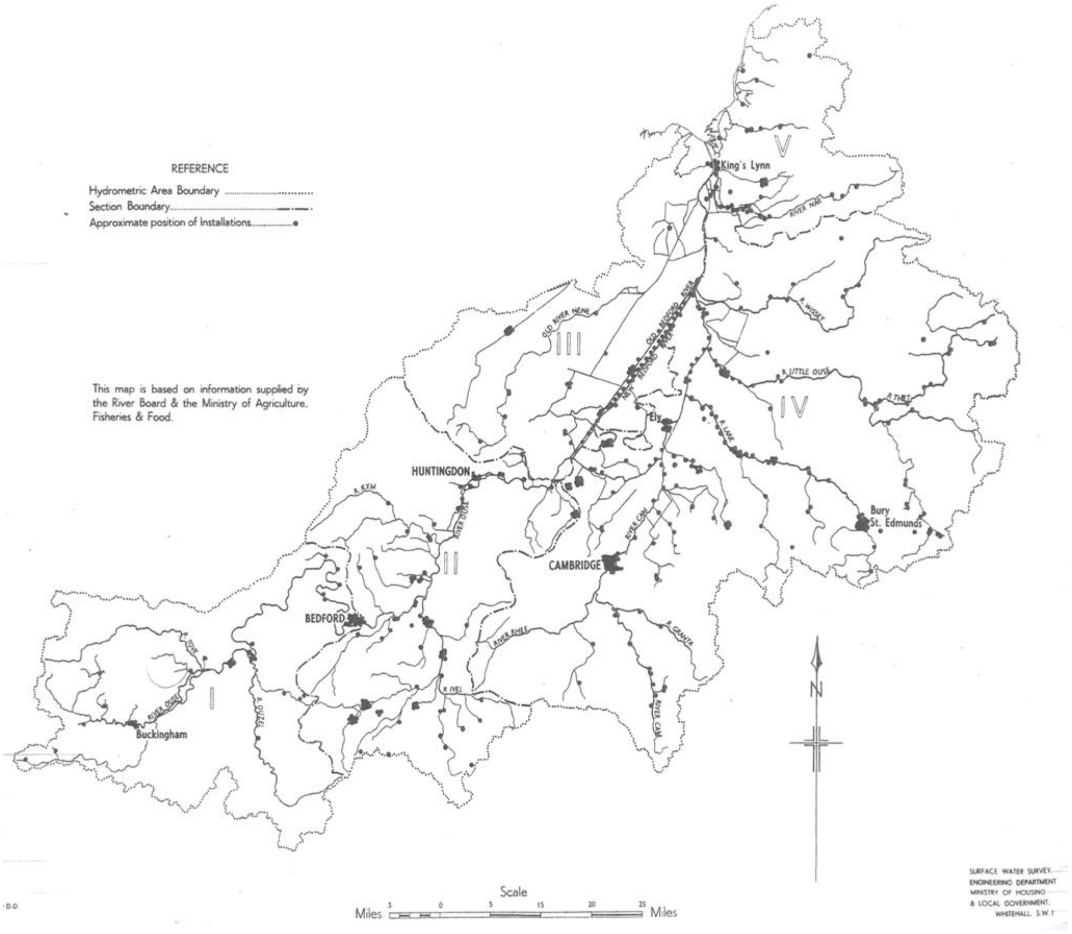
Irrigation has been practised in Great Britain for several centuries, and a report written in 1846 claims that irrigation was first introduced at Babraham in Cambridgeshire by Pallavicino (Withers, 1973) in the early 1560s (Porter, 1978). Pallavicino bought the estate at Babraham, procured a grant from the Crown for the river flowing through the estate, presumed to be the River Granta, and introduced irrigation (Withers, 1973). Although this type of irrigation was quite widely practised in the first half of the nineteenth century, the agricultural depression is thought to have been responsible for the decline in irrigation, by the 1930s irrigation had been virtually abandoned (Porter, 1978).

The modern practice of spray irrigation was introduced following the Second World War, and by the 1950s the increasing demand for water in all consumer sectors was one of the factors that resulted in the appointment of the Sub-Committee on the Growing Demand for Water in October 1955. According to Van Oosterom (1967) the greatest single consumptive increase took place in the East and South-East of the country where the rapidly rising demand for irrigation water was described as causing serious embarrassment to the River Boards and Internal Drainage Boards. Demand for irrigation water was and indeed still is greatest in the areas of lowest rainfall, with irrigation required more than eight years in ten in the majority of the area south-east of a line from the Wash to Hampshire (Prickett, 1966).

In 1959, the driest summer in nearly 250 years, a drought described by Downing (2004) as a ‘signal event’, focused attentions on the precariousness of the water supply situation and on the emergence of potentially excessive abstraction for spray irrigation (Porter, 1978). Indeed, one of the main recommendations made in the First Report of the Sub-Committee on the Growing Demand for Water (Central Advisory Water Committee, 1959) was to carry out detailed hydrological surveys in areas where the expected surplus of supply over demand was lowest. The survey of the River Great Ouse basin was the first to be completed in December 1959 partly due to concerns over the increasing demand for spray irrigation and partly because consideration was already being given to possible schemes for meeting future water supply demands in Bedfordshire, Huntingdonshire and parts of Northamptonshire by surface water abstraction (Ministry of Housing and Local Government, 1960b).

Across the River Great Ouse catchment, the area irrigated increased from 3970 acres (16.1 km^2) in 1950 to 28200 acres (114.1 km^2) in 1962 (Van Oosterom, 1967). Figure 2.3 illustrates the distribution of installations for spray irrigation across the catchment in December 1959. Concerns relating to the growth of irrigation across the catchment resulted in the publication of four major reports (Porter, 1978) in the early 1960s which attempted to forecast the real demand for irrigation water across the catchment. The enactment of the 1963 Water Resources Act, however, resulted in a sharp decline in demand for irrigation water (O'Riordan, 1970), with the periodic surveys of irrigation carried out by the Ministry of Agriculture indicating that following a peak in 1965, there was a decline in the irrigated area of the catchment (Porter, 1978). Although it is clear that spray irrigation never became the runaway water demand it was feared to be in the early 1960s, spray irrigation still represents a significant artificial influence across the catchment.

Figure 2.3: Distribution of spray irrigation installations across the Great Ouse catchment - December 1959



Ministry of Housing and Local Government (1960b); page 9.

Recent data published by the Department for Environment, Food and Rural Affairs for the period 2000-2012 (https://www.gov.uk/government/statistics/water-abstraction-estimates) indicates that nationally and regionally, abstractions for spray irrigation do not show any particular trend. For England and Wales abstractions for spray irrigation averaged 82 x 10^6 m^3, ranging from 50 to 118 x 10^6 m^3. This represented about 24 per cent of the volume licensed for that purpose. The Anglian Region accounted for 36 per cent of all licences in force for spray irrigation and estimated abstractions averaged 30 x 10^6 m^3 from non-tidal surface waters and 20 x 10^6 m^3 from groundwater, with annual totals varying from 33 to 71 x 10^6 m^3.

2.3 DATA SOURCES

The remainder of this Chapter outlines the sources of the rainfall and river flow data used to identify the driest years in the two study periods and to explore the variability of low-flows across the Trent and Great Ouse catchments, respectively. Information on the availability of river flow data across both study catchments and on the issues surrounding the accurate measurement of low-flows is provided.

2.3.1 Rainfall data

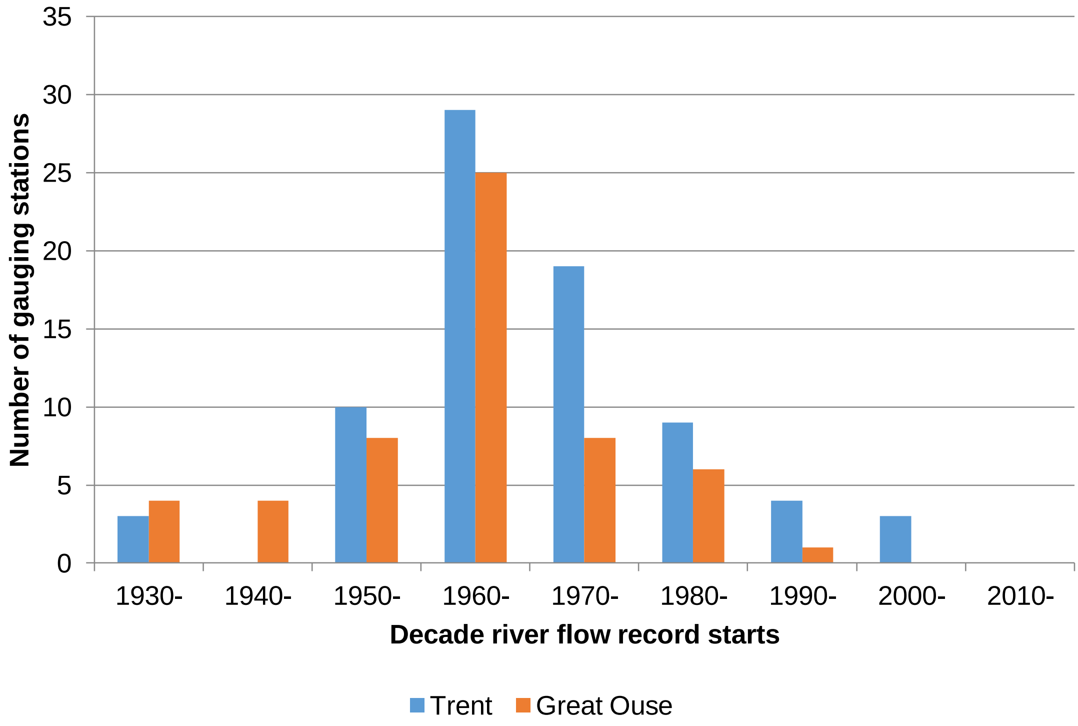
Due to the paucity of reliable long-term flow records that are available for both the Trent and Great Ouse catchments, in order to identify potential periods of historical drought across the Trent and Great Ouse catchments rainfall records have to be used. Although historical annual and monthly rainfall totals for the Trent and Great Ouse catchments are not available, the Met Office holds monthly and annual rainfall records commencing in January 1910 for the Midlands and East Anglia regions.

It is worth noting that although the Midlands region incorporates the Trent catchment, it also incorporates the Severn and Avon valleys and part of the River Wye. In addition the East Anglia region does not just incorporate the Great Ouse catchment. Historical monthly rainfall totals recorded between January 1910 and December 2009 inclusive, i.e. 100 complete years of rainfall data formed the basis of rainfall assessments.

2.3.2 River flow data

Daily river flow data for the United Kingdom and information on gauged catchment characteristics are available from the National River Flow Archive (NRFA) website http://www.ceh.ac.uk/nrfa/. A map illustrating the location and the unique station reference for every operational gauging station is available from the NRFA at http://nora.nerc.ac.uk/503628/1/N503628MAP.pdf. Additional flow data for the Trent catchment was sourced from the Environment Agency. According to the NRFA, daily mean flows within watercourses located in the Trent catchment (Hydrometric Area 28) and Great Ouse catchment (Hydrometric Area 33) have been measured and recorded at 77 and 58 locations at various times respectively. Although Figure 2.4 illustrates that the majority of gauging stations became operational in the 1960s, in response to requirements for increased hydrometric monitoring stipulated in the 1963 Water Resources Act, a number of these flow records unfortunately have extended periods of missing data.

Figure 2.4: Histograms illustrating the start of the period of river flow data availability across the Trent basin (77 gauging stations) and the Great Ouse basin (56 gauging stations)



In order to be utilised in the flow assessments, flow records ideally had to have a minimum of 20 years of continuous mean daily discharge data. At least 12 years of continuous flow data are required for statistical integrity (Gurnell and Petts, 2011) and it is preferable that flow records cover the same time period (Clausen and Biggs, 2000).

2.3.3 Selection of study sites: Trent catchment

Following a detailed assessment of data availability using information contained within the NRFA, flow data in the form of daily mean discharges recorded at 26 gauging stations was obtained. In addition, mean daily discharge data recorded at five sites; River Churnet at Basford Bridge, River Derwent at Church Wilne, Meece Brook at Shallowford, River Penk and Penkridge and the River Ryton at Blyth was obtained from the Environment Agency. Following this initial stage of data collection, mean daily discharge data covering the 20-year 01/01/1990 to 31/12/2009 period for 31 study sites was available (Table 2.1). Additional information on the 31 study sites is provided in Appendix 2.1.

Table 2.1: Selected information on the 31 Trent study sites (the last two digits of the NRFA reference number identify the gauging station location in Figure 2.1)

Watercourse	Study Site	NRFA Ref[1]	Catchment Area (km^2)	BFI[2]	1990-2009[3]		
					Mean Flow (m^3s^{-1})	Q_{95} (m^3s^{-1})	Q_{95} (% Mean Flow)
River Wreake	Syston Mill	28024	413.8	0.41	2.963	0.369	12.5
Rothley Brook	Rothley	28056	94	0.46	0.732	0.115	15.7
River Ecclesbourne	Duffield	28055	50.4	0.49	0.627	0.099	15.8
River Sence	South Wigston	28086	113	0.41	0.915	0.146	16.0
River Manifold	Ilam	28031	148.5	0.53	3.463	0.605	17.5
River Trent	Stoke on Trent	28040	53.2	0.44	0.609	0.11	18.1
River Soar	Littlethorpe	28082	183.9	0.49	1.307	0.244	18.7
River Cole	Coleshill	28066	130	0.43	0.958	0.182	19.0
Meece Brook	Shallowford	28079	86.3	0.63	0.68	0.13	19.1
River Ryton	Worksop	28049	77	0.63	0.413	0.086	20.8
River Churnet	Basford Bridge	28061	139	0.45	1.937	0.407	21.0
River Derwent	Yorkshire Bridge	28001	126	0.47	2.07	0.475	22.9
River Derwent	Chatsworth	28043	335	0.55	6.419	1.487	23.2
River Dove	Rocester Weir	28008	399	0.62	7.587	1.812	23.9
River Dove	Marston	28018	883.2	0.61	13.933	3.478	25.0
River Derwent	St Marys Bridge	28085	1054	0.63	16.618	4.22	25.4
River Anker	Polesworth	28026	368	0.51	3.406	0.865	25.4
River Penk	Penkridge	28053	272	0.58	2.355	0.605	25.7
River Rea	Calthorpe Park	28039	74	0.46	0.751	0.202	26.9
River Derwent	Church Wilne	28067	1177.5	0.64	18.558	5.051	27.2
River Amber	Wingfield Park	28048	139	0.5	1.4	0.387	27.6
River Dove	Izaak Walton	28046	83	0.79	1.926	0.544	28.2
River Sow	Great Bridgford	28052	163	0.65	1.196	0.352	29.4
Dover Beck	Lowdham	28060	69	0.75	0.155	0.048	31.0
River Trent	North Muskham	28022	8231	0.65	88.286	28.23	32.0
River Greet	Southwell	28072	46.2	0.71	0.297	0.095	32.0
River Trent	Colwick	28009	7486	0.64	83.538	26.91	32.2
River Ryton	Blyth	28091	231	0.73	1.534	0.516	33.6
River Idle	Mattersey	28015	529	0.78	2.149	0.788	36.7
River Torne	Auckley	28050	135.5	0.7	0.851	0.317	37.3
River Tame	Lea Marston	28080	799	0.69	14.289	7.576	53.0

[1] NRFA gauging station reference numbers are unique and serve as the primary identifier for the station record on the NRFA.

[2] BFI: (Base Flow Index) values were obtained from the NRFA.

[3] Mean and Q_{95} flows were calculated from daily mean flows recorded between 01/01/1990 and 31/12/2009.

Unfortunately three of the flow records were incomplete. Mean daily discharge data was not available for the River Anker at Polesworth between 01/08/1990 and 31/08/1990 inclusive (31 days), the River Ecclesbourne at Duffield between 01/01/1990 and 09/04/1990 inclusive (99 days), and the River Penk at Penkridge between 01/01/1990 and 23/01/1990 inclusive (23 days). In order to extend the spatial distribution and range of study sites, during the initial flow assessments, the results from these three gauging stations were included. In addition, some watercourses have more than one study site; River Ryton (2 sites), River Dove (3 sites), River Trent (3 sites), and River Derwent (4 sites).

2.3.4 Selection of study sites: Great Ouse catchment

Table 2.2: Selected information on the 17 Great Ouse study sites

Watercourse	Study Site	NRFA Ref[1]	Catchment Area (km^2)	BFI[2]	1981-2010[3]		
					Mean Flow (m^{3}s^{-1})	Q_{95} (m^{3}s^{-1})	Q_{95} (% Mean Flow)
River Granta	Linton	33066	59.8	0.46	0.189	0.007	3.7
River Kym	Meagre Farm	33012	137.5	0.26	0.610	0.023	3.8
River Stringside	Whitebridge	33029	98.8	0.84	0.486	0.041	8.4
River Wittle	Quidenham	33045	28.3	0.64	0.142	0.016	11.3
River Tove	Cappenham Bridge	33018	138.1	0.54	1.082	0.200	18.5
Bedford Ouse	Bedford	33002	1460.0	0.53	12.144	2.252	18.5
River Rhee	Burnt Mill	33021	303.0	0.74	1.142	0.258	22.6
River Heacham	Heacham	3332	59.0	0.96	0.212	0.050	23.6
River Little Ouse	Knettishall	33063	101.0	0.67	0.483	0.122	25.2
River Thet	Melford Bridge	33019	316.0	0.78	2.014	0.513	25.5
River Cam	Dernford	33024	198.0	0.77	0.883	0.244	27.6
River Lark	Temple	33014	272.0	0.77	1.319	0.404	30.6
River Nar	Marham	33007	153.3	0.91	1.111	0.341	30.7
River Babingley	Castle Rising	33054	47.7	0.95	0.501	0.168	33.5
River Ivel	Blunham	33022	541.3	0.73	2.930	1.052	35.9
River Flit	Shefford	33028	119.6	0.74	0.965	0.466	48.3
River Hiz	Arlesey	33033	108.0	0.85	0.681	0.344	50.5

[1] NRFA gauging station reference numbers are unique and serve as the primary identifier for the station record on the NRFA.

[2] BFI values were obtained from the NRFA.

[3] Mean and Q_{95} flows were calculated from daily mean flows recorded between 01/01/1981 and 31/12/2010.

An initial assessment of data availability using the information contained within the NRFA eliminated a number of sites with no recent data available. Following this assessment, flow data in the form of mean daily discharge recorded at 40 gauging stations was obtained from the NRFA. The River Trent flow assessments utilised flow data recorded during the 01/01/1990 to 31/12/2009 inclusive 20-year period. Due to two significant drought events (1989-1991 and 1995-1996), a longer 01/01/1988 to

31/12/2010 inclusive 25-year study period was analysed within the Great Ouse. However, over the extended study period the trade-off was fewer usable gauging stations.

A more detailed assessment of data availability indicated that a number of the mean daily discharge records contained multiple, and in some cases prolonged periods of missing data which unfortunately could not be infilled due to a lack of suitable donor sites. Following these data checks the decision was made to base the detailed low-flow assessments on the extended 30-year mean daily discharge records from 17 gauging stations on contrasting watercourses (Table 2.2 on the previous page). Additional information on the 17 study sites is provided in Appendix 2.2

2.3.5 Selection of study sites: Trent and Great Ouse regional database

In Chapter 6 the Trent and Great Ouse catchments were combined to generate a regional dataset. This required a reassessment of the flow records in order to optimise the number of gauging stations, and record length and integrity. Flow data in the form of daily mean discharges recorded at 38 gauging stations (21 located across the Trent and 17 across the Great Ouse catchment) for the 01/01/1988 to 31/12/2010 inclusive 25-year period were considered. Unfortunately, 11 of the 38 flow records were incomplete, with missing data ranging from between 2 days (River Rhee at Burnt Mill) to a maximum of 87 consecutive days (River Torne at Auckley).

The second stage of flow assessments in Chapter 6 involved a reduced number of study sites with contrasting flow regimes that were selected to avoid issues relating to missing flow data during periods of low flows and the calculation of low-flow metrics (e.g. Marsh, 2002). The 10 study sites had 25-year daily mean discharge records with no periods of missing data.

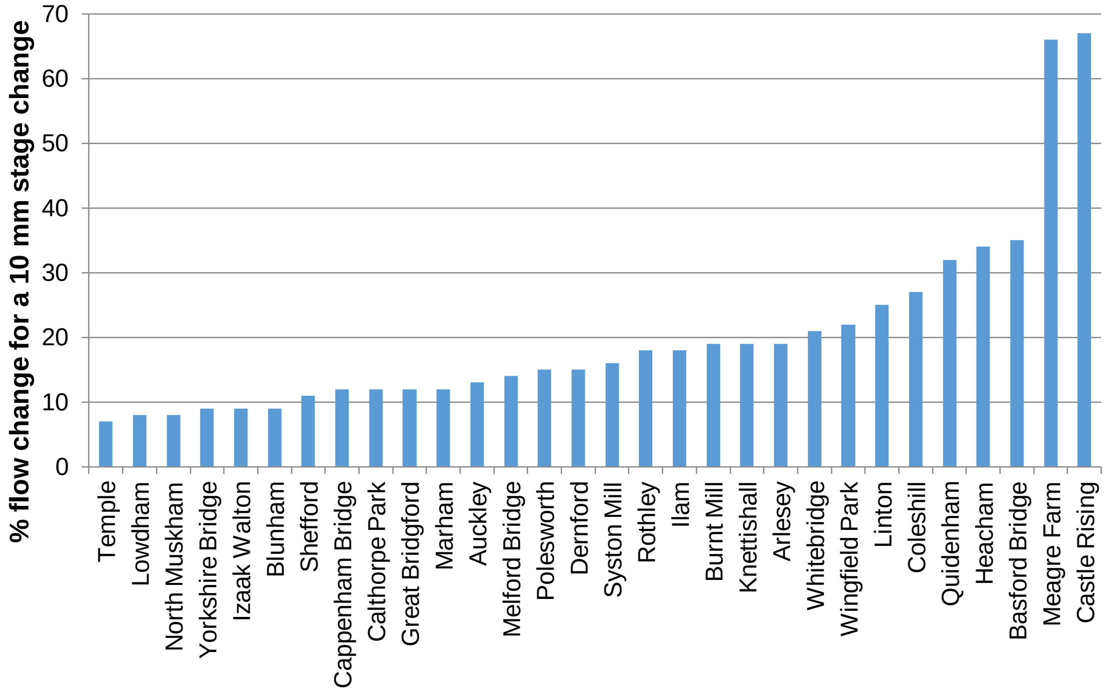
2.3.6 Determination of the degree of flow modification

Naturalised Q_{95} and mean flow statistics were estimated using Low Flows Enterprise (information on the science behind the Low Flows software is provided in Young *et al*., 2000, Holmes *et al*., 2002, Young *et al*., 2003 and Holmes *et al*., 2005) and used to determine the degree of flow modification at each of the final 10 study sites.

2.3.7 Accuracy of river flow data

The relatively modest flow and limited depth of rivers in England presents significant hydrometric difficulties, particularly at low flows (Hannaford and Marsh, 2006). Although a number of factors can combine to reduce the accuracy of flow data, of most significance is the limited water depth in watercourses – stage values corresponding to low flows are commonly less than 100mm, often less (Marsh, 2002). Given the limited depth of most watercourses in England, the accuracy of river flows depends primarily on the precision of the stage measurement. Although there have been developments in water level sensing and recording, systematic bias in measured river levels caused, for example, by datum errors, can be substantial and difficult to eliminate (Marsh, 2002).

Figure 2.5: The sensitivity of the gauging stations used in flow assessments (30 study sites; River Trent and River Great Ouse catchments)



Please note that Sensitivity values are not available for the following gauging stations: (1) Bedford Ouse at Bedford, (2) Meece Brook at Shallowford, (3) River Greet at Southwell, (4) River Idle at Mattersey, (5) River Ryton at Worksop, (6) River Sence at South Wigston, (7) River Soar at Littlethorpe and (8) River Tame at Lea Marston Lakes.

The UK Hydrometric Register includes information on the sensitivity of the majority of gauging stations located in England. The sensitivity index used is defined as the percentage change in flow associated with a 10mm increase in stage at the Q_{95} low-flow (Marsh and Hannaford, 2008). The higher the sensitivity, the greater the uncertainty in computed flows associated with a given systematic error in stage measurement. According to Marsh and Hannaford (2008) a high percentage change is indicative of an insensitive gauging station. Figure 2.5 provides an illustration of the sensitivity of the gauging stations used in this thesis.

The sensitivity of gauging stations ranges from between 7 (River Lark at Temple) and 67 (River Babingley at Castle Rising). The majority of gauging stations have sensitivity values of less than 30; five gauging stations however, have higher sensitivity values indicating a greater degree of uncertainty at low flows. Interestingly, four of these gauging stations are located within the Great Ouse catchment, Marsh (2002) identified that gauging stations in the English Lowlands are disproportionately represented in the higher error bands.

2.3.8 Flow metrics

One of the aims of this thesis was to explore the utility of a range of potential descriptors of ecological drought. A range of drought indicators were calculated within Excel. These indicators included the long-term annual Q_{95} flow duration statistic; 20 and 30 per cent of the long-term average daily flow (20% ADF and 30% ADF); the minimum and average values of the annual 7-, 20-, 30-, 50-, and 100-day minimum flow, drought indicators that combine flow magnitude and duration.

Because of the different flow recession in the Great Ouse, compared with the Trent, an expanded list of indicators was determined. These indicators include the long-term annual Q_{95} and Q_{84} flow duration statistics, and 10, 15, 20, 25, 30, 35 and 40% ADF. In addition, the temporal variability of low-flow events was explored using the 1-, 7-, 10-, 20-, 30-, and 50-day mean annual minimum (MAM) flow. Detailed information on the flow metrics and potential descriptors of ecological drought is included in Appendix 2.3 (Trent descriptors) and Appendix 2.4 (Great Ouse descriptors).

The timing of low-flow events was defined using Julian dates, and deviation of flows from monthly benchmark flows were also explored using the IHA software (The Nature Conservancy, 2009). Although the number of calendar days varies in each year depending on whether or not it is a leap year, the start and end Julian dates in each year are always 1 and 366 respectively. Leap years have a Julian date for February 29th (60), while non-leap years skip from Julian date 59 to Julian date 61. This ensures that each calendar date is represented by the same Julian date in each year (The Nature Conservancy, 2009).

In order to explore the diversity of low-flow responses across the study sites, the total number of days that daily mean flows fell below each indicator was calculated. In addition, the longest record of consecutive days that daily mean flows fell below each of the drought indicators was recorded to provide information on the spatial and temporal persistence of low flows across the Trent and Great Ouse catchments.

2.4 ANALYTICAL METHODS

The following analytical methods were employed to classify the catchments and to determine the driest years in the study periods.

2.4.1 Catchment Classification using Base Flow Index

The Base Flow Index (BFI) was used to index study sites in both the Trent and Great Ouse catchments to aid in the exploration of the variability of low-flow responses between sub-catchment types. The BFI may be thought of as a measure of the proportion of the river runoff that derives from stored sources; the more permeable the rock, superficial deposits and soils in a catchment, the higher the baseflow and the more sustained the river flow during periods of dry weather. The BFI was, therefore, considered a simple but effective means of indexing catchment geology.

2.4.2 Identification of driest years

Rainfall data was analysed in order to identify the years with the lowest annual rainfall totals in the study period and possible drought/low-flow periods. The decision to use rainfall rather than river flow data was made due to the legacy of the varying impacts of artificial influences across the study sites.

2.4.3 Statistical analyses

All statistical analyses were undertaken using IBM SPSS Statistics.

2.4.3.1 Principal Component Analysis

Data reduction by Principal Component Analysis (PCA) assists in the interpretation of flow regimes in different sub-catchments by producing a low dimensional ordinal space in which similar sites are close together and dissimilar sites are far apart (Poff *et al*., 2006). Although PCA is designed for unskewed, multinormal data (Legendre and Legendre, 1998) it is, in general, relatively robust (Beveridge *et al*., 2012) and was therefore considered a suitable statistical approach.

In this thesis PCA was utilised to summarise patterns of variation in the hydrological characteristics of multiple study sites during periods of below average rainfall. Daily mean flows standardised by the long-term average flow recorded during the three years experiencing the lowest annual rainfall were used in the PCA in order to focus on potential drought periods. Within the PCA, varimax rotation was employed to reduce the dimensionality of the flow data.

2.4.3.2 The Spearman rank correlation

The Spearman rank correlation was used to investigate the inter-annual temporal variability of a range of the potential descriptors of ecological drought. The Spearman rank correlation is a nonparametric technique for evaluating the degree of linear association or correlation between variables. The approach is similar to the Pearson's product moment correlation except that it operates on the ranks of data rather than the raw data. There are advantages to using the Spearman rank correlation coefficient, it is a nonparametric technique so is unaffected by the distribution of data, and by using ranks it is relatively insensitive to outliers.

CHAPTER 3: ENVIRONMENTAL FLOWS IN ENGLAND – THE CASE FOR HYDROLOGICAL APPROACHES

3.1 INTRODUCTION

In England, anthropogenic activities have modified the flow regimes of the majority of watercourses. Some date back more than 1000 years, with Domesday records in 1086 referring to in excess of 5000 water-mills (Gurnell and Petts, 1999). The beginning of the 19th Century saw rapid industrial expansion and urban growth (Petts, 1988) and by 1936 nearly 200 small reservoirs had been constructed in the Pennines (Gurnell and Petts, 1999) to support the highly industrialised areas of Lancashire and Yorkshire. Today the flow regimes of the majority of main rivers in England are modified by a range of anthropogenic activities. There are approximately 21,500 abstraction licences in England and Wales, only 17 per cent of licences, however, have restrictive conditions that prevent abstractions at low flows (Environment Agency, 2011). The current system for managing abstraction was introduced in the 1960s and was designed to manage competing human demands for water rather than to protect the environment (Department for Environment, Food and Rural Affairs, 2011). Concerns that many watercourses are being damaged by over abstraction, combined with uncertainties surrounding climate change and an increasing demand for water, have resulted in proposals to reform the abstraction regime.

This Chapter reviews the evolution of *e-flow* practice in England in order to establish a basis for advancing hydrological approaches to setting *e-flows* in the future. Over the decades *e-flow* research and practice has advanced through several key stages (Table 3.1). The following sections review of the evolution of *e-flow* approaches in England and assess potential constraints to developing new approaches. Then a discussion of the ecological principles for the sustainable management of water resources provides the context for advancing hydrological approaches to determine *e-flows* within England.

3.1.1 The legislative context

The legislative framework for water resources in England stretches back over more than two centuries (Barker and Kirmond, 1998). The modern era of river regulation was founded in Bills submitted to Parliament during the late 19th Century to construct large reservoirs in the Vyrnwy and in the upper Wye valleys of Wales to supply Liverpool (1880) and Birmingham (1892) respectively (Sheail, 1984; Petts, 1988). Three schemes illustrate an early awareness of the need to balance water abstractions and reservoir storage with the needs of downstream users, including the needs of fisheries. In the setting of compensation flows downstream of the proposed Vyrnwy scheme, a precedent was created by offering an additional amount ‘for flushing purposes’ (Petts, 1988). The Birmingham Water Bill of 1892 for the construction of the Elan Valley waterworks was the first occasion when attention was paid to the needs of fisheries, as opposed to industry (Sheail, 1984). Later, in 1919, a Bill to enlarge Haweswater in the Lake District included the setting of a guaranteed minimum flow with periodic freshets to improve conditions for fish-breeding (Gurnell and Petts, 1999).

Table 3.1: The evolution of *e-flow* practice in England

APPROACH	**REFERENCE(S)**
(1) Early rainfall-based approaches allocating 1/3 for compensation water - widely adopted	Montagu (1870) Lapworth (1930)
(2) Compensation water linked to rainfall, losses, character of stream flow and the user factor.	Binnie (1922) Ministry of Health (1930)
(3) Early streamflow approaches	
Compensation water based on flows during dry periods	Sandeman (1921) Dixon (1925)
(4) Sliding-scale - compensation water linked to volume of water stored in reservoir.	Blackburn (1936) Mawson (1936)
(5) Providing flows for migratory fish as percentage of average daily flow	Baxter (1961; 1963)
(6a) Minimum Acceptable Discharge: resulted in a shift towards a single, minimum flow.	Central Advisory Water Committee (1962)
(6b) Minimum Acceptable Flow	Boulton (1965)
(7) Measures of dry weather flow	
(7a) The 95th percentile/Q_{95} low-flow – widely used in England	Boulton (1965)
(7b) The Mean Annul Minimum 7-day flow	Hindley (1973)
(8) PHABSIM and IFIM	Bovee (1982; 1986)
(9) Classification approaches	
(9a) Classification of homogenous river reaches using the concept of Environmental Weighting	Drake and Sherriff (1987)
(9b) Surface Water Abstraction Licensing Procedure	Barker and Kirmond (1998)
(10) Determination of Ecologically Acceptable Flows Regimes	
(10a) Determination of environmental objectives – River Wissey case study	Petts and Bickerton (1994)
(10b) Development of a procedure for deriving an ecologically acceptable flow regime – River Babingley case study	Petts (1996)
(11) The Catchment Abstraction Management Strategy approach	Environment Agency (2002a)
(11a) The updated CAMS approach linked to the Water Framework Directive	Entec (2008)

Although there was clearly an early awareness of the need to link flow management with environmental concerns, or at least downstream users and political concerns, the legislative infrastructure needed for the detailed consideration of flows to maintain in-river needs was not in place until the Water Resources Act 1963 (Petts *et al*., 1995). The 1963 Act introduced the concept of Minimum Acceptable Flow (MAF), and although no formal MAFs were set, the MAF concept became embedded in the management of water resources in England (Petts *et al*., 1999).

Increasing human demands on water resources and growing concerns about environmental change focused attention on the need to determine, and then protect, flows to sustain riverine ecosystems (Petts *et al*., 1999). Unfortunately, until the late 1970s, river management remained more of an ‘art’ than a science (Petts, 2007), with early attempts to set instream flows focused on measures of the dry weather flow. By the early 1990s, however, the management of regulated rivers had expanded from the determination of instream flows focusing on a single target species to environmental flows (*e-flows*) (Petts, 2007). For a detailed review of the advancement of *e-flows* science refer to Petts (2009). *E-flow* approaches recognise that a single set of minimum flow constraints do not provide sufficient protection for riverine ecosystems; they incorporate flows not only for different times of the year, but also for different years to meet the flow needs of the different species (and their life stages) within a riverine-dependent community (Petts, 2007).

3.2 EARLY APPROACHES TO MANAGING RIVER FLOWS IN ENGLAND

3.2.1 Early rainfall-based approaches

Although Parliamentary Committees were quick to identify when reservoir compensation water should be given, the absence of river flow data meant that determining the quantity was challenging. Before compensation water requirements could be determined, the yield of the catchment being impounded had to be estimated. In the absence of flow data, engineers had to estimate the yield based on rainfall records (Prescot Hill, 1906). For example, one of the early pioneers of reservoir construction, Thomas Hawksley, determined the proportion of rainfall that could be economically utilised in the early schemes in North England and in Wales (Baker, 1934).

In 1868 Hawksley proposed to the Royal Commission on Water Supplies an empirical equation to calculate the reliable yield of a catchment (Sheail, 1987). Hawksley suggested this should be equal to the flow of the three driest consecutive years or approximately 80 per cent of the average rainfall less evaporation (Lapworth, 1930). This “available rainfall” or “reliable yield” could then be expressed in terms of gallons per day for the catchment under consideration (Sheail, 1984). In the United Kingdom, the first reservoir developments were in the Pennines and the quantity of compensation water was fixed as a proportion of the reliable yield during the three driest consecutive years (Sandeman, 1921).

In the Pennines, the reliable yield was found to be approximately 27” (685.8 mm) per year, but experience demonstrated that approximately 9” (228.6 mm) of run-off, or one-third of the reliable yield was considered satisfactory by the Millowners on the industrialised streams of North England. This high proportion of the reliable yield reserved for compensation water appears to have influenced subsequent awards (Risbridger, 1963). The introduction of the one-third rule for compensation water was introduced before 1870. In a paper entitled *Watershed Boards or Conservancy Boards for River Basins* dated April 28th 1870 submitted as evidence to the Royal Sanitary Commission 1869-1871, Lord Robert Montagu stated:-

> *“Again, it would be highly injurious to catch all the waters which fall from a watershed. The Legislature has always required that at least one third should flow down the ordinary channel of the river...”*

Montagu (1870); page 344.

Binnie (1922), however, emphasised that compensation awards were dealt with on a case-by-case basis with awards ranging from one-tenth up to one-half of the reliable yield.

Debates during the 1920s and 1930s indicate that the engineers employed by water companies considered that the method of calculating compensation water based on long-term rainfall records was not fit for purpose. However, given the continuing lack of river flow data, rainfall-based approaches continued to dominate until the 1960s. During the early period of reservoir development, reliable rainfall data was also scarce, with Hawksley identifying that to determine mean rainfall, between 30-40 years of data was required (Tait, 1907). Dixon (1925) observed that in many early schemes the lack of rainfall data meant that compensation was fixed by Parliament as high as 50 per cent of the reliable yield.

Sandeman (1921) provided an indication of the variation in the proportion of compensation water to available rainfall as fixed by Parliamentary Committees for a range of catchments. The data in Table 3.2 indicate that the largest proportion of compensation water was one-third and the smallest one-eighth of the available rainfall.

Table 3.2: Data as to compensation water determined by Parliamentary Committees to support early reservoir schemes

Reservoir	Autho -rised	Assumed average rainfall (mm)	Available rainfall in 3 dry years (mm)	Proportion Assumed average rainfall to Available rainfall (%)	Water for Compen-sation (mm)	Proportion Compen-sation Water to Available Rainfall (%)	Area of Catch-ment (km^2)
Thirlmere	1879	2540.0	1828.8	138.9	228.6	12.5	43.7
Loch Katrine	1855	1879.6	1148.1	163.7	381.0	33.3	187.8
Elan	1892	1752.6	914.4	191.7	251.5	27.5	178.1
Vyrnwy	1880	1549.4	937.3	165.3	251.5	27.0	89.0
Dunsop	1877	-	685.8	-	228.6	33.3	27.5
Alwen	1907	1320.8	701.0	188.4	233.7	33.3	25.5
Derwent Valley	1899	1193.8	594.4	200.8	198.1	33.3	129.5
Weardale	1866	76.2	254.0	300.0	82.6	32.5	24.3

Sandeman (1921); page 43.

Estimates of the losses due to percolation and evaporation also evolved, with a value between 14” (355.6 mm) and 15” (381.0 mm) generally adopted. Binnie (1922), however, identified that in reality, actual evaporation losses ranged from between 8” (203.2 mm) in the Highlands and 18” (457.2 mm) in Southern England. In many cases, the early estimates of losses may have been inaccurate, not least because of the lack of quantification of evapotranspiration Lloyd (1935 a,b,c and d).

Although the limited rainfall data and scientific knowledge of evapotranspiration perhaps represent the key limitations of the early rainfall-based approaches, another issue that cannot be overlooked was the limited power and influence of the Parliamentary Committees. The relatively weak position of Central Government combined with the fact that the Millowners were highly influential, meant that the Millowners were able to ensure that compensation awards contained a generous factor of safety in their favour (Risbridger, 1963).

The early schemes set local precedents and rules of thumb Parliament appeared to be keen to use as a guide in the setting of subsequent statutory compensation agreements (Sheail, 1987). It is, however, surprising given the amount of evidence against the use of rainfall-based approaches that the numerous Technical Committees (for example the Water Power Resources Committee, 1921 and the Technical Sub-

Committee on the Assessment of Compensation Water, 1930) that investigated the issue of compensation water were unable to develop a viable, alternative approach.

3.2.2 Compensation linked to rainfall, losses, character of stream flow and the user factor: Formula of the 1930 Technical Sub-Committee

A Technical Sub-Committee on the Assessment of Compensation Water was established in 1930, its context is considered in Appendix 3.1. The Technical Sub-Committee undertook a number of investigations before concluding that the volume of compensation water to be passed down any watercourse should be determined by reference to; (1) rainfall on the catchment, (2) losses due to evaporation and absorption, (3) the character of the flow of the watercourse, and (4) the user (Ministry of Health, 1930). The approach benefitted from new stream gauging data as well as lengthening rainfall records.

The Sub-Committee proposed a new formula based on new flow data that was becoming available from across the country:-

$$C = UK\,(0.8\,R - L)$$

Where:

C = compensation water
U = a user factor
K = stream characteristic
R = the long-term average annual rainfall
L = average annual loss in a three dry year period

Values of U and K were to be determined in accordance with the extent to which the watercourse was industrialised and the ‘flashiness’ of the watercourse, respectively. The stream characteristic K was calculated as the average daily flow on those days when the flow was equal to or below the mean gauged flow as a ratio of the mean daily gauged flow, therefore, flashy streams had lower K values (Sheail, 1987). The Sub-Committee suggested user factors ranging from 0.35 (rural class of riparian user) to 0.70 (fully industrialised watercourse) (Sheail, 1987). This was the first explicit recognition of catchment type – natural and human modified – in setting compensation flows.

The overall effect of applying the 1930 Formula was a reduction of existing statutory compensation awards by between 64 per cent (unindustrialised ‘flashy’ watercourse) and 28 per cent (highly industrialised ‘steady’ river) (Risbridger, 1963).

The Sub-Committee emphasised that the 1930 formula was based on limited river flow data, but Lloyd (1936) observed how the gaugings accepted by the Sub-Committee represented the few correct gauging records available in the country, indicating that the 1930 formula was based on the best (only) flow data available.

Prescot Hill (1931) noted that the 1930 Report recommended the use of flow readings during a critically dry season rather than rainfall data. He considered this to be both logical and appropriate, but doubts were raised as to whether it would be feasible in the near future to adopt the proposals due to the lack of available flow data.

Although the Ministry of Health accepted the proposals of the Technical Sub-Committee, they recommended that the 1930 formula should be adopted with one modification that losses due to absorption should be taken as 15” (381.0 mm) in all cases. However, in 1936, after hearing detailed evidence from individuals representing a wide range of interests and organisations, the Joint Committee on Water Resources and Supplies rejected the modified 1930 formula. Noting that the application of the formula would have resulted in a significant reduction in some existing statutory compensation awards, the Joint Committee doubted that Parliament could have been so seriously in error when the compensation awards were originally fixed (Sheail, 1984).

3.2.3 Early streamflow approaches

In the 1920s and 1930s engineers recognised that it was preferable to base compensation water on gaugings of the stream to be impounded. Flows had seldom, if ever, been efficiently gauged for a sufficiently long period (Mawson, 1936), and incomplete flow records would be misleading. Lapworth (1930) recognised that few, if any, records of flows recorded during dry periods existed and argued that it was data covering the fluctuations of stream flows during the driest years that were most urgently required.

Nevertheless, Sandeman (1921) had postulated that when determining compensation flows, some regard should be had to the natural flow of the river in dry periods. Dixon (1925) found it strange that when setting compensation flows, all parties had totally ignored the actual conditions of the dry weather flow, resulting in higher than natural flows in watercourses downstream from reservoirs. In order to demonstrate the manner in which river flows had been artificially increased by compensation water, Sandeman (1921) provided the data in Table 3.3.

Table 3.3: Comparison of compensation water with dry weather flow

Reservoir	**Compensation Water (m^3s^{-1})**	**Dry Weather Flow**			**Proportion of Compensation Water to Dry Weather Flow of**		
		1 Day (m^3s^{-1})	**1 Week (m^3s^{-1})**	**1 Month (m^3s^{-1})**	**1 Day**	**1 Week**	**1 Month**
Elan	1.421	0.210	-	-	6.75	-	-
Vyrnwy	0.710	0.126	0.134	0.205	5.6	5.3	3.5
Dunsop	0.200	0.095	0.100	0.116	2.1	2.0	1.7
Alwen	0.189	0.010	0.014	0.025	19.0	14.0	7.7
Derwent	0.800	0.263	0.316	0.400	3.0	2.5	2.0
Weardale	0.064	-	0.008	-	-	7.5	-

Adapted from Sandeman (1921); page 44

The data in Table 3.3 highlights one of the key issues surrounding the use of the dry weather flow to determine compensation water; how should the dry weather flow be defined? Sandeman (1921) considered that using the dry weather flow based on one week’s data to compare against existing compensation water awards was reasonable.

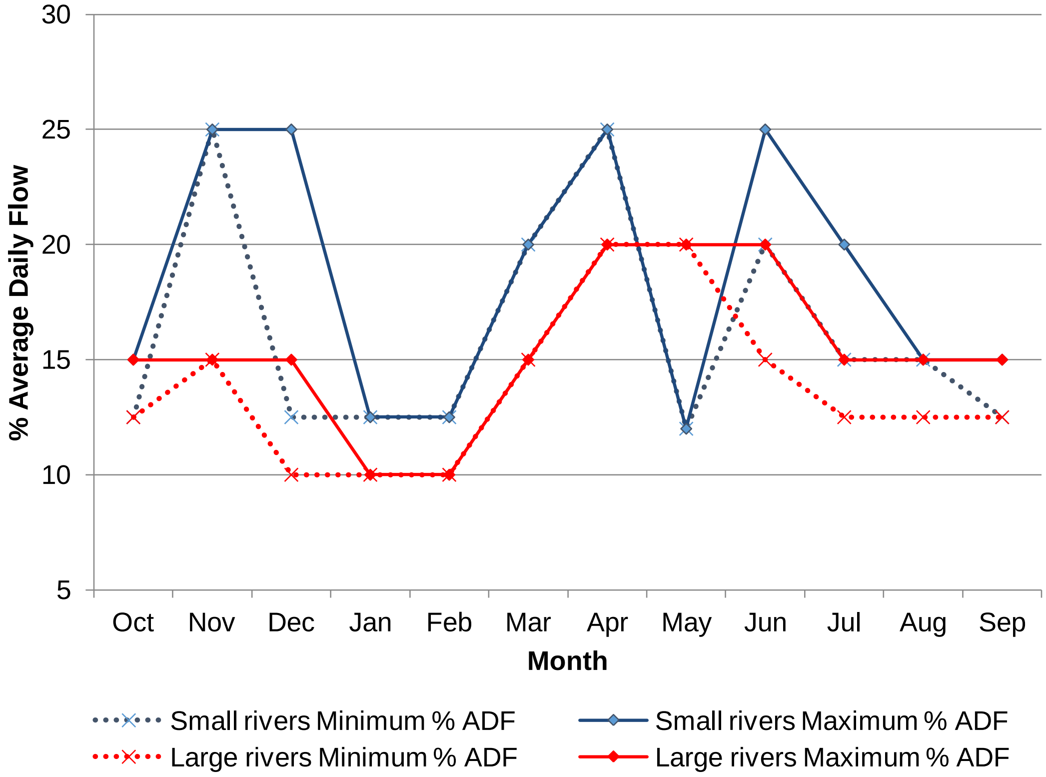
Mawson (1936) outlined proposals for a new approach to setting compensation water that incorporated four emerging principles: (a) compensation should be based on the maximum amount of water to be abstracted; (b) regard should be had to the relative importance of the stream and to the extent that the watercourse is populated and industrialised; (c) the method of discharging compensation water should enable riparian interests to derive the maximum benefit from the impounding of the stream; and (d) all compensation awards should be reviewed when actual flow conditions are understood. With regard to the third principle, Mawson (1936) proposed that compensation water should be discharged on a sliding-scale graded according to the reservoir storage with compensation being automatically increased in wet years and decreased during dry years. Similarly, Blackburn (1936) advocated the use of an alternative sliding-scale approach for compensation water, this time based on the quantity of water in a reservoir during the winter months, with a minimum daily rate during the summer months based on the observed flow of the driest month.

3.2.4 Providing flows for migratory fish as a percentage of the average daily flow

A detailed review of the alternative approach to setting compensation flows proposed by Baxter (1961; 1963) is included in Chapter 4, therefore, only the key points of the approach are considered here. Baxter (1961; 1963) introduced a new hydrological approach to setting the compensation flows required for the protection of fish.

Internationally of potential significance, this work preceded that in the United States by Don Tennant (1976), which advocated a similar approach, be more than a decade. Baxter expressed the compensation flow as a fixed percentage of the average daily flow, and included a 'Schedule of Flows' for migratory fish (Figure 3.1).

Figure 3.1: Schematic illustrating Baxter's (1961) Schedule of Flows for migratory fish



Adapted from Baxter (1961); page 240.

When investigating the requirements of fish, Baxter (1961) identified the unsuitability of the traditional fixed rate of compensation water based quantitatively on yield and unrelated to ecological requirements. Indeed, Baxter (1961) was perhaps one of the first to identify the need for a variable flow regime based on the seasonal requirements of the fish and of the character of the river. It is, therefore, unfortunate that the approach proposed by Baxter (1961; 1963) was never implemented. Such an approach would have represented a move towards linking together instream flows with temporally variable ecological requirements. Chapter 4 provides a detailed review of the reasons for the failure for the adoption of Baxter's pioneering work.

3.3 MINIMUM ACCEPTABLE DISCHARGE

The 1962 Proudman Report introduced the concept of the Minimum Acceptable Discharge (MAD), defined as:-

> *"The minimum discharge, or level corresponding thereto (defined from time to time by the river authority having regard to the needs of all interests downstream) below which the flow in the river or stream at the point of reference should not be diminished by abstractions"*

Central Advisory Water Committee (1962); page 37.

Although no further guidance was provided in the Proudman Report, Petts *et al*. (1996) were of the opinion that the concept of MAD was fundamental to a view of river management which was based on comprehensive rationality as opposed to incremental decisions based on licence applications.

Bleasdale *et al*. (1963) identified that a MAD was a quantity that could not be determined using a mathematical formula, as it depended solely on the needs of those interested in the use of the river downstream of a reservoir. Bleasdale *et al*. (1963) referred to cases quoted in the Severn Hydrological Survey (Ministry of Housing and Local Government, 1960a); in three of the four cases the MAD had been set at 1.5 times the minimum flow to which the natural river had been known to fall to in drought periods. However, in two cases in the Wear and Tees Hydrological Survey (Ministry of Housing and Local Government, 1961), the MAD was as low as approximately 1/30 of the long-term mean flow (Bleasdale *et al*., 1963). Bleasdale *et al*. (1963) proposed that a possible basis for determining the MAD in a fishing river could be that a proportion of the reservoir capacity (10 to 25 per cent) should be allocated for improvement of the flow in the river below the abstraction points, and the remainder to support the actual abstraction.

Although in England compensation flows have been set downstream of reservoirs by Acts of Parliament for over 100 years (Gustard *et al*., 1987), it was not until the 1963 Water Resources Act that general provision for controlling abstraction where necessary and the setting of a Minimum Acceptable Flow (MAF) was introduced (Petts *et al*., 1996, Dunbar *et al*., 2004). A formal procedure for consultation, making the actual settings, and the preparation of statements for the Minister on MAFs was presented in

Sections 19 to 22 of the Water Resources Act 1963 (Bradford, 1981). Additional information on the 1963 Water Resources Act is provided in Appendix 3.1.

Although there was no precise legal definition of a MAF (Petts *et al*., 1999), the 1963 Act stated:

> *"In determining the flow...the river authority shall have regard to the character of the inland water and its surroundings...and to the flow of water therein from time to time; and the flow so specified shall be not less than the minimum which in the opinion of the river authority is needed for safeguarding the public health and for meeting (in respect both of quantity and quality of water) the requirements of existing lawful uses of the inland water, whether for agriculture, industry, water supply or other purposes, and the requirements of land drainage, navigation and fisheries, both in relation to that inland water and in relation to other inland waters whose flow may be affected by changes in the flow of that inland water"*

Section 19 (5) Water Resources Act 1963.

The 1963 Act stimulated considerable discussion. Notably, Boulton (1965) provided information on the key factors likely to enter into the determination of MAFs. Boulton (1965) considered; river flow, regulation of flow, existing use, quality and temperature and river use (land drainage and land use, fisheries, ecology, siltation, amenity and navigation). However, Boulton (1965) emphasised that the MAF was a user, not a hydrological, concept. He believed that the flow record should cover a long period, and not less than five consecutive years including a period of 'severe drought'.

Boulton (1965) stressed the need to consider the setting of MAFs on a case by case basis. However, he felt that it was not likely to be practicable or desirable to specify the MAF for all of the watercourses in an area; points of control of the main rivers would probably be determined, and these would represent the control to be exercised over the catchment above and below the control point. The control would be supplemented by provisions contained in licences as to the manner of abstraction (Boulton, 1965). The discussions in Boulton (1965) contain some very valuable information, representing a range of different interests, key points are summarised in Appendix 3.2.

Although in practice no formal MAFs were set (Petts *et al*., 1999), the less formal policy of using prescribed flows was adopted (Bradford, 1981). Consequently, the MAF concept has become embedded (Petts *et al*., 1999) in the control of abstraction licenses and in the management of water resources in England.

3.4 MEASURES OF DRY WEATHER FLOW

Within England two flow metrics emerged as the most widely used measures of dry weather flow (DWF); the 95th percentile flow and the mean annual minimum (MAM) 7-day flow frequency statistic.

3.4.1 The 95th percentile Q95 flow

Within England much emphasis has been placed on the 95th percentile flow (Q_{95}), the flow which is exceeded for 95 per cent of the time or on all but 18 days per year, with most surface water licensing policies based on the Q_{95} low-flow (Pirt, 1983). The Q_{95} flow was adequate to protect rivers in the majority of cases because only a small proportion of the available resource was actually abstracted, and abstractions were allocated from the reliable baseflow component of the annual hydrograph (Gurnell and Petts, 1999).

One of the key limitations surrounding the use of Q_{95} as an *e-flow* relates to the fact that previous studies have found the Q_{95} flow to be an unstable statistic unless the flow record exceeds 12 years (Pirt and Douglas, 1982). Increasing pressure on water resources and the increased use of the 'stacking' of licenses led not only to the greater exploitation of the reliable baseflow, but also to abstractions during periods of higher flow; flows available to the environment declined resulting in the need to define *e-flows* more precisely (Gurnell and Petts, 1999).

3.4.2 Mean Annual Minimum 7-day flow

Hindley (1973) highlighted the lack of a universally accepted definition for the DWF of a river and developed a new concept, the seven-day minimum flow defined as:-

> *"...the lowest total discharge occurring over seven consecutive days in any year expressed as a mean daily flow being the average daily flow over those seven days".*

Hindley (1973); page 439.

Once the annual seven-day minimum flow for each year was determined, the DWF of the river was defined by Hindley (1973) as:-

> *"...the average of all the seven-day minimum flows for all the years of record".*
>
> Hindley (1973); page 440.

Pirt and Douglas (1982) identified the index of DWF developed by Hindley (1973) as a more stable statistic than the Q_{95} flow as it gives equal weight to each year. In addition, the seven day period covered by the DWF was identified as being important as it eliminates the day to day variations in the artificial component of river flow, notably the reduction in abstraction and effluent returns frequently seen at weekends (Pirt, 1983).

3.5 INSTREAM FLOW INCREMENTAL METHODOLOGY (IFIM) AND PHYSICAL HABITAT SIMULATION (PHABSIM)

One fundamental limitation of hydrological approaches is the exclusion of any explicit consideration of habitat requirements (Petts and Maddock, 1996). PHABSIM developed in the late 1970s in the United States (Bovee, 1982; 1986) provided an approach to integrate changing hydraulic conditions with discharge and the habitat preferences of biota (Petts and Maddock, 1996). PHABSIM relies on three principles; (1) the chosen species exhibits preferences within a range of habitat conditions that it can tolerate; (2) these ranges can be defined for each species; and (3) the area of stream providing these conditions can be quantified as a function of discharge and channel structure (Petts, 2009). Considerable efforts, e.g. Kondolf *et al*. (2000), have been spent on attempts to assess the ecological integrity of PHABSIM by demonstrating the biological significance of carrying capacity as a limiting factor of population size (Petts, 2007).

Following trials in the early 1990s, the PHABSIM approach has been used in a number of applied studies in England and Wales with Acreman *et al*. (2008b) identifying 78 study sites. According to Spence and Hickley (2000) typical PHABSIM applications have included investigation of the following; (1) alleviation of low flows: impacts of abstractions, the effect of compensation discharge solutions; (2) reservoirs: minimum maintained flows to protect fish spawning, compensation needs; (3) general licensing: renewal of time-limited licences, determination of optimum flow regimes to set restrictions on licences; (4) drought management: impact of temporary changes to allowable abstraction rates or reservoir compensation releases; and (5) habitat improvements: restoration schemes associated with flood defence schemes.

In 1996, PHABSIM was scrutinised during the Axford Public Inquiry. PHABSIM had been used as part of an assessment of the impact of groundwater abstraction at Axford on the River Kennet, a low-flow chalk stream. The Inquiry Inspector concluded that PHABSIM was a suitable tool for assessment and that it had been correctly applied (Dunbar *et al*., 2002). However, issues surrounding the transferability of habitat suitability data from the River Piddle, a relatively natural chalk stream, to the River Kennet were raised. In addition, questions surrounding the representativeness of the PHABSIM reaches on the River Kennet were also asked (Dunbar *et al*., 2002). Following the Axford Inquiry the Environment Agency concluded that further testing of PHABSIM was important to ensure that water resource management decisions made on the basis of the model were robust and capable of withstanding detailed examination (Dunbar *et al*., 2002).

3.5.1 Critique of PHABSIM

Within PHABSIM, habitat suitability curves are combined with the computed cell water depth, velocity and substrate in order to calculate the Weighted Usable Area (WUA). Much criticism has centred on the biological meaning of the WUA concept. WUA implicitly considers each habitat unit as biologically equivalent (Bovee, 1982). Research (e.g. Orth, 1987) however, has indicated that large areas of less than optimum habitat do not have the same capacity as small areas of optimum habitat. Other criticisms include the lack of development for use with invertebrates and plant species (Acreman *et al*., 2005) and the patchiness of validation for example Nehring and Anderson (1993). Some of the early criticisms centred on deficiencies in the original version of PHABSIM (Acreman *et al*., 2005). Other criticisms appear to have been based on a misunderstanding of the PHABSIM approach and unrealistic assumptions as to the capabilities of PHABSIM.

In spite of the widespread application of PHABSIM, the approach has received criticism (e.g. Orth and Maughan, 1982; Mathur *et al*., 1985). However, some criticisms are based on testing assumptions that are unrealistic or due to a lack of understanding of how PHABSIM actually works. PHABSIM has been used in water resources decision making in over 20 countries (Petts. 2009) and represents the most widely applied habitat simulation *e-flow* approach suggesting that there is, at least in some areas, widespread acceptance of both the approach and of the theory and assumptions behind the approach. Away from the United States, however, in countries with different legal systems, acceptance of the approach has been rather cautious (Petts *et al*., 1995).

3.6 CLASSIFICATION APPROACHES

3.6.1 Classification of homogeneous river reaches using an Environmental Weighting: Drake and Sherriff 1987

In England, prior to 1989 there was no uniform methodology for the setting of prescribed flows but there were a number of policies sharing many common elements (Barker and Kirmond, 1998). For many years, the importance of ‘river-type’ had been a recurrent theme in discussions on compensation flows; this was advanced for rivers in Yorkshire by Drake and Sherriff (1987). This approach classified homogenous river reaches using an environmental weighting derived from scores based on the local significance of (1) fisheries, (2) angling, (3) aquatic ecology, (4) terrestrial ecology, (5) amenity, and (6) recreation (Drake and Sherriff, 1987). For each river a maximum permitted volume of abstraction was derived by factoring the environmental weighting and the DWF (Barker and Kirmond, 1998).

Drake and Sherriff (1987) identified that using seasonal volume limitation to control abstraction would still allow abstraction during low flows; abstractions were, therefore, limited by applying prescribed flows. Values for prescribed flows were determined by taking into account (a) the river environment, (b) downstream water quality objectives, and (c) the rights of existing licensed abstractors (Drake and Sherriff, 1987). As water quality objectives had to be taken into account, Drake and Sherriff (1987) decided that the best approach would be to calculate both the minimum flow required for environmental protection and for the protection of water quality.

Using the environmental weighting as a measure of the environmental sensitivity of rivers, a relationship was derived between the environmental weighting and an ‘environmental prescribed flow’ (Drake and Sherriff, 1987). Environmental prescribed flows were expressed in terms of a simple multiple of DWF. The environmental prescribed flow of the most sensitive rivers was set at 1.0 x DWF, and at 0.5 x DWF for the least sensitive rivers (Drake and Sherriff, 1987).

3.6.2 Surface Water Abstraction Licensing Procedure

The National Rivers Authority appointed consultants to develop previous work into a simple, reliable guidance for abstraction licence determination (Barker and Kirmond, 1998). The main drivers for the work were to protect the river environment and adjacent habitats as well as protecting the existing abstraction rights and other legitimate uses of the river (Barker and Kirmond, 1998). Three basic principles underpinned this approach:-

(1) Protection of low flows was fundamental, as was ensuring that naturally occurring low flows were not artificially reduced.
(2) The occurrence, frequency, magnitude and duration of high flows were identified as important factors in shaping the river channel.
(3) The maintenance of flow variability between these two extremes was considered important.

The results of this work were developed into the Surface Water Abstraction Licensing Procedure (SWALP). The SWALP also used the concept of environmental weighting to classify each reach of a watercourse according to an aggregation of scores for physical characteristics, ecology and fisheries. Each characteristic could score from 1 to 16 according to sensitivity to changes in flow (giving an overall range of environmental weighting score of 3 and 48) (Barker and Kirmond, 1998).

Scores were based on the current ecological status of the catchment that could be ‘impacted’ rather than the potential status although allowance was made for improvements likely to occur in the short term (Logan, 2001). Logan (2001) identified a possible issue with this methodology, that a highly sensitive component could be downgraded by lower classes in the other two components.

The overall class was then related to a series of flow management regimes. The important aspects of these management regimes were (1) the concept of the HOF, and (2) differential ‘take’ for rivers of different sensitivities (Logan, 2001). Higher HOFs were set for more sensitive rivers and differential take was achieved by differentiating between rivers with different sensitivities; a lower percentage take was permitted for sensitive rivers. Table 3.4 summarises the use of environmental weighting within the SWALP procedure to derive abstraction controls.

Table 3.4: Environmental Weighting to deduce abstraction controls

Total EW Score[1]	Band	HOF[2]	INT[3]			TAKE[5] %
			1st (INT1)	2nd (INT2)	3rd+ (INT3)	
41-48	A	QN95	0.1K[4]	0.3K	0.5K	25
31-40	B	QN95	0.1K	0.3K	0.6K	25
21-30	C	QN95	0.2K	0.4K	0.7K	50
11-20	D	QN98	0.2K	0.5K	0.8K	75
10-less	E	QN99	0.3K	0.6K	0.9K	75

[1] Based on exceedance values of naturalised flow sequence

[2] The level stated here for hands-off flow (HOF) is based on environmental weighting only and may be over-ridden by other considerations for example flow already committed to downstream users

[3] INT is the interval between successive flow thresholds

[4] $K = (QN_{50} – QN_{95})$

[5] TAKE is the licensable proportion of INT

Barker and Kirmond (1998); page 255.

The SWALP was viewed as creating a framework allowing the rapid, consistent, defensible determination of abstraction licences in a way which balanced the needs of abstraction and the aquatic environment (Barker and Kirmond, 1998). However, in March 1999 the Government published *Taking Water Responsibly* which outlined its decisions following consultation, on changes to the abstraction licensing system (Environment Agency, 2002a). Foremost among these changes was the requirement of a national approach to the estimation of the ‘environmental needs’ for water within the catchment (Logan, 2001).

3.7 THE CATCHMENT ABSTRACTION MANAGEMENT STRATEGY (CAMS) APPROACH 2001-2008

The CAMS process was launched in 2001 with the aim of providing a consistent and structured approach to local water resources management, recognising both abstractors’ reasonable needs for water and environmental needs (Environment Agency, 2002a). The first CAMS cycle was completed in 2008 providing information on water resources availability across England for the first time. Central to the CAMS process is the resource assessment and management (RAM) framework which aims to provide a consistent technical approach to water resources assessment through the quantification of both the natural availability of water and the current level of water use within a defined catchment (Holmes *et al*., 2005).

During the first CAMS cycle the *e-flow* needs of a river were related exclusively to the sensitivity of the ecosystem to reduced flow, with the RAM framework focussing on the production of an ecologically acceptable flow duration curve. The ‘sensitivity’ of the ecosystem was determined through the consideration of four elements; (1) physical characterisation; (2) fisheries; (3) macrophytes; and (4) macroinvertebrates.

Each element was given a score from 1 (least sensitive) to 5 (most sensitive). The scores were then combined to categorise a river into one of five Environmental Weighting Bands, Band A the most sensitive (average score of 5) and Band E the least sensitive (average score of 1) (Acreman and Dunbar, 2004). RAM then specified allowable abstractions at different flow percentiles for each weighting band. Table 3.5 summarises the percentage of Q_{95} that could be abstracted for different environmental weighting bands within CAMS.

Table 3.5: Percentages of Q_{95} that can be abstracted for different Environmental Weighting bands within CAMS

Environmental Weighting Band	Flow Sensitivity	Percentage of Q_{95} that can be abstracted
A	Very High	0-5
B	High	5-10
C	Moderate	10-15
D	Low	15-25
E	Very Low	25-30
Others		Special Treatment

Acreman *et al*. (2008a); page 1116.

Acreman and Dunbar (2004) emphasised that the allowable abstractions in Table 3.5 were not well supported by hydro-ecological studies. The methodology used to determine the ‘sensitivity’ of the ecosystem therefore raised important questions. Furthermore, although the flow duration curve retains many characteristics of the flow regime, for example the basic magnitude of low flows and floods; it does not retain some of the other characteristics such as the duration and timing of flows known to be important to river ecosystems (Poff *et al*., 1997). The introduction of the European WFD meant that the CAMS process had to evolve.

3.7.1 CAMS and the Water Framework Directive

The European WFD came into force in December 2000. Under the WFD Member States are obliged to maintain or restore all surface waterbodies to GES by 2015. The exceptions to this are heavily modified waterbodies which must achieve GEP by 2015. Both GES and GEP are defined by using biological quality elements (fish, macroinvertebrates and macrophytes). Associated hydromorphological quality elements (flow regime and elements of the channel structure) support the biological quality elements rather defining status in their own right (Acreman *et al*., 2008a). Although the WFD placed ecology at the centre of *e-flow* definition, the WFD itself does not specify the measures required to restore or maintain GES. Each country was left with the task of defining environmental standards such as maximum abstraction rates and flow releases from dams (Acreman and Ferguson, 2010).

E-flow standards to inform the WFD resource assessments were determined through two projects; WFD 48 (Acreman *et al*., 2006; 2008a) and WFD 82 (Acreman, 2007; Acreman *et al*., 2009). Work in both was limited to defining *e-flows* using existing science and data (Acreman and Ferguson, 2010) including the RAM framework of the CAMS process. One of the outputs from WFD 48 was a set of look-up tables for various river types specifying the maximum allowable abstraction at a range of flows.

The initial standards were reviewed along with assessments of the impacts of standards defined in CAMS by the Environment Agency. The Environment Agency identified very few examples of degraded river ecosystems that could be attributed to inappropriate abstraction limits in CAMS (Acreman *et al*., 2008a).

Nevertheless, it was felt that standards for GES did not need to be significantly tighter than those defined in the existing CAMS guidance. The final standards are therefore, broadly consistent with the percentages of flow that can be abstracted for different environmental weighting bands under CAMS, with the addition of seasonal variations for the WFD environmental standards (Acreman *et al*., 2008a).

3.8 THE CURRENT CATCHMENT ABSTRACTION MANAGEMENT STRATEGY APPROACH

In the first CAMS cycle, scenario flows (recent actual and fully licensed) were assessed against Ecological River Flow Objectives (ERFOs). In the current CAMS, Environmental Flow Indicators (EFIs) have replaced ERFOs. EFIs were developed following a review of the first cycle CAMS results and of the standards recommended in the WFD 48 project (Entec, 2008). The EFI represents a fundamental component in the assessment of water availability Environment Agency (2013), and is described as a percentage deviation from the natural flow represented using a flow duration curve. This deviation differs at different flows and according to the sensitivity of the river to changes in flow (Environment Agency, 2013).

The CAMS RAM framework uses map based, physical parameters to predict abstraction sensitivity bands (the new environmental weighting), with associated allowable abstraction impact limits (Entec, 2008). The EFIs are broadly similar, with local variations to the ERFOs used in the first CAMS cycle. EFIs permit abstraction impacts on flows between 10 to 20 per cent of the natural Q_{95} (the range was previously 5 to 30 per cent). In addition, abstraction sensitivity is determined on the basis of similar components (physical character, expected fish and macroinvertebrate communities) (Entec, 2008).

Resource availability within CAMS is expressed as a surplus or deficit of water resources in relation to the EFI. According to the Environment Agency (2013) the difference between the fully licensed scenario flow and the EFI determines the volume of water available for abstraction and also when the water is available. The use of a fixed hands-off flow remains central to the CAMS approach. In the current CAMS, the EFI is defined for four flow conditions ranging from ‘naturally low’ (Q_{95}) to ‘naturally higher’ (Q_{30}) flows (Environment Agency, 2013). To help manage abstraction at higher flows and to protect flow variability, greater percentages of flow are allowed to be abstracted (Environment Agency, 2013). Table 3.6 summarises the acceptable abstraction limits at different flows.

Table 3.6: Percentage allowable abstraction from natural flows at different abstraction sensitivity bands

Abstraction Sensitivity Band	**Q_{30}**	**Q_{50}**	**Q_{70}**	**Q_{95}**
ASB3: High Sensitivity	24	20	15	**10**
ASB2: Moderate Sensitivity	26	24	20	**15**
ASB1: Low Sensitivity	30	26	24	**20**

Environment Agency (2013); page 2.

The current approach represents a simplification of the five bands, 5 to 30 per cent range system used in the first CAMS cycle and also a more consistent approach to determining sensitivity to abstraction (Entec, 2008). Reviews of the outcome of the first CAMS cycle indicated that this simplification was justified (Entec, 2008).

3.8.1 Critique of the CAMS approach

The CAMS process provides a consistent approach to abstraction licensing and represents a major step forwards towards the consistent management of water resources in England (Dunbar *et al*., 2004). The first cycle CAMS process included participation of interested parties through stakeholder groups. These normally included abstractors (water supply companies, industries and farmers), other water users (navigation and fishing) and local wildlife groups (Acreman and Dunbar, 2004). Stakeholder engagement enabled transparency and openness in CAMS, although Acreman and Dunbar (2004) were of the opinion that stakeholder involvement was consultative rather than truly participatory. Unfortunately, the current CAMS approach does not incorporate stakeholder involvement.

The CAMS process provided the Environment Agency with the first comprehensive baseline of water availability in England and Wales (Environment Agency, 2008a), enabling information on water resources availability to be made publicly available. The CAMS process also introduced a more flexible approach to licensing through the granting of time-limited licences and licence trading (Dunbar *et al*., 2004). Prior to CAMS, the majority of abstraction licences issued since the 1963 Water Resources Act were not time-limited.

The requirement for a nationally consistent approach to the estimation of the environmental needs for water within catchments was outlined by the Government in March 1999 in *Taking Water Responsibly*. Prior to CAMS, a number of methods had been developed, frequently concentrating on the Q_{95} low-flow (Waddingham *et al*., 2008), and there was little consistency to determining *e-flows*. The RAM framework aimed to integrate surface and groundwater resources to; (1) reflect the varying sensitivity to flow of different biota and habitats; (2) protect low flows and flow variability; and (3) produce an easily understood, structured and consistent method which explicitly included uncertainty, and allowed the setting of catchment wide *e-flows* in a consistent and objective manner (Dunbar *et al*., 2004).

Two of the most frequently cited limitations of the RAM framework are the use of flow duration curves and the fact that *e-flow* requirements are related purely to the sensitivity of the ecosystem to abstraction. Following the calculation of abstraction sensitivity bands, RAM specifies allowable abstractions at different flow percentiles for each band. Acreman and Dunbar (2004) emphasise that the values used in the first CAMS cycle were not supported by hydro-ecological studies. These values were, however, intended as a default and more detailed methods such as habitat modelling (PHABSIM) were recommended for sites where more accurate *e-flows* needed defining.

Following the calculation of the environmental weighting or abstraction sensitivity band, the RAM framework focused on producing an ‘ecologically acceptable’ flow duration curve. Flow duration curves have represented a fundamental tool in water resources assessments for many decades (Acreman, 2005), and retain some of the characteristics of the flow regime, for example flow magnitude. They do not however, retain other characteristics including temporal sequencing, duration or timing of flows (Acreman *et al*., 2005). These characteristics are now widely recognised as being important for the river ecosystem (e.g. Poff *et al*., 1997). In addition, the RAM framework used an annual flow duration curve which does not allow for the ecological importance of flows at different times of the year for example for spawning and migration (Acreman *et al*., 2005).

The second fundamental limitation surrounds the concept of sensitivity to abstraction. Before the overall environmental weighting or abstraction sensitivity could be calculated, four different elements (physical character, fish, macroinvertebrates and macrophytes) were scored based on sensitivity to flow modification due to abstraction. Recognising the need for increased research into the concept of ecological sensitivity to flow modification due to abstraction, the Environment Agency and the Centre for Ecology and Hydrology undertook a research project entitled Rapid Assessment of the Physical Habitat Sensitivity to Abstraction (RAPHSA) between 2002 and 2006. Part of the RAPHSA project was an assessment of the sensitivity of changes in river hydraulics caused by different types of abstraction for rivers and the different RAM classes (Booker *et al*., 2006a) used in the first CAMS cycle.

Results of the assessment of sensitivity to abstraction in relation to RAM class of; (1) change in weighted usable area for 10 per cent reduction in flow; (2) change in wetted area for 10 per cent reduction in flow, and (3) change in mean velocity for 10 per cent reduction in flow were evaluated in detail. The analysis found no evidence that sites with higher RAM scores (4 and 5) are more sensitive to abstraction in terms of loss of wetted area, weighted usable area or velocity than sites with lower RAM scores (1 and 2) (Booker *et al*., 2006b). The results raised important issues surrounding the ability of the RAM classes used in the first CAMS cycle to differentiate between sites with different sensitivities to abstraction. As no significant differences were indentified between sensitivity to abstraction in different RAM classes, the use of physical characterisation in the RAM framework was reviewed during the RAM review undertaken by Entec (2008).

Limitations in the CAMS process relating to the availability of data must also be highlighted. The RAM framework requires a large quantity of data in order for accurate information on water availability to be produced. Fundamental to the CAMS process and the RAM framework is natural flow data. In some CAMS natural flow data was estimated using tools such as Low Flows 2000 and Low Flows Enterprise. In other catchments natural flow data was obtained from rainfall-runoff models, groundwater models and gauged flow naturalisation. Given the fundamental importance of natural flow data within the CAMS process this inconsistency raises concerns. The representation of artificial influences (impoundments, discharges, abstractions and transfers of water) was also highly dependent on data availability. As impoundments and discharges often have the largest influence on the low-flow regime this highlights another potential issue.

Other limitations in the CAMS process are a result of a range of both current and historical legislative and regulatory constraints. All assessments in the current CAMS cycle are based on natural flows, as the default requirement of the WFD is to work towards achieving or maintaining GES. As the WFD reference flow is always natural, the use of higher than natural ‘benchmark’ flows considered in the first CAMS cycle is no longer appropriate (Entec, 2008). The RAM ledger now flags up discharge-rich catchments where further resources should be available, and where it may be reasonable to consider protecting flows higher than the default EFIs (Entec, 2008).

Finally, Waddingham *et al*. (2008) raise an important issue when they highlight how increases in flow regime have usually been regarded as positive, or at least not detrimental to river ecology. Initial characterisation for the WFD suggested that as many or more river reaches are ‘discharge-rich’ as are over abstracted. As a result, Waddingham *et al*. (2008) felt that this means the position on artificially higher flows should be reviewed.

3.9 ECOLOGICAL PRINCIPLES UNDERPINNING ENVIRONMENTAL FLOWS

Over the past three decades, increasing human demands upon water resources has led to growing concerns about environmental change and focussed attention on the need to determine, and then protect, flows to sustain riverine ecosystems (Petts *et al*., 1999). Petts (1996) identified that traditionally within England the provision of flow controls has generally only considered minimum flows and developed the concept of ‘ecologically acceptable flows’. Detailed information on the procedure is provided in Section 3.11.1.

3.9.1 The Natural Flow Regime paradigm

An awareness that flow management approaches were failing to recognise a fundamental scientific principle, that the integrity of flowing water systems depends largely on their natural dynamic character, led Poff *et al*. (1997) to propose the natural flow regime paradigm. The paradigm was based on the premise that streamflow can be considered a ‘master variable’ (Power *et al*., 1995) limiting the distribution and abundance of riverine species and also regulating the ecological integrity of flowing water systems (Poff *et al*., 1997). The paradigm proposes that the structure and function of riverine ecosystems, and the adaptations of their constituent aquatic and riparian species are dictated by patterns of both intra- and inter-annual variation in river flows (Kennard *et al*., 2010a).

A number of ecologically important streamflow characteristics constitute the natural flow regime. These include the seasonal patterning of flows; timing of extreme flows; the frequency, predictability, and duration of floods, droughts, and intermittent flows; daily, seasonal, and annual flow variability; and rates of change (Poff *et al*., 1997; Olden and Poff, 2003).

3.9.2 Ecological principles for the sustainable management of water resources

The fundamental ecological principles for the sustainable management of water resources have been summarised by Naiman *et al*. (2002) focusing on the need to sustain flow variability that mimics the natural, climatically driven variability of flows (Petts, 2007). There are three key principles (Petts, 2007):

(1) The natural flow regime shapes the evolution of aquatic biota and ecological processes.

(2) Every river has a characteristic flow regime and an associated biotic community.

(3) Every river sector has a channel form determined by the interaction of the flow regime with the available sediment load, within a valley of particular slope and width, modified by the type of riparian woody debris.

From these Bunn and Arthington (2002) elaborated a number of principles for advancing the provision of *e-flows*:

(i) Flow is a major determinant of physical habitat in rivers, which in turn is a major determinant of biotic composition.
(ii) Maintenance of the natural patterns of connectivity between habitats (a) along a river and (b) between a river and its riparian zone and floodplain, is essential to the viability of populations of many riverine species.
(iii) Aquatic species have evolved life history strategies primarily in response to the natural flow regime and the habitats that are available at different times of the year.
(iv) The invasion and success of exotic and introduced species along river corridors is facilitated by regulation of the flow regime, especially with the loss of natural wet dry cycles.

There is now wide recognition and acceptance that a dynamic, variable water regime is required to maintain the native biodiversity and ecological characteristic of riverine and wetland ecosystems (e.g. Poff *et al*., 1997; Postel and Richter, 2003; Lytle and Poff, 2004; Arthington *et al*., 2010). The general acceptance of the natural flow regime paradigm and the development of a solid conceptual understanding of the importance of natural flows for river ecosystems, has led to much research devoted to the extraction of key parameters of river flows that appear to be of ecological importance (Gurnell and Petts, 2011). Information on the ecology of drought in flowing waters, however, remains somewhat limited. The next section provides background information on the impacts of drought on riverine ecology.

3.9.3 Drought and ecology

Drought is a natural event resulting from lower than normal precipitation for an extended period of time. Although each drought event has unique characteristics, some broad categories of drought can be identified. Meteorological droughts defined on the basis of rainfall deficiency; hydrological droughts where accumulated shortfalls in runoff or aquifer recharge are of primary importance, agricultural droughts, where the availability of soil water during the growing season is the critical factor (Marsh *et al*., 2007) and socio-economic droughts; definitions associating droughts with supply of and demand for an economic good (Hisdal and Tallaksen, 2000). According to Lake (2003), however, what constitutes a drought in freshwater ecology is ill-defined.

Recently, hydrologists and ecologists have come to recognise the importance of flow generated disturbances in rivers and streams (Lake, 2007). Information on the ecology of drought in flowing waters is, however, both limited and scattered, with research generally focussing on high flow events (Lake, 2000; 2003). Research has investigated the influence of drought on the fish and invertebrate populations in upland streams (Cowx *et al*., 1984), and lowland rivers (Extence, 1981; Ledger and Hildrew, 2001). More recent research has included investigations into the response of biota to supra-seasonal droughts (Wood *et al*., 2000; Wood and Armitage, 2004 and Stubbington *et al*., 2009). Although recently empirical research into the effects of drought has increased rapidly, a lack of synthesis of the ecological consequences of low flows including droughts remains (Rolls *et al*., 2012a).

Lake (2003) postulates that drought as a perturbation consists of two parts (1) the disturbance (impacts of the decrease in water availability) and (2) the biotic response to the disturbance. Biotic responses to disturbance may be viewed as including (a) resistance: the capacity of the biota to withstand the drought, and (b) resilience: the capacity of the biota to recover from the drought (Lake, 2000; 2003). Communities experiencing predictable, seasonal droughts, frequently display physiological and behavioural adaptations that enable them to withstand prolonged periods of low-flow and even cessation of flow (Stubbington *et al*., 2009). Biota in drought-prone systems may possess adaptations which allow them to survive the drought either by sitting it out (resistance traits for example possessing desiccation resistant life-history traits) or to recolonise and recruit after the drought breaks (resilience traits) (Bond *et al*., 2008).

The United Kingdom tends to experience supra-seasonal droughts which are unpredictable in both timing and duration, and are, therefore, difficult for riverine biota to deal with through evolved adaptations (Lake, 2003). Communities in riverine ecosystems subject to irregular and/or high magnitude events are rarely adapted to withstand extreme conditions and, as a result, may be severely impacted when flow declines or ceases (Stubbington *et al*., 2009). For example, Wood and Armitage (2004) identified that in a small groundwater-dominated watercourse, supra-seasonal droughts, particularly over the winter months when groundwater aquifers are recharged, have the potential to result in significant changes in instream community structure.

Droughts may have both direct and indirect impacts on riverine biota. Direct impacts are those impacts caused by the loss of water and flow, and habitat reduction and reconfiguration, indirect impacts are those impacts associated with predation and competition, and the nature of food resources (Lake, 2003). In addition, droughts in heavily developed catchments may potentially impact riverine biota by altering the physiochemical conditions and water quality of watercourses (Everard, 1996). Furthermore, the first pulse of storm water entering watercourses at the end of a prolonged drought period tends to introduce a large load of suspended solids and associated pollutants into watercourses (e.g. Davies, 1978; Everard, 1996; Rivett *et al*., 2011; Edwards *et al*., 2012; Halliday *et al*., 2014).

3.9.3.1 Ecologically relevant attributes of droughts

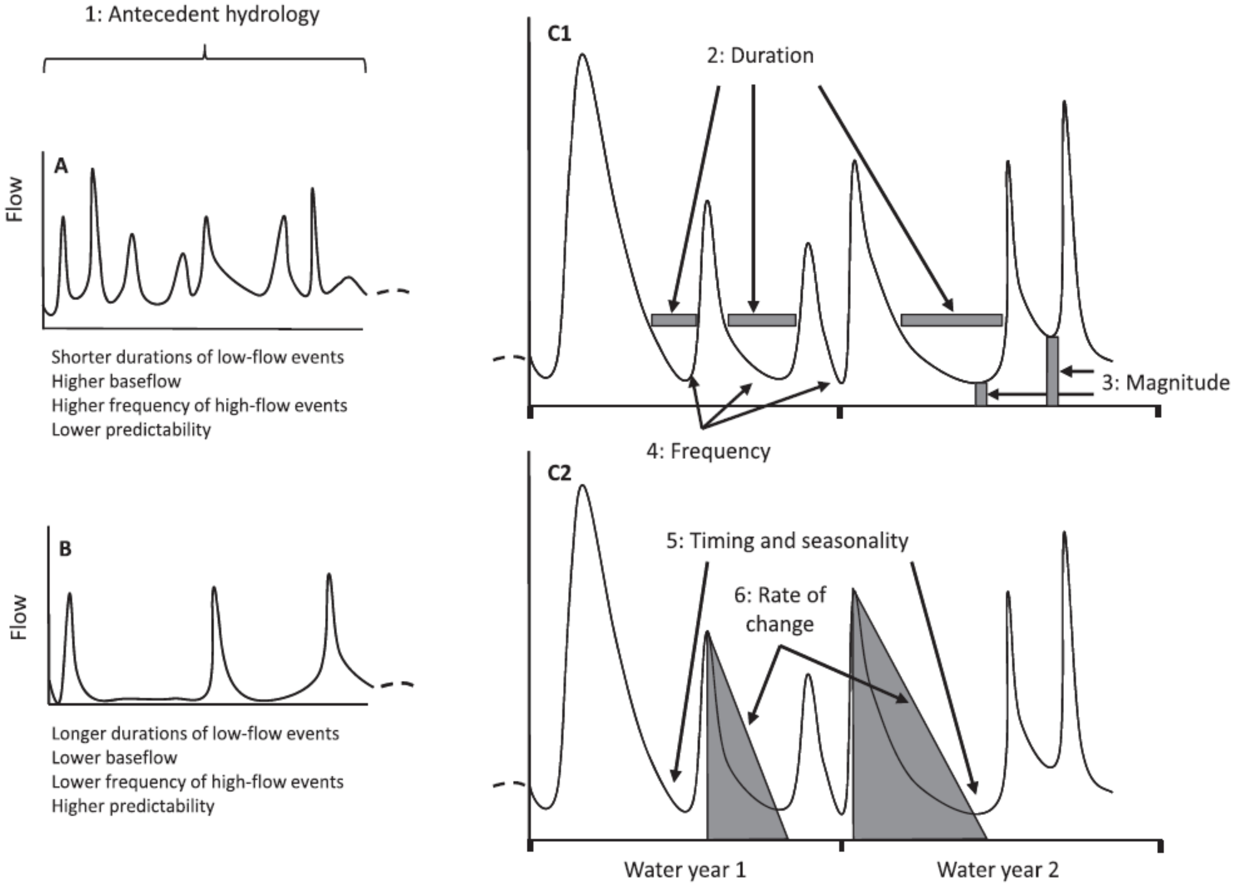
Identifying facets of the flow regime that are ecologically relevant is a common goal of hydroecological research (Rolls *et al*., 2012a). Five components of the natural flow regime (magnitude, frequency, duration, timing (seasonality) and rate of change of both high and low flows) are generally accepted as regulating ecological processes in watercourses. Rolls *et al*. (2012a) postulate that antecedent flow conditions may represent a sixth ecologically relevant hydrological attribute: that of the low-flow regime. In addition, it is likely that the state of the physical habitat, and the health of riverine biota at the time of a drought will also be significant. The schematic hydrographs in Figure 3.2 describe variations within, and interactions between, ecologically important low-flow attributes.

3.9.3.2 Low-flow magnitude

Flow magnitude is frequently adopted as an *e-flow* approach to determine the minimum flows required to maintain ecosystem health and function. Falling river flows will lead to a reduction in the available habitat for key aquatic life forms (Everard, 1996), with fragmentation leading to riverine biota becoming concentrated in pools and other refugia (Lake, 2003). As water flow and therefore volumes decrease, water temperature may start to increase and may become lethal to some riverine biota including fish (Lake, 2003).

Rolls *et al*. (2012a) state that a small percentage change in low-flow magnitude may cause a disproportionately large change in ecological response. Indeed, in an experimental flow-diversion study carried out in New Zealand, a reduction in discharge by up to 90 per cent resulted in limited impacts on invertebrate communities, restricted to changes in the relative abundance of just a few taxa (James and Suren, 2009). Conversely, during the severe drought experienced in the United States in 1999 when discharge was 96 per cent lower than average, brook trout (*Salvelinus fontinalis*) populations were significantly reduced (adult 60 per cent, Young-of-the-year 67 per cent) (Hakala and Hartman, 2004). These results suggest that different thresholds of low-flow discharge (probably interacting with duration) may induce different ecological responses (Rolls *et al*., 2012a).

Figure 3.2: Schematic hydrographs describing variation within, and interactions between, ecologically important low-flow attributes, and the integration of sequential low-flow events within the flow regime



A-Antecedent hydrology in a watercourse with short durations of low-flow events interspersed with frequent high-flow events. B-Antecedent hydrology in a watercourse with long-term flow low and infrequent floods. C1-Schematic representation of duration, magnitude, and frequency of periods of low-flow.C2-Schematic representation of seasonality and timing of periods of low-flow and rate of change in the flow hydrograph.

Rolls *et al*. (2012a); page 1165.

3.9.3.3 Low-flow timing (seasonality)

The timing of droughts may have significant impacts on the recruitment and migration of riverine biota, especially if low flows occur during key migration periods (Rolls *et al*., 2012a). Indeed, low flows may impede or deter access of migratory salmonids into river systems (Atlantic Salmon Trust and Scottish Office Agriculture and Fisheries Department, 1995). Conversely, low flows occurring during the summer period are likely to have a limited impact on riverine ecosystems, as riverine biota are generally inactive during this period (G. Petts *pers. comm,* 2013). However, low flows during the critical spring and autumn ecological periods may have more of an impact, as these are periods of naturally higher productivity and dispersion (Rolls *et al*., 2012a).

3.9.3.4 Low-flow frequency

The frequency of low-flow and drought events is also likely to be critical from an ecological perspective. Watercourses experiencing frequent and predictable low-flow periods are likely to support riverine biota capable of persisting through low-flow disturbances (Rolls *et al*., 2012a). As seasonal droughts are predictable, biota can be expected to have evolved adaptations, for example life history scheduling and the adaptive use of refugia to survive low flows (Yount and Niemi, 1990; Lake, 2003). Some biota may actually rely on periodic drought conditions for part of their life histories (Everard, 1996). Non predictable, supra-seasonal droughts, in contrast, represent a period of stress (Gordon *et al*., 1992). Watercourses rarely experiencing ecologically critical low flows are likely to support a larger proportion of biota with life history traits that are unsuited to survival during drought periods (Rolls *et al*., 2012a).

3.9.3.5 Antecedent conditions

Antecedent conditions are defined by Rolls *et al*. (2012a) as the hydrological characteristics that aquatic biota and their habitats are exposed to before each low-flow and drought event. These conditions affect the response and recovery of the biota and ecosystems to low flows and droughts (Rolls *et al*., 2012b). Biggs *et al*. (2005) consider that antecedent flow patterns and long-term characteristics of the flow regime help to determine ecological responses to individual flow events, and Rolls *et al*. (2012a) state that ecological responses may be more pronounced when recent flow events are atypical. The interplay between antecedent hydrology and ecological response is related to morphological, behavioural and life-history adaptations of the biota resident within a particular landscape that have evolved within the context of the natural flow regime (including low-flow periods) (Lytle and Poff, 2004; Rolls *et al*., 2012a). However, when low-flow periods are more extreme than those experienced on average, the riverine ecology may not possess the adaptations required for adequate resilience or resistance, creating potential opportunities for invasions by taxa able to tolerate and persist in the altered (drought) conditions (Rolls *et al*., 2012a).

Flow conditions prior to a supra-seasonal drought experienced within a groundwater-dominated stream, were identified by Wood and Armitage (2004) as one of the main factors that resulted in the recovery of the macroinvertebrate community being extended. In this study, Wood and Armitage (2004) examined the effect of natural low-flow variability over an eight-year period on the macroinvertebrate community of the Little Stour, a small perennial chalk stream located in Kent. The study is unusual because the study period included two high magnitude supra-seasonal droughts (1989-1992 and 1996-1997) which were followed by periods of natural flow recovery. Severe low flows associated with drought periods resulted in low macroinvertebrate community abundance and high diversity indices. Recovery of discharge and the macroinvertebrate community occurred over a two-year period, which was longer than the recovery period reported for other droughts. Wood and Armitage's study (2004) highlight the potential importance of antecedent conditions, with the full impact of one drought period on the macroinvertebrate community of the Little Stour not becoming apparent until following low winter rainfall in 1995; the drought progressed to a supra-seasonal event in the summer of 1996.

3.9.3.6 Recovery following drought periods

Recovery of riverine biota following drought conditions must be preceded by the recovery of key physical habitats (Petts, 1987). Rivers are inherently unstable systems, subject to continual changes in discharge, which in turn influence the formation of substrate-based or dynamic habitats through geomorphological processes (Harper, 1996). The lack of 'flushing flows' during prolonged droughts may lead to the progressive accumulation of fine sediment and organic debris. In the absence of bed turnover during droughts, siltation may be progressive, effectively clogging the substratum (Petts and Gurnell, 2013) and reducing the available habitat and refugia for riverine biota.

Unless aquatic organisms have developed adaptations such as rapid development, long dormant phases, and prolific reproduction, the ecological impacts of drought may be more long-lasting than the effects of floods (Rolls *et al*., 2012b). Generally, however, recovery is rapid over the months following drought periods in the majority of impervious catchments with natural flow regimes (Wood and Armitage, 2004). This swift recovery possibly reflects the long evolutionary history of drought in most aquatic environments (Boulton, 2003). Recovery may, however, be delayed in anthropogenically impacted systems (Humphries and Baldwin, 2003). Research on the recovery of instream macroinvertebrate fauna following unpredictable, supra-seasonal droughts has reported relatively rapid recovery times ranging from approximately one month (Ledger and Hildrew, 2001), several months (Cowx *et al*., 1984) for impervious catchments, to more than a year in a small groundwater dominated stream (Wood and Armitage, 2004).

3.10 ECO-HYDROLOGICAL APPROACHES

Eco-hydrological approaches are founded on the premise that over evolutionary timescales the biota of rivers have become adapted to the natural flow regime and its inter-annual variations. They rely on the statistical analysis of historical flow records (Petts, 2007). In their most simple form, *e-flow*s can be expressed as a hydrological statistic to define the DWF most commonly for setting minimum flows to protect fish (Petts, 2007). Hydrological methodologies have also expressed *e-flow*s as a fixed percentage of the average daily flow (Petts and Maddock, 1996), for example Tennant (1976) and Baxter (1961). A detailed review of the hydrological methodology proposed by Baxter (1961) is provided in Chapter 4. In England, the preferred hydrological methodology has been to employ a flow duration statistic, for example the long-term Q_{95} or the MAM7 flow frequency statistic (Petts, 2007).

In hydrological methodologies, flow is considered as a simple proxy for a number of related parameters that may influence the range of aquatic, wetland, and riparian habitats present along the river corridor (Gurnell and Petts, 2011). Tharme (2003) identified hydrological *e-flow* methodologies as representing the highest proportion of the overall number of methods recorded (30 per cent), with a total of 61 different hydrological indices or techniques applied. Reiser *et al*. (1989) highlighted the Tennant (Montana) method as the second most widely applied *e-flow* methodology in North America (Tharme, 2003). The Tennant method has subsequently become the most commonly applied hydrological methodology worldwide (Tharme, 2003).

3.10.1 The Tennant (Montana) method

The Tennant (Montana) method (Tennant, 1976) was developed to specify minimum flows to protect a healthy stream environment in the Midwestern United States (Acreman *et al*., 2005). The method was developed after measurements of width, average depth, and average velocity in 11 streams in Montana, Wyoming and Nebraska indicated that the quality of habitat changed more rapidly from zero flow to a flow of 10 per cent of the average than in any higher range (Orth and Maughan, 1981).

Percentages of mean flow are linked to different categories of river conditions, on a seasonal basis, as the recommended minimum flow (Tharme, 2003). Table 3.7 summarises the Tennant methodology.

Table 3.7: Instream flow regimens for fish, wildlife, recreation, and related environmental resources

Narrative description of flows*	**Recommended base flow regimens**	
	Oct – Mar	**Apr - Sep**
Flushing or maximum	200% of the average flow	
Optimum range	60%-100% of the average flow	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	10% of average flow to zero flow	

*Most appropriate description of the general condition of the stream flow for all parameters listed in the title of this paper (fish, wildlife, recreation and related environmental resources)

Adapted from Tennant (1976); page 6.

The Tennant method was modified by Tessmann (1980) in order to calibrate the percentages of average annual flow to local hydrologic and biologic conditions including monthly variability (Annear *et al*., 2004). This modification introduced the percentage of the mean monthly flow as an additional constraint below which no water should be removed or diverted for other users (Mathews and Bao, 1991). The modified Tennant method is widely applied in the United States at the catchment scale.

The main strengths of the Tennant methodology are the method is inexpensive, quick and simple to apply (Annear *et al*., 2004). Estes and Orsborn (1986) highlighted that the Tennant methodology was considered one of the simplest techniques for selecting or qualitatively evaluating instream flows for fish and wildlife. The Tennant method was described by Mathews and Bao (1991) as being applicable to streams of all sizes, and Annear *et al*. (2004) were of the opinion that if calibrated to the local hydrologic and biologic conditions, the method is transferrable from Tennant’s original streams. Jowett (1997) however, stated that the Tennant method differed from other hydrological methods in that it is based on the assumption that a proportion of the average flow will maintain suitable depths and water velocities for trout, and considered that this assumption only applies to watercourses similar in size and gradient to Tennant’s study rivers.

Although the Tennant methodology is widely used at the catchment level in the United States, it is not recommended for site-specific studies (Bureau of Land Management, 1979 cited in Acreman *et al*., 2005). Where the Tennant methodology is employed, a number of potential limitations have been identified. The methodology takes no account of flow fluctuations, and in addition, Annear *et al*. (2004) state that the average annual flow does not reflect seasonal patterns in hydrographs. The methodology has been identified as being more suited to larger streams which normally have less flow variability (Acreman *et al*., 2005). The methodology takes no account of stream geometry, and does not provide quantitative information about biological or geomorphologic processes (Annear *et al*., 2004). Estes and Orsborn (1986) stated that although the methodology is simple to apply, there is potential for inadvertent misuse because it does not account for specific species/life phase habitat requirements. In addition, Annear *et al*. (2004) identified the derivation of the average annual flow from hydrological data as a key limitation of the Tennant methodology; any flow recommendations are only as good as the flow data they are based on. Annear *et al*. (2004) emphasised that recommendations should always relate to naturalised hydrographs otherwise they will relate to depleted stream conditions, resulting in less than intended flow protection.

3.10.2 Indicators of Hydrologic Alteration/Range of Variability Approach

Recognition that flow variability is a primary determinant of species distribution between and within riverine systems led to researchers analysing flow regimes in order to define “ecologically relevant” hydrological variables (Petts, 2007). The Indicators of Hydrologic Alteration (IHA) method was developed in order to enable rapid processing of flow records to characterise natural flow conditions, and to allow evaluations of anthropogenic induced changes to flow regimes (Mathews and Richter, 2007). The IHA software has been widely used for the purpose of evaluating current/proposed future flow conditions relative to the natural flow regime (Richter *et al*., 1997; 1998). However, although the IHA software has been shown to successfully characterise all of the major components of the flow regime (Olden and Poff, 2003), users naturally wanted to know how to determine how much flow alteration was “too much” (Mathews and Richter, 2007).

As a result, Richter *et al*. (1997) introduced the Range of Variability Approach (RVA) for the setting of preliminary *e-flow* targets based on a rivers natural flow variability. The RVA uses daily flows from a period representative of “natural” or pre-impact flow conditions. These flows are characterised using the 32 ecologically relevant flow variables described in Richter *et al*. (1996). When the RVA was first incorporated into the IHA software the program would compute statistics describing the dispersion (i.e. on standard deviation or the 25th and 75th percentiles) of annual parameter values around their mean for each of the parameters during the pre-impact (reference) period (Mathews and Richter, 2007). Users were then able to adopt a targeted range of values for each parameter for example the 25th and 75th percentile flow, as the basis for an *e-flow* target (Mathews and Richter, 2007).

Recognition that application of the RVA could lead to unintended consequences, i.e. the mid range of the variability in hydrologic conditions could be preserved at the expense of extreme values led to a revision of the default RVA (Mathews and Richter, 2007). Difficulties in applying the RVA in *e-flow* assessments led the IHA developers to begin evaluating other ways of characterising flow conditions that could be more easily translated into *e-flow* recommendations (Mathews and Richter, 2007). As a result 34 new parameters termed Environmental Flow Components (EFCs) were added to the IHA software to complement the original parameters, and to characterise the hydrograph in a way representative of flow-ecology relationships (Mathews and Richter, 2007). The EFCs are summarised in Table 3.8.

The main advantage of the IHA methodology is the ease of operation (Mathews and Richter, 2007) and ability to rapidly process large amounts of flow data. This allows the identification of the aspects of the hydrological regime altered by various types of anthropogenic influences (Richter *et al*., 1996), allowing the user to quickly pinpoint areas that need to be addressed in order to restore ecosystem integrity (Annear *et al*., 2004). The IHA methodology has been shown by Olden and Poff (2003) to successfully characterise all of the major components of the natural flow regime. Annear *et al*. (2004) identified the IHA as representing one of the better tools available for developing baselines for hydrological regimes. Unfortunately, although the IHA is a useful tool, it does not identify how much flow alteration is too much.

The RVA was introduced with a very specific application in mind, setting individual river management targets for systems in which the hydrological regime has been substantially altered by human impacts. Application of the RVA does not depend on extensive ecological information (Richter *et al*., 1997), and provides flow management targets which may be monitored and refined over time (Tharme, 2003). The basic assumption behind the RVA is that the full range of natural variability in the hydrologic regime is necessary to conserve aquatic ecosystems (Annear *et al*., 2004). However, Annear *et al*. (2004) stated that restoring a natural flow regime to river channels that have been geomorphologically altered or impounded may not be in the best interest of aquatic ecosystem integrity.

Table 3.8: List of environmental flow components that may be used in developing *e-flow* recommendations

Environmental Flow Component	**Definition**	**IHA Statistics**
Extreme low flows	10th percentile of all low flows	Mean or median values for: Magnitude Frequency Duration Timing (subtotal 4 parameters)
Low-flow	Low-flow (base flow in each month)	Mean or median values for: Monthly low flows (subtotal 12 parameters)
High-flow pulses	Flows greater than low flows but less than bankfull	Mean or median values for: Magnitude Frequency Duration Timing Rate of rise and fall (subtotal 6 parameters)
Small floods	Flows equal to or greater than bankfull flows but less than the 10-year flood	Mean or median values for: Magnitude Frequency Duration Timing Rate of rise and fall (subtotal 6 parameters)
Large floods	Flows equal to or greater than the 10-year flood	Mean or median values for: Magnitude Frequency Duration Timing Rate of rise and fall (subtotal 6 parameters)

Mathews and Richter (2007); page 1406.

Another limitation of the methodology relates to data availability. Richter *et al*. (1998) highlighted that scarcity of long-term measurement records will limit the approach, and that in situations where only short flow records are available, the validity of any assessment of hydrologic alteration must be carefully considered. In the United States, The Nature Conservancy (2009) recommends that at least 20 years of daily flows are used for each pre-impact and post-impact period. Annear *et al*. (2004) identified that developing a natural (pre-impact) flow period of sufficient length may be difficult and that unavailability of adequate data may lead to uncertainty in interpretation of flow statistics. Annear *et al*. (2004) also highlighted another potential limitation, parameters used in the IHA/RVA reflect conditions associated with intra-annual variation in hydrological regimes; as a result ecosystem processes which operate on longer timescales may not be adequately addressed. In addition, although Richter *et al*. (1997; 1998) provide detailed worked examples of the IHA/RVA there is no known calibration or validation of the methodology (Annear *et al*., 2004).

Other potential limitations relate to the RVA methodology itself. In their review of the RVA, Acreman *et al*. (2005) identified a key question that still needs to be addressed: how much deviation from natural flow ranges is too much? In cases where no ecological information is available, a default range of variation from the mean may be set. Acreman *et al*. (2005) were of the opinion that further research was required on how to set the limits for individual flow variables in the RVA as they considered the approach outlined by Richter *et al*. (1997) was rather arbitrary. Mathews and Richter (2007) identified that first time users of the approach may have difficulty in interpreting the results and that the complexity had limited the utility of the RVA in developing *e-flow* targets.

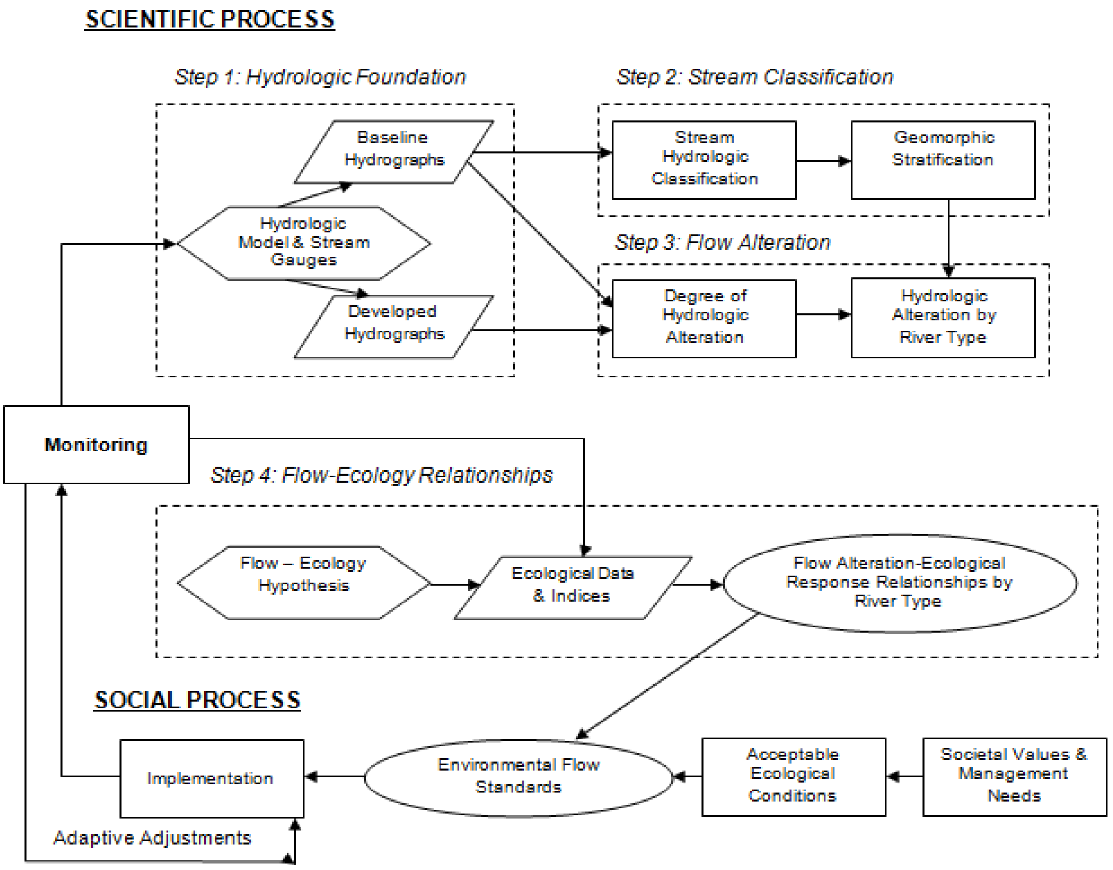
Acreman *et al*. (2005) concluded that the RVA methodology shows potential for application within the United Kingdom. Annear *et al*. (2004) however, identified the requirement to amend strategies and targets given regulatory considerations as one of the constraints in the RVA. It is probable that similar issues would be encountered within England due to the existing regulatory licensing framework. The RVA is also more appropriate for retrospective assessment of how the statistics of the current flow regime compare with the natural flow regime (Annear *et al*., 2004). Such an approach is not readily applicable to the operational management of abstraction, although it could be applied to releases from reservoirs (Acreman *et al*., 2005). Finally, as the majority of watercourses in England are heavily modified, would using the natural flow regime in the determination of *e-flows* be appropriate?

3.10.3 Ecological Limits of Hydrologic Alteration

In order to meet the need for *e-flow* assessment on par with the speed and large scale of water development (Sanderson *et al*., 2012), Poff *et al*. (2010) developed a new framework for assessing *e-flow* needs at the regional scale. This framework, the ecological limits of hydrologic alteration (ELOHA) was described by Poff *et al*. (2010) as a synthesis of a number of existing hydrologic techniques and *e-flow* methodologies that are currently being used to various degrees and that can support comprehensive regional flow management. By synthesising existing hydrologic and ecological databases from many rivers within a region, ELOHA generates flow alteration-ecological response relationships for rivers with different types of hydrological regimes.

The ELOHA framework (Figure 3.3) involves a number of interconnected stages, feedback loops and iterations, with relationships between flow alteration and ecological characteristics for different river types constituting the key element linking the ecological, hydrologic and societal aspects of *e-flow* assessment (Poff *et al*., 2010).

Figure 3.3: Overview of the ELOHA framework



The ELOHA framework comprises both a scientific and social process. Hydrologic analysis and classification (blue) are developed in parallel with flow alteration-ecological response relationships (green), which provide scientific input into a social process (orange) that balances this information on societal values and goals to set environmental flow standards.

Redrawn from Poff *et al*. (2010); page 151.

A detailed stepwise presentation of the ELOHA framework is provided in Poff *et al*. (2010), therefore, only a summary is provided here. The scientific process consists of four major steps (1) building a hydrologic foundation; (2) classifying rivers according to flow regimes and geomorphic features; (3) computing flow alteration, and (4) formulating flow alteration-ecological response relationships for *e-flows*. Poff *et al*. (2010) emphasise that each step contains a number of technical components building upon the approach recommended in Arthington *et al*. (2006). The social process comprises of three key steps (a) determining acceptable ecological conditions; (b) developing *e-flow* targets, and (c) the implementation of *e-flow* management. Poff *et al*.

(2010) emphasise that the ELOHA framework should proceed in an adaptive management context, where the collection of data allows for the testing and validation of the proposed flow alteration-ecological response relationships. This empirical validation process allows for the adjustment of *e-flow* targets where required (Poff *et al*., 2010).

The ELOHA framework was developed relatively recently, and Sanderson *et al*. (2012) identified that although few efforts had been made to comprehensively apply the ELOHA framework, several had developed one or more components (e.g. Kennard *et al*., 2010b). The key findings from two studies, Arthington *et al*. (2012) and McManamay *et al*. (2013) that tested the efficacy of the entire ELOHA framework are summarised here. Arthington *et al*. (2012) tested the central concepts of the ELOHA framework using south-east Queensland as a study region, and summarised a number of key findings. Overall, the findings of Arthington *et al*. (2012) supported the ELOHA principle that it is necessary to classify the hydrologic regimes of a region and to examine ecological responses to each type of hydrologic alteration within each flow class.

Arthington *et al*. (2012), however, found mixed support for the concept that ecological characteristics of rivers within each flow regime class will be relatively similar compared to those of other flow regime classes. In addition, Arthington *et al*. (2012) found mixed support for the concept that rivers within each flow regime that are regulated in the same way by dams and other infrastructure will display similar ecological responses to flow regime change. Since no two dams in the study area produced the same types of hydrologic change, the ecological effects identified also varied among the sites located below dams across the study region (Arthington *et al*., 2012). In a second study, McManamay *et al*. (2013) tested the utility of ELOHA in informing flow restoration applications for fish and riparian communities in regulated rivers located in the Upper Tennessee River Basin. McManamay *et al*. (2013) concluded that although ELOHA provided a robust template to construct hydrologic information and to predict the hydrology of ungauged locations, the results of the study did not suggest that univariate relationships between flow and ecology could produce results sufficient to guide flow restoration in regulated rivers. The finding that flow-ecology relationships cannot be consistently applied to similarly classified rivers may represent an important limitation in the ELOHA framework.

The cost of implementing ELOHA has been identified as a key limitation, with Richter *et al*. (2012) identifying that many government entities were unable (or unwilling) to afford the cost of applying ELOHA (generally ranging from $100k to $2M), particularly in situations where existing hydrologic models and biological data had poor spatial coverage. In addition, Richter *et al*. (2012) identified time constraints as representing a frequent hindrance to the implementation of the ELOHA framework, especially for jurisdictions involved in politically challenging situations, for example responding to extreme drought events.

3.11 APPLICATIONS OF HYDROLOGICAL APPROACHES IN ENGLAND

The justification for a hydrological approach is that over the long term, flora and fauna have evolved to survive periodic adversities without significant population change (Petts and Maddock, 1996). In natural systems, stresses on biological communities are balanced by recovery mechanisms; however, any anthropogenic impact that reduces the effectiveness of these recovery mechanisms will influence the level of flow required (Petts and Maddock, 1996). A criticism of hydrological methods is their exclusion of any explicit consideration of actual habitat requirements. In addition, concern arises from the complex array of processes, influenced by flow, which may affect biota (Petts and Maddock, 1996). However, based on current knowledge, hydrologically based methodologies are as good as any other *e-flow* approaches (Caissie *et al*., 2015).

Acreman *et al*. (2005) stated that although a Tennant type methodology could provide a model for development of similar guidelines for use in England, the methodology needs to be underpinned by extensive fieldwork in the regions it was developed for. The Tennant approach, however, represents a relatively simple method for making *e-flow* recommendations and was preceded in the United Kingdom by the hydrological approach advanced by Baxter (1961; 1963) (Chapter 4).

Petts (2009) and Gurnell and Petts (2011) highlighted a number of the key issues that hinder the apparently simple and reasonable application of hydrological approaches. Firstly, standards need to be set to apply an appropriate record length with at least 12 years of flow data required for statistical integrity (Petts 2009; Gurnell and Petts, 2011). Even longer flow records may be required to incorporate variable weather patterns over decadal timescales and to provide for scales of variability in the timing and magnitude of flows and the natural frequencies of these flows (Gurnell and Petts, 2011). Although hydrological data may not be widely available in some countries, England has a dense hydrometric network with many flow records starting in the 1960s.

Another potential limitation relates to the issue of naturalising the gauged flow regime (Petts 2009; Gurnell and Petts, 2011). In many areas the envisioned pristine catchment has no relevance to the modern day (Petts, 2009). Across England a large number of watercourses are supported in the summer by compensation flows maintaining minimum flows, and in some cases watercourses may even experience enhanced flows during dry summers. The hydrology of catchments characterised by long-term human interference, therefore, bears little resemblance to the hydrologic character of unmodified catchments (Gurnell and Petts, 2011). According to Petts *et al*. (2000), the concept for such catchments may be to produce functionally diverse self regulating ecological systems.

In a report produced for the Environment Agency, Petts *et al*. (1996) concluded that flow restrictions were being implemented in a piece-meal manner across England. As a result a more formal approach of setting river flow objectives was proposed as a management tool (Dunbar *et al*., 2004). This required determination of environmental objectives for setting flows and specification of an ecologically acceptable flow regime (EAFR). The approach became one of the precursors to the CAMS process and was founded upon six well established scientific principles that underpin the determination of ecological need in rivers; (i) longitudinal connectivity, (ii) vertical exchanges, (iii) floodplain flows, (iv) channel maintenance flows, (v) minimum flows and (vi) optimum flows (Petts, 1996). In addition, this innovative approach required consideration of hydrological variables; (a) flow magnitude and timing, and (b) flow frequency and duration (Petts, 2007), variables which were identified by Poff *et al*. (1997) in the natural flow regime paradigm, as of fundamental importance to the riverine ecosystem.

3.11.1 Determination of environmental objectives

Petts and Bickerton (1994) used PHABSIM to define environmental objectives for study sites located within the River Wissey catchment, a chalk stream of high conservation value with a rich invertebrate diversity and a natural brown trout (*Salmo trutta*) population (Petts and Bickerton, 1994) adversely affected by groundwater abstraction. Weighted Usable Area/Discharge relationships for the target species/life stages were examined to derive specific monthly flow levels to achieve specific environmental objectives (Gustard and Elliott, 1997) including: (a) Desirable Ecological Flow (DEF): the flow providing at least a minimum area of suitable habitat for a given target species/life stage in every reach type within each sector of concern; (b) Ecological Minimum Flow (EMF): the flow providing at least a minimum area of suitable habitat for a target species/life stage in at least one reach type within each sector of concern; and

(c) Threshold Ecological Flow (TEF): the absolute minimum flow necessary to sustain life stages for biota associated with relatively high velocity, clean substrate riffle and run habitats, below which there is no suitable habitat for target species. Three seasonal flow regimes were defined (Table 3.9).

Table 3.9: Ecological Flow Regimes for the River Wissey based on flows at Northwold gauging station

1956-1988	**DEF (m^3s^{-1})**	**EMF (m^3s^{-1})**	**TEF (m^3s^{-1})**
January	2.79	0.60	0.60
February	2.83	0.90	0.60
March	2.55	0.90	0.60
April	2.32	0.90	0.60
May	1.74	0.80	0.50
June	1.30	0.70	0.40
July	1.01	0.60	0.30
August	0.90	0.50	0.30
September	0.90	0.45	0.30
October	0.90	0.45	0.30
November	1.25	0.40	0.30
December	2.07	0.40	0.30

Adapted from Petts and Bickerton (1994); page 77.

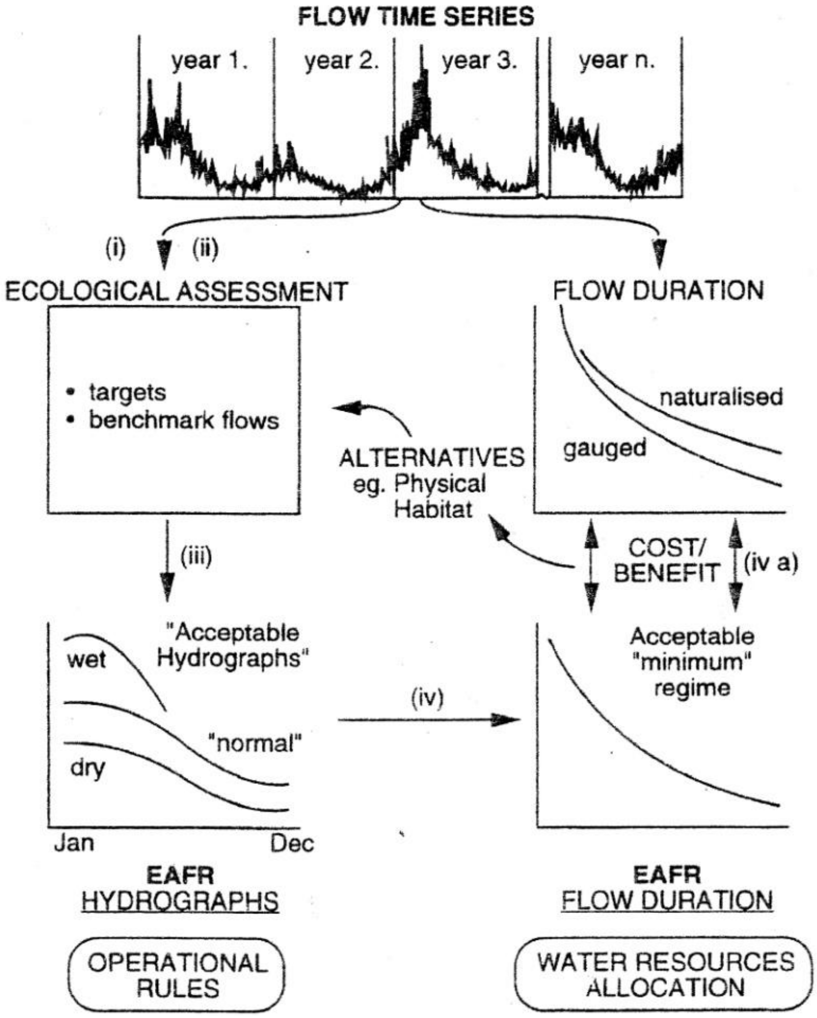
Identifying that traditionally within England the provision of flow controls had generally only considered minimum flows; Petts (1996) developed the concept of Ecologically Acceptable Flow Regimes (EAFRs), another precursor to the current CAMS approach. Figure 3.4 outlines the general procedure for establishing the EAFR.

Derivation of the EAFR involves four stages; in Stage 1 there must be an ecological assessment of the river and specification of an ecological objective comprising of specific targets, and in Stage 2 benchmark flows must be determined to meet these targets (Petts *et al*., 1999). In the case study described in Petts *et al*. (1999) four general benchmark flows were defined:

(a) Threshold Ecological Flow (TEF) the flow which sustains a few habitat refuges; below this level all habitat for a target species will be lost.
(b) Adequate Ecological Flow (AEF) the flow which sustains normal low-flow habitats.
(c) Desirable Ecological Flow (DEF) the flow which sustains connectivity between, and the usable habitat in all reaches.
(d) Optimum Ecological Flow (OEF) the flow which maximises usable habitat for the target.

In addition, high flows were defined as the Channel Maintenance Flow (CMF), the bankfull discharge, and the Habitat Maintenance Flow (HMF), flushing flow to prevent excessive siltation (Petts *et al*., 1999).

Figure 3.4: A general procedure for deriving an Ecologically Acceptable Flow Regime (EAFR) represented as one or more hydrographs for defining operational rules and as a flow duration curve for assessing abstractable volumes



Petts (1996); page 358.

Stage 3 of the derivation of the EAFR involves the determination of ‘Ecologically Acceptable Hydrographs’. Having defined the benchmark flows in Stage 2 to meet the ecological targets for each sector of river, the third stage is the allocation of ‘acceptable’ frequencies and/or durations to the benchmark flows (Petts, 1996).

The specification of individual ‘normal’ year, wet year and dry year hydrographs is important for defining operational rules for managing river flows (Petts, 1996). The final stage is to combine the ‘Ecologically Acceptable Hydrograph’ into a flow duration curve for determining the allocation of water required to meet the agreed targets (Petts, 1996). The area below the EAFR flow duration curve defines the MAF volume (Petts *et al*., 1999). Concern about low flows between 1988 and 1990 – the lowest flow sequence on record – led to a research project to establish the relationships between important ecological features and flow (Petts *et al*., 1999), the ecological target was to protect the brown trout (*Salmo trutta*) population, six benchmark flows were defined (Petts, 1996).

Table 3.10: Benchmark flows for the River Babingley and their ‘acceptable’ flow duration percentiles

Benchmark	**General target**	**Method**	**Flow (m^3s^{-1})**	**Flow duration (%)**	
				EAFR1	**EAFR2**
CMF	Bankfull discharge	Field survey and flow data	1.80	0.3	0.3
HMF	Flushing flow	0.66 x CMF	1.20	1.5	1.5
OEF	Optimum usable habitat for adult trout	Transfer from River Wissey PHABSIM study	0.70	10.0	10.0
DEF	Overwinter habitat for adult trout in all reach types along the river	Transfer from River Wissey PHABSIM study	0.45	27.0	27.0
AEF1	Minimum flow to protect adult trout in summer and autumn spawning habitat	PHABSIM	0.28	87.0	55.0
AEF2	Minimum summer flow to protect juvenile trout	PHABSIM	0.20		87.0
TEF1	Minimum summer flow to protect juvenile trout	PHABSIM	0.20	100.0	
TEF2	Minimum summer flow to protect the invertebrate community	PHABSIM and historical analysis	0.10		100.0

Key: Channel Maintenance Flow (CMF) the gauged bankfull flow with a return period of 5 years. Habitat Maintenance Flow (HMF) a normal flushing flow, important for preventing problems of excessive siltation. The Optimum Ecological Flow (OEF) provides optimum physical habitat for the target. The Desirable Ecological Flow (DEF) will sustain usable overwintering habitat and will sustain connectivity throughout the river system over the normal winter period. The Adequate Ecological Flow (AEF) is the normal end of summer flow, and finally, the TEF is the threshold flow below which habitat for the target disappears.

Adapted from Petts (1996); pages 360-362.

The benchmark flows summarised in Table 3.10 were utilised to construct hydrographs considered acceptable in wet, dry and average years (Petts, 1996) the acceptable hydrographs in Figure 3.4. The acceptable hydrographs were combined to form acceptable flow duration curves for comparison with the naturalised and gauged flow data; Figure 3.4. The EAFRs were subsequently used to determine the volume of water required to sustain the Babingley as a trout stream; approximately 62 per cent of the gross resource (12 000 tcm) with 8000 tcm available for abstraction (Petts, 1996).

.

3.11.2 Critique of the EAFR approach

The EAFR approach was founded upon six well established scientific principles that underpin the determination of ecological needs, and moved away from the concept of a ‘single acceptable minimum flow’ or a ‘single acceptable minimum flow hydrograph’ to advance an EAFR that recognised the functional role of not only between-year flow variability, but also between-season flow variability (Petts, 1996).

Fundamentally, the EAFR approach gave explicit recognition to the role of both flow and water quality (especially temperature) variability and channel dynamics in evaluating water resource scenarios to manage riverine ecosystems (Petts, 2007). The approach required consideration of hydrological variables; (a) flow magnitude and timing, and (b) flow frequency and duration (Petts, 2007), variables which were subsequently identified by Poff *et al.* (1997) as of fundamental importance to the riverine ecosystem. The determination of *e-flows* to meet specific ecological targets recognised that species will experience good years, average years and poor years, with varying flow conditions, or different life stages experiencing conditions that are more or less favourable at critical times (Petts, 2007).

Petts (1996; 2007) identified two main ‘problems’ or potential limitations in the EAFR approach. The first limitation surrounds the assignment of ‘acceptable’ frequencies and/or durations in the determination of ecologically acceptable hydrographs, and draws attention to the need for long-term coupled datasets (Petts *et al*., 2006; Petts, 2007). Each *e-flow* must be assigned an ‘acceptable’ frequency, with this stage involving the specification of typical (normal), wet-year and dry-year hydrographs (Petts, 2007). Petts (1996) emphasised that given current scientific knowledge, the process of assigning ‘acceptable’ frequencies and durations was largely arbitrary, recommending the combination of flow time series with habitat suitability curves for the target species to create habitat suitability time series.

A second problem related to the definition of ecological targets for a river reach or catchment (Petts, 2007). According to Petts (2007) ecological targets had to be defined as precisely as possible to ensure that the available tools provided the ‘best estimates’ of the *e-flows*. Petts (2007) recognised that it was ‘inevitable’ that final decisions were based upon 'expert judgement'. The evaluation of the EAFR was, however, described by Petts (1996) as an 'iterative process' meaning that ecological targets could be revised following comparison of the EAFR with actual flow time series or durations. This meant that ecological needs could be balanced against the needs of other users on the basis of the best available ecological information (Petts, 1996).

3.12 CONCLUSION

This Chapter provided a critical literature review which focussed initially on the evolution of *e-flow* practice in England from early rainfall-based approaches up to the CAMS approach and its links with the European WFD. The Chapter then considered selected literature on the ecological principles underpinning the science of *e-flows*. This included the natural flow regime paradigm, the ecological principles for the sustainable management of water resources and drought and ecology. Finally, selected hydrological *e-flow* approaches were critically evaluated and the case for using hydrological *e-flow* approaches in England was made.

Despite the expansion of hydrological databases and of research linking hydrology and ecology, limited progress has been made in advancing holistic models for determining how flows might be manipulated for water supply, irrigation and hydro-power. Furthermore, at a time of growing realisation that we may be entering a period of significant climate change, empirical research using the past as a basis for determining the future may no longer be appropriate. The next Chapter explores the development of lessons from the practical experience of Baxter (1961; 1963) to re-look at the flow regulation debate in order to better balance human and environmental needs. Chapter 5 investigates the potential ecological significance of low-flow variability across the heavily developed River Trent and regulated lowland Great Ouse catchments, and Chapter 6 utilises river flow data from both catchments to create a regional dataset to explore the application of a selection of hydrological *e-flow* approaches.

CHAPTER 4: GEORGE BAXTER AND THE BIRTH OF ENVIRONMENTAL FLOWS

4.1 INTRODUCTION

In the early 1960s, the compensation water provided below dams in Britain was, in the majority of cases, a fixed rate throughout the year and in some it was inadequate for the support of all but a minimum of fish life. The pressure of growing water demands within the post-War period together with the effects of droughts in 1952, 1955 and again in 1959 required innovation in flow management in order to meet water demands and protect environmental interests, specifically salmon populations. Baxter (1961), reinforced by Baxter (1963), stated that from the fishery and biological standpoints, the practice of a fixed rate discharge had little to commend it; in the majority of schemes the discharge could be varied not only to better suit the seasonal needs of the river and its fish but also to use less water than current practice realised. Over the past five decades, hydroecology has emerged as the ecological basis for water resources management and river regulation (Petts, 2007). In many ways, Baxter may be seen as the first British hydroecologist, and his work had high immediate impact. Nevertheless, this failed to influence policy makers.

This Chapter examines the work of Baxter on *e-flows* in the early 1960s, assesses his impact and then explores the possible reasons for his lack of longer term influence as a context for understanding the lack of progress in advancing the *e-flow* agenda in England through to the present day. The Chapter also seeks to identify any lessons that might influence the development and implementation of a new approach to abstraction management and river regulation. The Chapter is a new synthesis of the original sources and analysis of secondary sources to Baxter's work and related contemporary debates of the time.

George Baxter (1892-1975) was an influential Scottish water engineer and architect of the Fruid water development scheme involving intakes on burns to augment the reliable yield to balancing reservoirs including the Talla Reservoir, completed in December 1952, and the Fruid Reservoir, opened in 1968. He was a pioneer in the gauging of streams, starting on the Rivers Meglam and Menzion in the late 1920s (Fulton, 1962). His work continued when he moved to Edinburgh, with the flow record of the River Fruid. According to his obituary in the *Journal of the Institution of Water Engineers* Anon (1975), Baxter was a member of the Secretary of State for Scotland’s Water Advisory Committee from 1946 for approximately 10 years, and also served on the Secretary of State’s Fishery Committee set up under the North of Scotland Hydro-Electric Act. Baxter was described as a ‘keen and expert angler’ and was able to draw upon experience from holidays spent fishing and membership of the Statutory Fisheries Committee during planning of the Fruid scheme.

Baxter's experiences were drawn together in compiling perhaps the first paper on *e-flows*, which he read to a meeting of the Institution of Civil Engineers in April 1961. His paper, entitled 'River Utilization and the Preservation of Migratory Fish Life', assumed acceptance of the importance of, and the need to ensure, the preservation of the migratory fish life in rivers which are, or may be, affected by abstraction, diversion, or impounding schemes for water supply or hydro-electric power. The concepts Baxter (1961) proposed appear to have been refined during the planning stages of the Fruid scheme. At the heart of the Scheme was a requirement to protect the river for Atlantic salmon (*Salmo salar*) but also the belief that the water requirements of migratory fish were smaller than was generally thought. He added that his practical experience with the schemes of the North of Scotland Hydro-Electric Board and with the Corporation of Edinburgh in the headwaters of the River Tweed had established the 'general adequacy' of his approach. His experience with the Scheme is summarised in Appendix 4.1. Baxter (1961) concluded:

> *"Viewed from the fisheries standpoint, the practice of assessing compensation water quantitatively as a fraction of the yield and the discharge of this water at a constant rate has little to commend it. Except for industrial or other riparian use in any particular case, the natural and logical basis of assessment is that of the seasonal needs of the fish and of the river."*

Baxter (1961); page 243.

Later, Baxter (1962) stated that the real purpose of his 1961 paper had been to afford some guidance to those engineers who had little knowledge of the water needs of fish. In Baxter (1963) he acknowledged that there were cases where the compensation water was inadequate for the support of all but a minimum of fish life, and where abstraction from the headwaters of a river had aggravated the impacts of pollution in the middle and lower reaches. He further noted that the preservation of angling interests was not always possible. However, in Baxter (1963) he concluded that there was no reason why the preservation of fish life and of angling on rivers and streams should prove incompatible with their public or industrial use.

4.2 BAXTER'S APPROACH

Baxter (1961) analysed flow data from 15 rivers and streams, 13 in Scotland and two in England: the Aberdeenshire Dee, the Garry, Moriston, Allt Bhlaraidth, Upper Spey, Lower Spey, Shin, Upper Cassley, Upper Lyon, Fruid, Melgam, Inzion, Severn, and the Wye. Most of the rivers were well-known salmon rivers and catchment areas ranged from 23.7 km^2 (River Fruid) to 4273.5km^2 (River Severn). Baxter (1961; page 227) also included information "by way of contrast and interest from the hydrological aspect" on the Allt Uaine, a small stream located in Argyll with a catchment area of 3.1 km^2. A summary of the flow analyses undertaken by Baxter (1961) is provided in Appendix 4.2.

Baxter (1961) considered it necessary to base his flow assessments on the average daily flow (ADF):

(a) To reduce to some common denominator the flows of the rivers which were examined and thereby establishing the general flow conditions (especially the dry weather and minimum flow conditions common to rivers carrying stocks of migratory fish) so that they could be compared and correlated.

(b) Because the determination of the flows required for the preservation of migratory fish life rested partly on conversance with the flow requirements of the fish, and partly on being able to visualise and recognise these requirements in a particular river. To do this in terms of a rate of flow was considered impracticable, but it was considered possible to arrive at a reasonable approximation of the flows required if these were visualised in terms of the ADF. At the ADF the flow was identified as approaching the conditions of a minor spate, particularly in a large river. At the other end of the scale, at approximately 0.125 ADF a river was identified as generally having the familiar appearance associated with dry weather conditions.

Baxter (1961) showed that the flows could be broadly grouped in ranges from 1-8 (Appendix 4.2). The number of days on which these flows occur was expressed as a percentage of the year. The figures in parentheses in Appendix 4.2 denote the corresponding durations for the driest year covered by the periods of the records. For the Scottish rivers these years were identified as being typical of years of extreme drought, for example 1932-33 and 1954-55. Baxter (1961) identified a number of key features from a hydrological standpoint:

(a) The regularity between different rivers in the number of days per year (250 to 260 days) when the flow is below the ADF.

(b) The broad similarity of the flow durations at similar rates in rivers of a like type.

(c) The overall similarity of the durations of flows between 2 ADF and 4 ADF and between 0.25 ADF and 0.50 ADF with averages of 9.2 per cent (35 days) and 32.2 per cent (85 days) respectively.

(d) The apparent uniformity of the normal mean daily maximum flows in rivers of a like type.

Baxter (1961) also identified a number of hydrological characteristics from a fishery standpoint:

(a) The durations of the dry weather flows below 0.25 ADF. In the River Dee this ranged from an average of 5 per cent (18 days) to a maximum of 10.7 per cent (39 days). In contrast, in the flashy rivers (Moriston, Garry and Upper Lyon) this ranged from an average of 25 per cent (91 days) up to a maximum in the range of 37 to 43 per cent (135 to 157 days).

(b) With the exceptions of the River Dee and the Lower Spey, flows fall below 0.125 ADF for durations ranging from less than 1 per cent up to a maximum of 25 per cent in the extreme cases of the Upper Lyon and the Allt Bhlaraidth. Secondly, in years of severe drought, flows ranging from 0.006 to 0.018 $m^3s^{-1}km^2$ were recorded usually representing from 1.4 per cent (the Garry) to 11.6 per cent (Inzion) of the ADF of the particular river.

(c) On most upland rivers, flows below 0.25 ADF are rare and last only for a few days at most. For example, the minimum flow of 0.017 $m^3s^{-1}km^2$ for the Fruid has only been recorded three times in 12 years, with one period of 3 days and two periods of 4 days.

(d) For the majority of the rivers analysed, the more normal minima (occurring 7 years in 10) ranged from 0.021 $m^3s^{-1}km^2$ or 5.5 per cent of the ADF (River Moriston) to 0.041 m^3 s^{-1} km^2 or 26 per cent of the ADF (River Inzion).

(e) Durations of these normal summer minima (occurring between May and early October), were for all practical purposes, those indicated in the analyses for flows below 0.125 ADF.

4.2.1 Flows and migratory fish

From his observations on Scottish rivers, Baxter (1961) noted that occasionally fish may enter the river during almost any month but they normally do so in well defined runs during spring and summer months. The actual times when these runs occur vary from river to river, but in most rivers the months when the heaviest runs usually occurred were March, April and May. Baxter recognised that the progress fish make in the ascent of a river is controlled by the adequacy of the flow conditions and, in the early spring, also by water temperature. Indeed, salmon had been identified as not attempting the ascent of obstructions until water temperature reached approximately 5.6°C, and at sites with larger obstructions, between 10 and 11.1°C. Baxter identified four flow conditions that must be maintained downstream of an impoundment or diversion to ensure the fulfilment of migratory fish and the maintenance of fish stocks.

a) **Minimum flows for the maintenance of healthy conditions both for the parent fish and for fry and parr.** The minimum flow i.e. the basic compensation or residual flow, must be sufficient to maintain healthy conditions for aquatic life, including that of the food supply of fry and parr. The upper limit of the dry weather flow was taken as 0.25 ADF, identifying that flows can fall below this figure from between 86 days (River Cassley) and 157 days (River Lyon) of which, excluding the River Severn and River Melgam, between 43 days (River Fruid) and 92 days (River Lyon and Allt Bhlaraidth) was below 0.125 ADF. Baxter (1961) emphasised that these periods essentially represented ‘extreme droughts’ and under these conditions in many rivers high fish mortality may occur from the virtual drying up of the smaller tributary streams, and from overcrowding.

Baxter (1961) highlighted that in the majority of rivers, in 7 years in 10 flows fell below 0.125 ADF. This was viewed as particularly relevant to smaller streams during hot weather, as periods of prolonged low flows below 0.125 ADF may have a ‘highly injurious’ effect on fish life especially where water quality problems were experienced along reaches prone to heavy algal growths. Baxter (1961) was of the opinion that the provision of freshets with controlled flow should to an extent prevent conditions which give rise to fish losses. Furthermore, during periods of hot weather flows between freshets should not be permitted to fall below 0.125 ADF.

b) **Spawning requirements.** Baxter considered that the flow required for spawning was not a matter that could be generalised, but in the majority of situations he suggested that the smaller the stream the larger the proportion of the ADF required. From his experience a minimum of 25 to 30 per cent ADF was necessary to provide adequate water in the headwaters of a river. Along the middle and lower reaches of a river of medium or large size, 20 to 12.5 per cent ADF should generally provide an adequate depth of water.

c) **The Requirements of the ova.** An indication of the rates of flow needed to ensure the water coverage of the ova was considered to be the level to which the river normally falls during the incubation period. In order to cover the different timings of spawning and the variation in winter temperatures, this period (for the Scottish rivers) was taken as extending from the start of November until the end of the following March. Baxter (1961) noted that his experience demonstrated that in the middle and lower reaches of larger rivers 10 to 12 per cent ADF normally provided adequate water, however, in the upper reaches between 12.5 and 15 per cent ADF was required.

d) **Freshets to induce fish to enter and ascend a river to their spawning grounds.** In order to induce fish to enter and ascend a river downstream of an impounding or diversion in which there is normally only the compensation or residual flow requires the provision of flows in the form of freshets from the impounded storage or river upstream of the diversion. Baxter (1961) felt that these required consideration under the following three headings: (i) the volume of water or rate of flow; (ii) frequency; and (iii) duration.

    i) ***Rate of flow.*** Experience demonstrated that generally, in summer and autumn, salmon will ascend most rivers in flows varying from 30 to 50 per cent of the ADF in the lower and middle reaches, to 70 per cent of the ADF in the upper reaches and streams of the headwaters. Spring fish require higher flows, usually due to lower temperatures, of 50 to 70 per cent ADF.

ii) ***Frequency****.* The timing and frequency of freshets depends on: (a) the quantity of water which may enter the river from tributary streams downstream of the impounding or diversion and on the entry points of this water; (b) on the position of the impounding or diversion in relation to the total length of the river; and (c) on the location of the principal spawning ground and other factors. For example, where the natural augmentation of the compensation or residual flow is small, Baxter (1961) was of the opinion that weekly freshets may be needed from the time the fish are due to enter the river until within a week or two of spawning time. However, if the impoundment or diversion is located in the upper reaches or headwaters of the river and the compensation or residual flow is supplemented by natural inflow, he considered that only a relatively few, comparatively small, freshets may be needed during the late summer or early autumn to take the fish from the point to which the natural run-off has led them to the pass in the dam.

iii) ***Duration****.* The duration of the freshets need not generally be for longer than 18 hours of which 12 hours should be at the full rate (30 to 70 per cent ADF), tapering off during the following 6 hours to the normal minimum compensation or residual flow.

4.3 THE SCHEDULE OF FLOWS

The flow requirements identified by Baxter (1961), excluding freshets, were summarised as a ‘Schedule of Flows’. This Schedule allocates proportions of the average annual flow for environmental protection with approximately 18.5 per cent ADF for fish in smaller streams and for larger rivers approximately 15 per cent ADF. The Schedule of Flows is summarised in Table 4.1.

Baxter (1961) envisaged that freshet flows would be added to the ‘minimum’ flows defined in the Schedule, ideally in the form of a block allocation to be used as circumstances may demand. Assuming the maximum possible requirements of 28 freshets, and taking these as 24 at 70 per cent ADF and 4 at 100 per cent ADF (smaller rivers) and 50 per cent ADF and 70 per cent ADF (larger rivers), these represent the equivalent of an extra 2.5 per cent and 2 per cent ADF. Thus, the total overall proportion of the ADF required would be 21 per cent for smaller rivers and 17 per cent for larger rivers. In addition, he concluded that provision for the release of larger flows i.e. 100 per cent and 70 per cent ADF would be ‘desirable’ for periodic flushing of the river bed.

Table 4.1: Schedule of Flows

Month	For the smaller rivers and streams: % ADF	For the larger rivers: % ADF	Remarks	Amended for smaller trout streams % ADF (Baxter 1963)
October	15 - 12.5	15 - 12.5	During alternate weeks	15
November	25	15		20
December	25 – 12.5	15 -10	Higher allocations normally during first two weeks only.	10
January	12.5	10		10
February	12.5	10		10
March	20	15		20
April	25	20		25
May	25	20		30
June	25 – 20	20 - 15	During alternate weeks	30
July	20 – 15	15 - 12.5	During alternate weeks	25
August	15	15 - 12.5	During alternate weeks	15
September	15 - 12.5	15 - 12.5	During alternate weeks	15

Note: these schedules were not intended to be rigidly applied and require varying up or down to suit the conditions of the particular river or stream, especially its flashiness, and season e.g. variations in spawning times.

Baxter (1961, page 240; 1963, page 64).

4.4 THE IMPACT OF BAXTER

Baxter’s work made an immediate impact (Appendix 4.3). Fulton (1962) observed how Baxter was one of several water engineers, who more than 30 years earlier had highlighted the unsatisfactory nature of the practice of applying an almost rigid assessment of compensation water for a watercourse. Fulton (1962) identified that Baxter (1961) shared the views in the 1930 Report of the Technical Sub-Committee on the Assessment of Compensation Water:

> *“We have reason to believe, from informal conversations which we have had with representatives of fishing interests, that more economic use of the water available in the river could be made in the interests of public water supplies by giving the compensation water required for fishery purposes at those times of the year when the additional water would be of real use for those purposes and conserving it at the other periods which usually coincide with high summer demands for public water supplies and the lowest yields of the river.”*

Ministry of Health (1930); page 28.

Boulton (1965; page 26) considered that Baxter had made “a valuable contribution to our knowledge; his principal conclusions….are that the water-needs of migratory fish are smaller than is perhaps generally accepted”. Berg (1963) commented that the suggestion of seasonal fluctuations of either a prescribed flow or a minimum acceptable discharge was a novel suggestion and saw no objection in Baxter’s (1963) proposals provided they did not clash with other interests in particular circumstances. Menzies (1962; page 896) accepted with “some reservation” Baxter’s (1961) statement that the water requirements of migratory fish were smaller than was generally supposed and Boulton (1965) provided new analyses to support the contention that a minimum flow of one-eighth of the average daily flow was not unsatisfactory during periods of hot weather, provided that there were freshets at intervals.

Baxter’s (1961) paper was immediately reported in the United States in a ‘Review of the Literature of 1961 on wastewater and water pollution control’ published in the *Journal of the Water Pollution Control Federation* (Okun *et al*., 1962). Okun *et al*. (1962; page 665) noted “Baxter (1961) concluded that the traditional fixed rate of discharge of compensation water based quantitatively on yield and unrelated to biological need is unsuitable for fish life and should be replaced by a variable compensation flow regime based on the seasonal needs of the fish and of the river and incorporating provisions for the release of freshets”.

4.4.1 Freshets for migration: insights from new data

Pentelow (1962) challenged the knowledge of salmon migration but Baxter (1962) replied that volume of water was certainly one of the key factors and that in his experience, once the fish were in a river they responded readily to artificially induced freshets irrespective of weather conditions. Sedgwick (1963) pointed to the particular problem of spring salmon rivers where early entering salmon were accustomed to high flows for long periods in the early part of the year, and compensation flows might be inadequate to provide the necessary stimulus for them to do so, leading to the stock of salmon becoming later in its entry or to the elimination of early runs of salmon after a number of years. He also considered that freshets could fail to induce the upstream passage of migratory fish in some cases, unless they were used to supplement natural minor spates following rainfall events. Baxter (1963) agreed that spring salmon needed high rates of flow, from 50 to 70 per cent ADF to induce them to enter a river, and that even with those rates there were cases where the fish had been slow to enter. However, in the majority of cases, his experience was that once in the river fish responded readily to a freshet.

With insights from new fish data recorded from electronic fish counters installed by the West Hampshire Water Company at Knapp Mill, Christchurch and with data from experimental trap catches of salmon on the River Axe, Devon during 1964, Brayshaw (1967) was of the opinion that Baxter (1961) had soundly justified describing discharges for fish migration as a proportion of the ADF. Both the count of ascending fish and to a smaller extent, the net catches indicated a maximum between 0.75 and 1.00 ADF. However, the maximum intensity of migration occurred at 1.30 to 1.42 ADF suggesting that larger freshets than those proposed by Baxter (1961) were the most effective in bringing fish in from the sea (Banks, 1969). Electronic fish-counting units on the River Lune commenced in 1961. During the period 1963-1965 inclusive, 4268 salmon had been investigated and July, August and September provided conditions suitable for 82.6 per cent of the salmon run. Stewart (1967) provided information on the fish runs at various flows:

1. Minor sporadic activity from 0 up to 0.2 ADF
2. Intermittent activity up to 0.33 ADF
3. Intensive activity up to 0.62 ADF
4. Declining activity up to 1.27 ADF; and
5. Minor sporadic activity from 3.2 up to 8.0 ADF

According to Banks (1969; page 116), the proposals made by Stewart (1968a;1968b) would have provided “somewhat more water at most times than indicated in the Schedule of flows given by Baxter”. Nevertheless, Banks (1969; page 116) concluded that although Baxter’s recommendations “did not have the supporting weight of experimental evidence on fish ascent, they were largely accepted by those fishery biologists with experience of those rivers which Baxter had used as examples”. Banks (1969) was also of the opinion that the Schedule may well be sufficient to maintain the stock of fish, although it was unlikely to be favoured by anglers.

4.5 CONTEMPORARY DEBATES

Baxter’s (1961) paper attracted much discussion at the time within engineering and fisheries circles, and this addressed four broad themes. These were further addressed by Baxter (1963) and the ensuing discussion of that paper. Table 4.2 provides basic biographical details of the main discussants of Baxter’s (1961) and (1963) papers.

Table 4.2: Biographical details of the main discussants of Baxter's (1961) and (1963) papers

Discussant	Post	Organisation	Area(s) of Expertise
Aitken, P.L.	Chief Hydraulic Engineer	North of Scotland Hydro-Electric Board	Engineering Hydro-power
Menzies, W.J.M.	Fisheries Adviser	North of Scotland Hydro-Electric Board	Fisheries
McLeod, G.	Engineer	Usk River Board	Engineering
Berg, C.L.	Engineer	Surface Water Survey	Engineering
Fulton, A.A.	General Manager	North of Scotland Hydro-Electric Board	Engineering Hydro-power
Lacey, G.	Consultant Engineer	Sir Murdoch MacDonald and Partners	Engineering River Hydraulics
Waddington, J.I.	Inspector and Chemist	Tweed River Purification Board	Water Quality
Herschy, R.W.	Hydrologist	Lothians River Purification Board	Hydrology Water Quality
Alexander, J.N.L.	N/A	Ministry of Works, Uganda (formerly)	Water Quality

Please note that the discussants are listed in order of citation in Section 4.5.

4.5.1 Issues relating to the Schedule of Flows

Aitken (1962) and Menzies (1962) challenged Baxter's use of ADF and both argued to base fishery needs on the average of the summer (April to September inclusive) flow. In response, Baxter (1962) stated that although he could easily envisage 25 per cent of the ADF, he could not do this for a given percentage of the summer flow, for example the 37.5 per cent cited by Aitken (1962). Baxter highlighted how in most rivers 25 per cent of the ADF generally represented the upper limit of the dry weather flow, and that experience had demonstrated that by way of minimum flow this percentage was generally adequate for maintenance of fish life and was in excess of what was required in larger rivers.

Baxter's proposal to maintain flows at 0.125 ADF was challenged by McLeod (1962) as under conditions of such low flows, water undertakers would be reluctant to discharge any additional water. The block grant of extra water would have to be stored and released during dry periods. In response, Baxter (1962) stated that for the smaller rivers which were normally impounded for water supply purposes, generally rather more water was provided by way of compensation during the months when fish were in most need of ample water than was presently the case, with the freshets in addition. Baxter (1962; page 910) argued that the percentage increase required for storage of the block grant was "comparatively trifling" (generally approximately 5 per cent) and that water supply undertakers could not reasonably object to this as they were gaining in respect of the reduced compensation water. Berg (1963) noted that the practice used in the Surface Water Survey for direct supply reservoirs was to allow 33 per cent of the three drought years input as a continuous ‘prescribed’ flow immediately below the dam; even in the dry areas of England, this was in the region of 20% ADF.

4.5.2 Hydrological data limitations and the need for definitions

Through until about 1960 the lack of river flow records was a major obstacle to setting compensation flows. In the United Kingdom an Inland Water Survey was set up in 1935. Following the suspension of the Surface Water Survey during the period of economy cuts (1951-54) (Lees, 1987) the survey was reconstituted in 1954 under Boulton who extended the hydrometric network. However, in response to Baxter (1961), Fulton (1962) argued that no progress could be made towards establishing the flows that would be sufficient for fish conservation unless there were records to illustrate how flows varied within nature and within which fish managed to survive. In many cases, run-off was still estimated from potentially limited rainfall data and Menzies (1962) commented, from personal experience, that this was not always satisfactory. Baxter (1962) argued that there was strong support for the reassessment of compensation water in the light of the actual ADF determined by subsequent flow gaugings.

But it was not just a lack of data; uncertainty of definitions was also a problem. Aitken (1962) drew attention to the need for standard definitions to differentiate between minimum flow and the flow to which the river fell more frequently during dry weather. Aitken (1962; page 896) acknowledged that although the lack of available flow data was an issue, for the North of Scotland area it “might not be unreasonable to take dry-weather flow as two to three times minimum flow”. Baxter (1962) agreed that there was a need for definitions to discriminate between the minimum and normal dry weather flow, as these were used loosely and incorrectly at times. One example was the incorrect interpretation of the term ‘dry weather flow’ by Risbridger (1963) in applying Baxter’s (1961) guidelines. It would be another 10 years until Hindley (1973) proposed what is now the widely accepted definition of DWF.

4.5.3 Hydraulic geometry

Baxter (1961) concluded that this has an important bearing on the flow regime to be maintained downstream of an impounding, diversion, or abstraction in rivers of different sizes for the preservation of fish. Baxter (1961; page 231) highlighted how the flow conditions for a given percentage of the ADF may be “widely different between rivers of different size”. Relating gradient and the ratio of ADF to width he demonstrated that the proportion of the ADF carried per unit width of channel progressively increases with the size of river. Generally, the recession of water from the bed begins in the wider reaches of a small stream at approximately 0.5 ADF. At 0.125 ADF the water may only occupy one-third to one-half of the stream bed. However, on the corresponding reaches of larger rivers, at 0.50 ADF the bed was identified as being fully covered with recession only beginning to show when flows fell to approximately 0.25 ADF.

Lacey (1962) observed how Baxter (1961) had stressed the similarity in the flow patterns of rivers and streams of like type, emphasising the need for a common denominator so that the general flow conditions could be established. Lacey (1962) highlighted that in the United States, Leopold and Maddock (1953) had adopted the mean annual discharge, which was as Lacey commented, none other than the average daily flow used by Baxter (1961). Lacey (1962) felt that his analysis confirmed Baxter's (1961) observation that discharge intensity progressively increased with river size with a measure of similarity in the flow patterns notably in the number of days when the flow was below the ADF and between 0.25 ADF and 0.50 ADF, and in the relationship of the normal maximum flow to the ADF.

4.5.4 Issues relating to water quality

Waddington (1962) argued that compensation schemes should be an integral part of river management but pointed out that when compensation water was most needed, during hot weather, it was frequently not available because an Order under the 1958 Water Act had been introduced. However, in winter a third of the gross yield was discharged when it was of far less value from a water quality perspective. Waddington (1962) was of the opinion that there appeared to be a very feasible possibility of using compensation water to improve water quality in some cases. Indeed, due to the usefulness of freshets for maintaining the water quality, Herschy (1962) also supported the use of freshets for river pollution prevention, providing flushing flows. Herschy (1962) provided some water quality data for rivers in the Lothians commenting that a freshet over 18 hours' duration in each of the rivers would have considerably improved the water quality.

In order to avoid the discharge of potentially de-oxygenated water, Baxter (1963) stated that it was desirable that the compensation water including the freshets, should be discharged from the upper levels of the reservoir. However, he noted that shallower reservoirs with depths of 15.2 m and less were less prone to temperature differences and de-oxygenation and there was less need for differentiating between the upper and bottom levels for the discharge of the compensation water. Alexander (1963) commented that the withdrawal of water from surface levels was contrary to normal water undertaking practice, and that in order to promote circulation and remove dead water; compensation water was very often bled off from the bottom of the reservoir, hence the familiar smell of sulphuretted hydrogen.

4.6 DISCUSSION

This Chapter aimed to provide a brief overview of the work of George Baxter, focusing on the proposals made by Baxter (1961) in his paper entitled ‘River Utilization and the Preservation of Migratory Fish’. Baxter (1961; page 243) identified that the practice of assessing compensation flows quantitatively as a fraction of reliable yield and the discharge of this compensation water at a constant rate was not ideal with “little to commend it”. In addition, Baxter (1961) identified that the flow requirements of both fish and rivers varied seasonally, requiring the supplementation of basic minimum flows with freshets. Baxter (1961) provided a ‘Schedule of Flows’ which illustrated the variable flow requirements of migratory fish, differentiating between small and large watercourses.

The reported discussions of Baxter’s 1961 and 1963 papers, and the citations of them within a few years of publication summarised in Appendix 4.3, demonstrate the high impact of Baxter’s pioneering work at the time. The majority of the responses from both engineers and fishery biologists appeared to support Baxter’s (1961) proposals. However, his proposals were never implemented within the United Kingdom. Indeed, the practice of discharging compensation flows at a constant rate with a lack of regard of biological need continued.

4.6.1 Policy and practice in the United Kingdom

Several reasons may explain the failure to adopt such a hydrological *e-flow* method on rivers in the United Kingdom, these are elaborated below.

4.6.1.1 Overwhelming pollution problems

During the 1960s the emphasis of river management in England was on water quality and dilution requirements; little reference was made to the needs of ecology including migratory fish. By the 1960s the effects of pollution had been substantial in England with most former salmon and trout rivers and streams adversely affected. Indeed, the report published by the Committee on Salmon and Freshwater Fisheries in 1961 stated that pollution together with the allied problem of water abstraction, constituted the most serious danger to inland fisheries. The main enactment dealing with the prevention of pollution at that time was the Rivers (Prevention of Pollution) Act 1951, which was designed to deal with the regular and long continued discharge or normal waste waters from industry or houses. The 1951 Act contemplated that such wastes would be purified to such an extent that they could be discharged without harm to other interests, and in streams which contained fish, the condition of discharge would be such that neither fish nor their food were destroyed (Salmon and Freshwater Fisheries Committee, 1961).

Baxter (1963) acknowledged that the role which the diversion of water for water supply or hydro-electric purposes had played in the reduction of fish stocks was by comparison with pollution of secondary importance. Baxter (1963) stated that suppression of pollution was the first and most obvious need. Although “considerable headway” Baxter (1963; page 63) had been made, Baxter (1963) considered that the prospect of rivers in more heavily industrialised areas being brought up to a standard that provided an acceptable environment for trout and migratory fish life was still somewhat distant.

Baxter (1963; page 59) identified how in some rivers in England the effects of pollution had been “particularly devastating”, and made reference to the work of Turing who had investigated the effects of pollution between 1946 and 1949. Turing had identified some 38 former salmon and trout rivers and streams which had been adversely affected by pollution; with impacts ranging from complete extinction to more or less serious depletion of the former stocks of fish (this list excluded the Rivers Thames and Mersey). By contrast, the effect of pollution in Scottish rivers had been far less damaging (Baxter, 1963). There were however, rivers where migratory fish life was extinct; cases included the River Clyde. Baxter (1963) cited the case of the River Forth which had within living memory been one of the finest Scottish salmon rivers. However, as a result primarily of pollution of the estuary of the river the salmon stock was threatened with extinction (Baxter, 1963).

Turing (1947a) carried out a survey of pollution within the catchment of the River Trent, identifying that until well into the third quarter of the 19th century the Trent was a salmon river with spawning grounds in the River Dove between Tutbury and Sudbury. However, industrial development between the 1880s and the First World War had reduced the condition of the main river and its Staffordshire tributaries to little better than an open sewer (Turing, 1947a). Such pollution was unfortunately not confined to the Trent catchment. Indeed, his series of reports on pollution affecting rivers in England and Wales, Turing (1947a; 1947b; 1949a) identified numerous examples of pollution.

Turing (1949b) also investigated the effects of pollution on Scottish rivers; his report included an analysis of the River Tweed. Turing (1949b; page 41) identified that although the general state of the Tweed had improved, there were still a large number of “quite unjustifiable” pollutions caused by the apathy of some local authorities and the casual attitude of mill owners.

Turing (1949b; page 41) identified that it was “more important than ever” that the Tweed should be properly clean, for the flow was being and would be restricted by the numbers of reservoirs both present and being proposed in the headwaters of the catchment. According to Turing (1949b) several of these reservoirs served towns in other catchments so that the water was never returned to the Tweed and as a consequence the river’s power of self-purification was considerably impaired.

4.6.1.2 Irrigation and the 1959 drought

During the 1950s and early 1960s, those interested in salmon and freshwater fisheries became increasingly concerned by the amount of water diverted from natural channels by abstraction, which was identified as having the potential to reduce flows therefore, increasing the concentration of polluting matter (Salmon and Freshwater Fisheries Committee, 1961). The Committee were concerned over the increasing abstraction of water from streams and rivers for irrigation, as this method of abstraction was highly consumptive with little water abstracted for irrigation returning to its source. Concerns appeared to focus on the abstraction of water for spray irrigation which was still in its infancy in England. These concerns resulted in the publication of two reports by the Ministry of Agriculture and Fisheries (1954a; 1954b) and led to the Sub-Committee on the Growing Demand for Water identifying that the demand for irrigation water in some areas could far exceed the demand made by industrial and domestic users combined (Central Advisory Water Committee, 1959).

Concerns over the potential impacts of abstraction for spray irrigation increased following the summer of 1959, which was the driest for 300 years (Ackroyd, 1966). The River Great Ouse Basin Hydrological Survey undertaken during 1959, reviewed the potential impacts of irrigation, concluding that if development within the basin continued at the present rate, the water required for spray irrigation in a dry year would be such that the river beds would be dry for the greater part of the summer and all other users of the river in distress (Ministry of Housing and Local Government, 1960b). The report added that it was difficult to escape the conclusion that if the present rate of expansion continued, in five years time when the present demand would have doubled, the condition of the river may well have become intolerable (Ministry of Housing and Local Government, 1960b).

In 1962, the Natural Resources (Technical) Committee produced a detailed report on irrigation in Great Britain. The Committee estimated that roughly 52,609 ha were equipped for irrigation and estimated a rate of increase of approximately 6,070 ha per year. The seasonal need in a dry year, calculated on the basis of a supply equivalent to approximately 102 mm was estimated at approximately 227 million cubic metres. The report identified that although the main expansion of irrigation had been based on direct abstraction from watercourses; local storage in farm reservoirs was increasing (Office of the Minister for Science, 1962). It is therefore probable that concerns and uncertainties relating to the rapidly increasing abstraction of surface water for spray irrigation coupled with the impacts of the 1959 drought would have focused on minimum acceptable discharges, rather than on Baxter style *e-flows*.

4.6.1.3 The 1963 Water Resources Act

The Final Report of the Sub-Committee on the Growing Demand for Water published in 1962 stated that surface water abstractions should be related to the discharges or levels of rivers and streams, introducing the concept of the MAD. The Water Resources Act 1963 enacted most of the recommendations of the Sub-Committee, recognising the problem of conflicting use in a multiple-purpose water resource system, giving particular regard to *in situ* (i.e. water available in rivers or lakes for such uses as fish breeding, pollution abatement, recreation and navigation) by developing the concept of Minimum Acceptable Flow (MAF) (O'Riordan, 1970). Comments made by Ainger and Barclay in an undated report, and the wording of Section 19 of the 1963 Act suggest that only a single annual flow value was required in the prescription of a MAF. The MAF concept was discussed in some detail by Boulton (1965). When referring to the question of the variability of MAF, Rydz (1965; pages 50-51) stated that the MAF had been presented in the Water Resources Act virtually as a fixed quantity and that is was to be hoped that rivers would not be reduced ultimately to a virtually constant flow for much of the year.

The introduction of such a concept appears to suggest that the emphasis in the 1960s was on the maintenance of a single minimum flow, and not the variable flows proposed by Baxter (1961; 1963). Indeed, when discussing the 1963 Act and the determination of MAF, Mitchell (1970) highlighted a fundamental issue stating:

> *"Determination of minimum acceptable flow has proven to be difficult under terms of the Act as no allowance has been made for varying the minimum acceptable level of flow to meet seasonal variations in flow at any given place. Under present circumstances, the minimum flow has to be fixed at a level which satisfies the highest requirements, even though such a need may either be intermittent or occur only once a year. An example would be the level to accommodate spawning fish which would tend to sterilize water resources for most of the year. It would seem that this weakness will only be overcome by an amendment to the Act."*

Mitchell (1970); page 585.

The comments made by Mitchell (1970) appear to suggest that the implementation of Baxter style *e-flows* (i.e. variable flows) would not have been possible under the 1963 Act.

4.6.1.4 Licences of Right

The Final Report of the Sub-Committee on the Growing Demand for Water dealt with the issue of existing abstractors, stating that priority should be given to established abstractions, and they should as far as possible be licensed to the full extent to which they had hitherto been made. The Government responded formally to the Final Report of the Sub-Committee in the White Paper *Water Conservation: England and Wales* published in 1962. The White Paper stated that although existing abstractors would have to register with the Water Authority, the granting of a licence for such abstractors would be automatic.

Van Oosterom (1967) stated that although it was necessary to make special provision in the Act for existing abstractors, this provision placed some river authorities, especially those in the East and South-East of England, in a difficult position. Any abstractor who could establish that he had taken water from a source covered by the Act at any time during the period of five years ended 1st April 1965, was automatically entitled to a Licence of Right, and the river authority concerned was required to issue such a licence without regard to the question whether the water was in fact available (Van Oosterom, 1967). Van Oosterom (1967) highlighted a real potential issue, that the licences issued accordingly may establish an excess of demand over supply, either in terms of the peak daily demand, or of the annual total demand, or both.

4.6.1.5 The 1963 Act and fisheries

The introduction of the MAF concept with the emphasis on a single minimum flow, and the issuing of Licences of Right with no regard to environmental need probably represented the major shortcomings of the 1963 Act. It is however worth identifying some of the positive aspects of the 1963 Act from a fisheries perspective. Ackroyd (1966) identified the determination of MAF as being of particular interest to coarse-fish anglers and those concerned with the well-being of fish, as it implemented one of the recommendations of the Salmon and Freshwater Fisheries Committee. Ackroyd (1966) then provided information on one of the few specific provisions in the Act for the protection of fisheries interest. Section 47 of the Act provided that when a licence was granted for a new abstraction from an inland water for which no MAF had been determined, then at any time after the expiration of one year, the owner of the fishing rights could apply to the Minister to have the licence revoked or varied on the grounds that he had sustained loss or damage attributable to the abstraction of water. Ackroyd (1966) concluded by stating that the purpose of the Act was to ensure that streams, as far as possible, were in a condition first to meet the demands which might be made on a good natural water, adding it followed that that must be of benefit to fishery interests.

4.6.1.6 Data limitations

It appears that the flow records required to calculate seasonal compensation water requirements using the ‘Schedule of Flows’ were more readily available in Scotland. A lack of data may have led to reluctance by water engineers to adopt what was in all probability the first hydrological *e-flow* approach. Prior to the 1960s there were relatively few flow measurement stations and flows were not routinely monitored across England, therefore limited data availability was still a fundamental issue. It was not until the enactment of the 1963 Water Resources Act that the number of flow measurement stations increased. Although the 1963 Act led to an increase in the number of flow measurement stations, concerns grew about the accuracy of river gauging, particularly at low-flow rates on larger rivers (Rowntree, 1966). Concerns over the accuracy of what limited flow data was available, could have resulted in a reluctance to implement the variable compensation flows proposed by Baxter (1961; 1963).

At the time there was little biological (fish ascent) data to demonstrate the relationship between migratory fish movement and river flows in support of Baxter's (1961;1963) proposals. In the same year Baxter's proposals were published, Le Cren (1961) carried out a review of what was known about the population biology of freshwater fish at that time, concluding that the key requirement was for more sound basic knowledge of the populations of freshwater fish and the factors that control them. Although Baxter's (1961; 1963) proposals were evidently supported by both engineers and fishery biologists (see Appendix 4.3) the relationship between fishery requirements and river flow was still not fully understood. For example, Rowntree (1966) observed that not enough was known of the water quantity and quality requirements needed by fish, stating that fishery research required co-ordination in order to make the best use of water in rivers for fishery purposes. Rowntree (1966) concluded that he was not satisfied that river flow was the sole criterion of fishery prosperity. Although Rowntree (1966) made no reference to the work of Baxter (1961; 1963) or of the work of other fishery researchers such as Stewart, the fact that the Director of the Water Resources Board held the view that more research in this area was required, would have made it highly unlikely that Baxter's (1961:1963) proposal of variable compensation flows linked to the requirements of fish would have been implemented.

4.6.1.7 The methodological legacy

The legacy of existing compensation agreements and of the rainfall-based methods used to determine the quantity of compensation water cannot be discounted. Information included in Sheail (1985; 1987) appears to indicate that Parliamentary Committees were generally reluctant to set precedents when it came to the issue of compensation water and compensation agreements. Perhaps if Baxter's (1961) work had been more widely accepted, Committees would have realised that Baxter's (1961) proposals would have almost certainly led to less water being allocated as compensation water in a number of cases.

Even now in 2015, although the principle of including ecological issues in regulating river flows has been embedded in legislation for many years (Petts, 2007), advances in linking hydrology and ecology in England have fallen behind those made in countries such as the United States. Arguably, the proposals (e.g. Acreman *et al.*, 2008a) suggest that knowledge has advanced little since the publication of Baxter's (1961) guidelines and 'Schedule of Flows'. Perhaps Baxter (1961) will finally get the recognition he deserves.

4.7 CONCLUSIONS

Although Baxter's (1961) flow methodology has not been used to determine *e-flows* for rivers in England, his approach introduced key principles which are still relevant today in the 21st century. Baxter (1961) advocated the use of average daily flows as the basis of flow assessments. However, the limited availability of flow data in the 1960s seemingly represented the main limitation preventing the implementation of his proposals. Average daily flow data is now widely available therefore; data availability should no longer be an issue. The majority of *e-flows* in England are based on a single low-flow duration statistic, the Q_{95}. Although the use of a flow-duration statistic may be seen as a more consistent benchmark because the ratio of Q_{95} to the mean flow varies in relation to the flow regime of natural rivers (usually in the range of 10 to 40 per cent) (Petts, 2009), potential limitations relating to the accuracy of the measurement of low flows should be considered. These issues suggest that the adoption of an *e-flow* approach based on percentages of average daily flows may represent an improvement on the current approach based on the measurement of a low-flow duration statistic.

Baxter (1961) also advocated the use of seasonally variable compensation flows taking into account the functional requirements of different life stages. The Natural Flow Regime paradigm (Poff *et al*., 1997) see Section 3.9.1, postulates that the ecological integrity of riverine ecosystems depends on their natural dynamic character. The fundamental ecological principle for the sustainable management of riverine ecosystems is the need to sustain flow variability mimicking natural climatically driven flow variability (Naiman *et al*., 2002). In addition to seasonally variable flows, Baxter (1961) stated that freshets should be used for migration and habitat management (flushing) and that the timing and duration of freshets should mimic natural spates. Within England, the majority of compensation flows are discharged at a constant rate with a lack of regard for the functional requirements of different life stages. Baxter's (1961) proposals could relatively easily be adapted for use in 21st century river regulation; the adoption of seasonally variable *e-flows* would represent an improvement on the current, minimum flow approach which is seemingly a legacy of the 1963 Water Resources Act.

Baxter's (1961) approach based on the concept of a variable compensation flow regime based on the seasonal needs of the riverine ecology, would have almost certainly led to less water being allocated as compensation water than existing methods. This would have resulted in more water being available for other users including the riverine ecosystem. Baxter's (1961) Schedule of Flows represented approximately 21 per cent of the ADF in smaller streams and 17 per cent of the ADF in larger rivers. Baxter’s (1961) water ‘savings’ however, were based on an unnatural flow regime with Baxter arguing for lower baseflows of 10 per cent ADF during the key period of reservoir recharge, this was perhaps the trade-off enabling Baxter (1961) to provide good baseflows during the key ecological periods during the spring and November, along with higher flows during the early and mid-summer.

Although Baxter’s (1961) water savings may have been flawed when viewed from an ecological perspective, a hydrological approach based on the natural flow regime paradigm, taking into account the key principles of Baxter’s (1961; 1963) approach could be used to determine *e-flows* for 21st century regulated rivers. Such an approach would represent an improvement on the existing method of basing *e-flows* within England on a single low-flow duration statistic released at a constant rate throughout the year with little or no regard to seasonally variable ecological need.

CHAPTER 5: EMPIRICAL ANALYSES OF THE TRENT AND GREAT OUSE CATCHMENTS

5.1 INTRODUCTION

This Chapter provides the results of a range of assessments of historical rainfall and river flow data that aimed to illustrate the potential ecological significance of low-flow variability across two contrasting catchments. Results for the heavily developed River Trent catchment are provided in the first half of the Chapter in Sections 5.2 to 5.8 with results for the highly regulated, lowland Great Ouse catchment provided in the second half of the Chapter from Section 5.9 onwards. Results for both the Trent and Great Ouse catchments are presented as follows; (1) the assessment of historical rainfall drought and identification of the driest years in the study period; (2) flows during the 1996 drought; (3) catchment classification using the Base Flow Index; (4) variability in runoff; (5) the heterogeneity of flows during periods of below average rainfall; (6) the variability of low-flow responses between sub-catchment types, (7) the timing of recovery from low-flows (Trent catchment only), and (8) the dimensions of ecological drought (Great Ouse catchment only).

5.1.1 Chapter aims

The overall aim of this Chapter is to illustrate the potential ecological significance of low-flow variability by considering two contrasting catchments located in central England; the heavily developed River Trent and the highly regulated, lowland River Great Ouse system. The first objective is to explore the heterogeneity of flows during periods of below average rainfall across two catchments with contrasting flow regimes. The second objective is to explore the variability of low-flow response between sub-catchment types (indexed using the Base Flow Index). Finally, throughout the assessments of ecological drought, the aim is to assess a range of possible hydrological indicators of drought severity that may be used to derive *e-flow* management approaches for use across heavily developed catchments and across highly regulated, lowland catchments where a key pressure is consumptive abstraction for irrigation.

It is postulated that even in heavily developed and highly regulated catchments like the Trent and Great Ouse respectively, unpredictable and prolonged droughts, occurring during the autumn critical ecological period (October and November) or extending into the spring critical ecological period (April to June inclusive) will have a greater impact on riverine ecology than a drought during the summer months (July to September inclusive), when in temperate rivers the majority of riverine biota are adapted to extreme low flows.

Droughts or extended periods of low flows during summer months are natural phenomena and as a disturbance serve as a key force in maintaining biodiversity (Everard, 1996; Lake, 2000, 2003). The resilience of riverine ecosystems draining heavily developed and highly regulated catchments, however, may be lower than in pristine (natural) catchments, not least because of their weaker connectivity and habitat simplification (Lake, 2003). As a result, riverine biota in heavily developed catchments are likely to be less resilient to prolonged periods of low flows if they extend into the critical ecological period. Due to this reduced resilience, unpredictable prolonged droughts, for example the spring 1995 to summer 1997 drought experienced across England, are likely to have a significant impact on riverine ecology in heavily developed and highly regulated catchments.

5.2 MIDLANDS REGION RAINFALL ASSESSMENTS

The paucity of reliable long-term flow records available for the Trent catchment; the longest flow record (River Derwent at Yorkshire Bridge) covers the period of 1933 onwards, means that in order to identify periods of historical drought, rainfall records have to be utilised. Historical annual and monthly rainfall totals for the Trent catchment are not available, but the Met Office holds monthly and annual rainfall records commencing in January 1910 for the Midlands region. Rainfall data was downloaded from http://www.metoffice.gov.uk/climate/uk/datasets/Rainfall/date/Midlands.txt

It is worth noting that although the Midlands region incorporates the Trent catchment, it also incorporates the Severn and Avon valleys and part of the River Wye. Historical monthly rainfall totals recorded between January 1910 and December 2009 inclusive, i.e. 100 complete years of rainfall data formed the basis of rainfall assessments.

5.2.1 Historical rainfall drought within the Trent catchment

Numerous studies have investigated the timings of historical droughts across England (for example Bryant *et al*., 1994; Jones *et al*., 1997; Jones and Lister 1998; Marsh *et al*., 2007; Hannaford and Buys 2012; and Kendon *et al*., 2013). Key droughts of the last century include those of 1920-1921, 1933-1934, 1975-1976, 1990-1992 and 1995-1997 (Marsh *et al*., 2007; Kendon *et al*., 2013). According to Kendon *et al*. (2013) the droughts of 1920-1921 and 1975-1976 stand out with approximately only 60 per cent of average rainfall across Lowland England. No studies, however, have focused on the identification of periods of historical drought across the Trent catchment.

Table 5.1 summarises the long-term monthly average rainfall totals and the minimum and maximum monthly rainfall totals for the 100-year rainfall record. Information on the year that the extremes, i.e. the minimum and maximum rainfall values were experienced is included, with extremes occurring during the last two decades.

Table 5.1: Analysis of historical Midlands rainfall – monthly average and extreme (minimum and maximum) rainfall totals

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Maximum Rainfall (mm)	Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Maximum Rainfall (mm)
Jan	74.1	**12.2** **(1997)**	147.4 (1948)	**Jul**	65.6	9.7 (1911)	**144.7** **(2007)**
Feb	56.0	6.3 (1959)	140.8 (1977)	**Aug**	71.6	**8.2** **(1995)**	165.7 (1912)
Mar	55.0	6.8 (1929)	148.4 (1947)	**Sep**	64.0	3.9 (1959)	164.3 (1917)
Apr	54.0	4.3 (1938)	**136.6** **(2000)**	**Oct**	74.2	13.5 (1947)	148.3 (1959)
May	59.1	**11.3** **(1991)**	146.3 (1932)	**Nov**	77.2	11.0 (1945)	169.7 (1951)
Jun	56.7	2.2 (1925)	**167.4** **(2007)**	**Dec**	77.9	12.9 (1933)	163.0 (1914)

Average monthly rainfall totals ranged from between 54.0 mm (April) and 77.9 mm (December) with an average of 65.5 mm. The lowest monthly rainfall total of 2.2 mm was recorded in June 1925, and the highest monthly rainfall total of 169.7 mm in November 1951. Three of the lowest monthly rainfall totals in the 100-year rainfall record occurred during the 1990 to 2009 inclusive study period, with the lowest January, May and August rainfall totals in the 100-year record recorded in 1997, 1991 and 1995 respectively. Conversely, three of the highest monthly rainfall totals in the 100-year record also occurred during the study period, with the highest April rainfall total recorded in 2000, and the highest June and July rainfall totals occurring in 2007.

The long-term average annual rainfall for 1910 to 2009 inclusive was 785.4 mm. Annual rainfall totals were ranked (lowest to highest) to identify the 10 driest years and the 10 wettest years in the 100-year Midlands rainfall record (Table 5.2). Three of the driest years (1996, 2003 and 1991) fall within the 1990 to 2009 inclusive study period, with four years (2000, 2008, 2007 and 2002) experiencing the highest annual rainfall totals.

Table 5.2: Analysis of historical Midlands rainfall – the 10 driest and wettest years in the 1910-2009 inclusive 100-year period based on annual rainfall totals

Year	Annual Rainfall (mm)	Percentage of 1910-2009 long-term average (%)[1]	Year	Annual Rainfall (mm)	Percentage of 1910-2009 long-term average (%)[1]
1921	540.9	68.9	1960	1032.9	131.5
1964	582.2	74.1	**2000**	**1018.3**	**129.6**
1975	589.0	75.0	1912	986.4	125.6
1996	**611.1**	77.8	1954	945.5	120.4
2003	**612.7**	78.0	**2008**	**937.3**	**119.3**
1933	613.9	78.2	1951	933.1	118.8
1953	644.0	82.0	**2007**	**928.5**	**118.2**
1973	644.5	82.1	1927	925.4	117.8
1911	653.0	83.1	1930	925.0	117.8
1991	**653.1**	83.2	**2002**	**925.0**	**117.8**

[1] The 1910-2009 long-term average rainfall is 785.4 mm

Table 5.2 also illustrates that 1921 was the driest year with only 68.9 per cent of the long-term average annual rainfall recorded. In 1996, 2003 and 1991, only 77.8, 78.0 and 83.2 per cent respectively of the long-term annual average rainfall was recorded. Conversely, 2000 was the second wettest year in the 100-year Midlands rainfall record with 129.6 per cent of the long-term average annual rainfall recorded. In addition, during 2008, 2007 and 2002 annual rainfall totals were higher than the long-term annual average for the Midlands.

5.2.2 Midlands region rainfall during critical ecological periods

The two critical ecological periods are defined for the purpose of this Chapter, as spring (April, May and June) and autumn (October and November). In the Trent basin prolonged periods of below average monthly rainfall are rare, with no years experiencing below average monthly rainfall totals throughout the April to November inclusive period. The long-term average rainfall totals were calculated as 169.9 mm, 201.2 mm and 151.4 mm for the spring, summer and autumn periods respectively. Below average rainfall totals during the spring period were experienced in 48 out of 100 years, including 10 years in the last two decades of the record. Below average rainfall totals during the summer period were experienced in 52 out of 100 years, with 9 years in the study period. Finally, below average rainfall totals during the autumn period were experienced in 55 out of 100 years, this included 9 years in the last two decades. Rainfall totals recorded during each of the three critical ecological periods were ranked (lowest to highest) and the 10 driest years identified. Table 5.3 summarises the 10 driest years in the Midlands region rainfall record based on rainfall recorded during the spring, summer and autumn critical ecological periods.

Table 5.3: Analysis of historical Midlands rainfall – the 10 lowest annual rainfall totals experienced during the spring, summer and autumn critical ecological periods

Year	Rainfall during Spring[1] (mm)	Percentage of 1910-2009 LTA[2] (%)	Year	Rainfall during Summer[3] (mm)	Percentage of 1910-2009 LTA[4] (%)	Year	Rainfall during Autumn[5] (mm)	Percentage of 1910-2009 LTA[6] (%)
1995	**82.9**	**48.8**	**1955**	79.8	39.7	**1922**	57.9	38.3
1921	85.1	50.1	**1959**	84.7	42.1	**1978**	58.6	38.7
1957	89.7	52.8	**1990**	**107.7**	**53.5**	**1956**	70.8	46.8
1976	96.6	56.9	**2003**	**109.4**	**54.4**	**1975**	74.8	49.4
1974	104.7	61.6	**1911**	110.0	54.7	**1962**	75.6	50.0
1990	**109.7**	**64.6**	**1964**	116.2	57.8	**1947**	76.3	50.4
1975	109.7	64.6	**1933**	117.3	58.3	**1964**	81.0	53.5
1919	110.0	64.7	**1913**	119.7	59.5	**1973**	88.4	58.4
1984	111.1	65.4	**1947**	122.4	60.8	**1920**	93.3	61.6
1938	112.7	66.3	**1989**	122.5	60.9	**1918**	98.1	64.8

[1] Spring critical ecological period is defined as April, May and June
[2] The 1910-2009 long-term spring average rainfall is 169.9 mm
[3] Summer critical ecological period is defined as July, August and September
[4] The 1910-2009 long-term summer average rainfall is 201.2 mm
[5] Autumn critical ecological period is defined as October and November
[6] The 1910-2009 long-term autumn average rainfall is 151.3 mm

Table 5.3 illustrates that 1995 experienced the lowest rainfall during the spring critical ecological period in the 100-year Midlands rainfall record, with only 48.8 per cent of the long-term average spring rainfall recorded. Although based on this assessment of rainfall deficiency, it is likely that ecological drought conditions may have been experienced across the Trent catchment during the spring of 1995, rainfall increased during the summer and autumn of 1995. Rainfall recorded during the 1990 and 2003 summer period represented two of the lowest rainfall totals experienced in the 100-year rainfall record, with only 53.5 and 54.4 per cent respectively of the long-term average summer rainfall recorded.

Finally, of the 10 driest years based on rainfall recorded during the autumn critical ecological period, none fell within the last two decades. The data summarised in Table 5.3 demonstrates that prolonged periods of below average rainfall across the Midlands region are rare, with no year featuring in the 10 driest years based on rainfall recorded during any two ecological periods.

5.2.3 Identification of the driest years in the Midlands region in the 1990-2009 study period

Although average annual rainfall totals for the Trent catchment are not available, average annual rainfall totals for the Midlands region are given in Table 5.4. Deficit years are highlighted in red.

Table 5.4: Comparison of annual rainfall totals for the Midlands with 1981-2010 long-term average rainfall[1]

Year	Midlands Total Rainfall (mm)	Annual Surplus/ Deficit (mm)	Annual Total (% LTA)	Year	Midlands Total Rainfall (mm)	Annual Surplus/ Deficit (mm)	Annual Total (% LTA)
1990	676.4	-121.9	84.7	**2000**	1018.3	220.0	127.6
1991	653.3	-145.0	81.8	**2001**	794.3	-4.0	99.5
1992	854.4	56.1	107.0	**2002**	924.8	126.5	115.8
1993	822.0	23.7	103.0	**2003**	612.7	-185.6	76.8
1994	832.3	34.0	104.3	**2004**	840.5	42.2	105.3
1995	665.0	-133.3	83.3	**2005**	683.9	-114.4	85.7
1996	611.1	-187.2	76.6	**2006**	795.7	-2.6	99.7
1997	724.1	-74.2	90.7	**2007**	928.6	130.3	116.3
1998	887.8	89.5	111.2	**2008**	937.4	139.1	117.4
1999	893.9	95.6	112.0	**2009**	780.6	-17.7	97.8

[1] The 1981-2010 long-term average rainfall is 798.3 mm

When annual surpluses/deficits are calculated using the 1981-2010 long-term average rainfall as a guide, 10 of the years studied experienced a deficit in annual rainfall and 10 years a surplus. The three years with the largest rainfall deficits were 1996, 2003 and 1991 when annual rainfall was 76.6, 76.8 and 81.8 per cent respectively of the long-term average. There were several clusters of years with below average rainfall for example 1990 and 1991; 1995 to 1997 and finally, 2005 and 2006.

5.3 TRENT FLOWS DURING THE 1996 DROUGHT

The assessment of annual rainfall totals indicated that 1996 experienced the largest rainfall deficit, receiving only 76.6 per cent of the 1981-2010 long-term average rainfall. In order to explore the impact this rainfall deficit had on river flows, a series of hydrographs were plotted using daily mean flows recorded within three contrasting watercourses. Figures 5.1 to 5.3 illustrate the average, minimum and maximum daily mean flows and flows recorded during 1996 at the three gauging stations.

Figure 5.1: Hydrographs illustrating the average, minimum and maximum daily mean flows in the 1990-2009 study period and the 1996 drought: River Dove at Izaak Walton

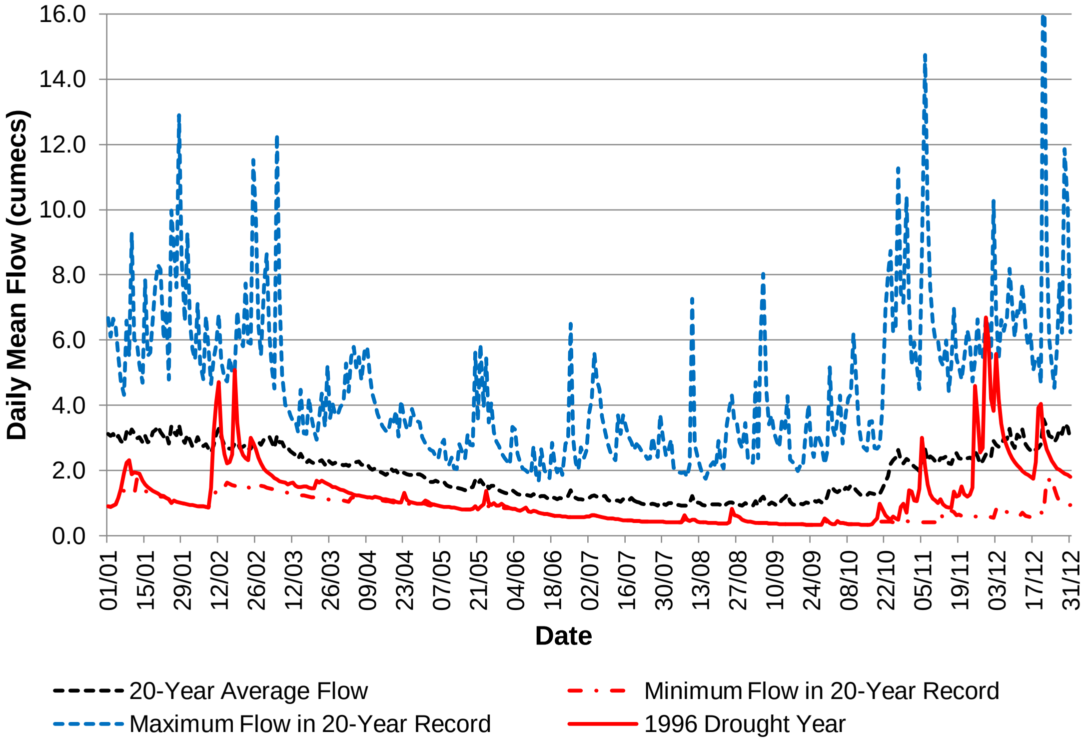


Figure 5.1 illustrates hydrographs for the River Dove at Izaak Walton, a small groundwater-dominated watercourse with an essentially natural flow regime. The 20-year average daily mean flow hydrograph demonstrates that generally, recovery from the summer/early autumn low-flow period did not occur until early October. Daily mean flows experienced during 1996 were the lowest throughout the 20-year study period between April and October inclusive. Interestingly flows within this essentially natural watercourse, appeared to recover quite rapidly from November onwards, and by the start of December 1996, approached the maximum flow recorded in the 20-year study period.

Figure 5.2 illustrates hydrographs for the Rothley Brook at Rothley, a small surface-runoff dominated watercourse with a responsive flow regime. Low-flow recovery within the Rothley Brook appears to have commenced earlier than in the River Dove, with daily mean flows recovering in early September. Flows experienced during 1996 were slightly higher than the 20-year average flow between January and the start of May and from late October onwards. The recovery from the drought conditions experienced during 1996 appears to have been less pronounced within the Rothley Brook.

Figure 5.2: Hydrographs illustrating the average, minimum and maximum daily mean flows in the 1990-2009 study period and the 1996 drought: Rothley Brook

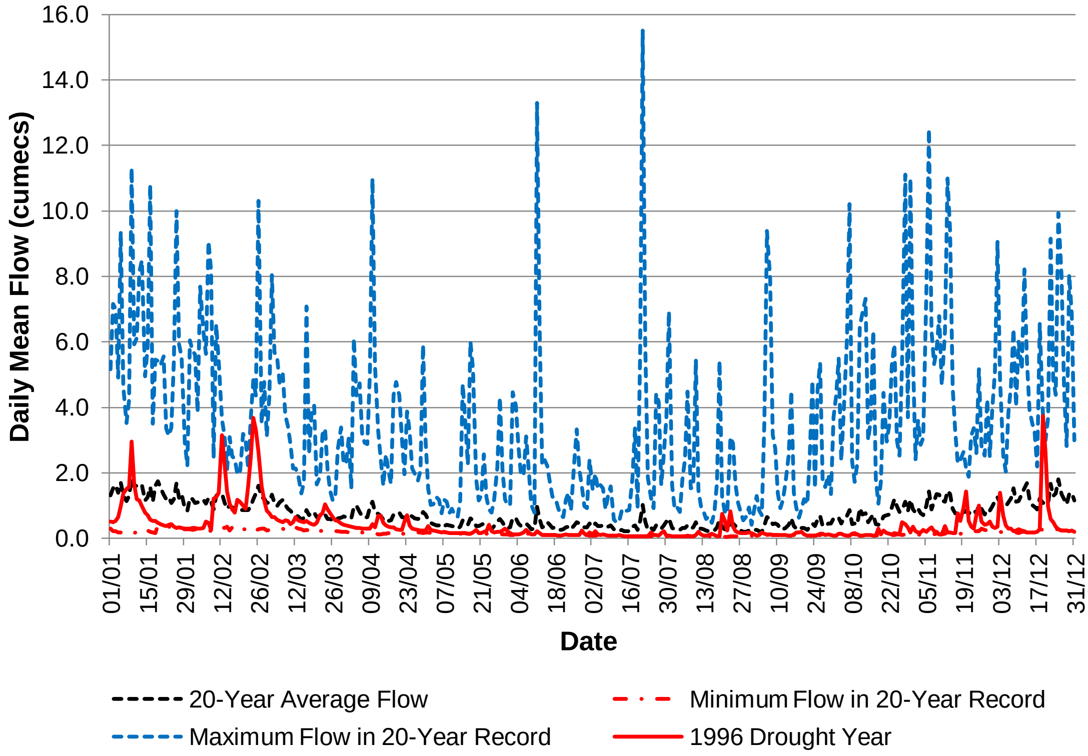
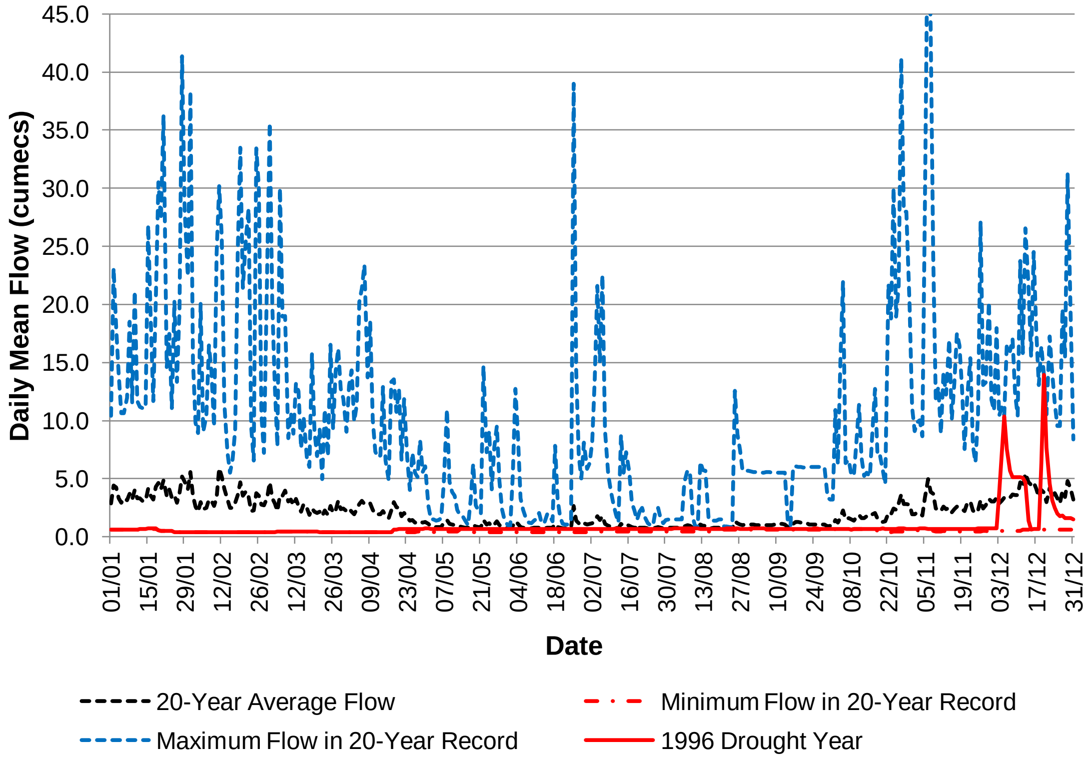


Figure 5.3: Hydrographs illustrating the average, minimum and maximum daily mean flows in the 1990-2009 study period and the 1996 drought: River Derwent at Yorkshire Bridge



Finally, Figure 5.3 illustrates hydrographs for the highly regulated River Derwent at Yorkshire Bridge. The lack of low-flow variability throughout the vast majority of 1996 is evident, with flows only increasing at the start of December. Low-flow conditions within the regulated River Derwent during 1996 also appear to have been prolonged in comparison to the River Dove, where low-flow recovery commenced much earlier.

5.4 TRENT CATCHMENT CLASSIFICATION

The 31 study sites were allocated to one of the four discrete regions indentified by Pirt (1983); Table 5.5 summarises the distribution of the study sites across the four regions.

Table 5.5: Distribution of study sites across Pirt's four regions

Region	Description	Number of Study Sites	Watercourses and study sites
1	The Uplands of the South Pennines.	11	River Derwent at Yorkshire Bridge, Chatsworth, St Mary's Bridge, and Church Wilne; River Amber at Wingfield Park; River Dove at Izaak Walton, Rocester, and Marston; River Manifold at Ilam; River Churnet at Basford Bridge; River Ecclesbourne at Duffield
2	The Trent Valley and associated terraces.	3	River Trent at Stoke on Trent, Colwick, and North Muskham
3	The Uplands to the south of the Trent.	11	Meece Brook at Shallowford; River Sow at Great Bridgford; River Penk at Penkridge; River Rea at Calthorpe Park; River Cole at Coleshill; River Tame at Lea Marston Lakes; River Soar at Littlethorpe; River Sence at South Wigston; Rothley Brook at Rothley; River Wreake at Syston Mill; River Anker at Polesworth
4	The Dukeries and Sherwood Forest.	6	River Ryton at Worksop and Blyth; Dover Beck at Lowdham; River Greet at Southwell; River Idle at Mattersey; River Torne at Auckley

Table 2.1 in Section 2.3.3 illustrated that across the Trent catchment, BFI values range from between 0.41 for the surface-runoff dominated River Wreake at Syston Mill and 0.79 for the groundwater-dominated River Dove at Izaak Walton. The average BFI across the 31 study sites is 0.58, the range 0.38 and the standard deviation 0.11. The average BFI of study sites located in Regions 1 to 3 is comparable, ranging from between 0.52 (Region 3) and 0.58 (Region 2). In Region 4 the average BFI of 0.72 of the study sites is higher, with the lowest BFI of 0.63 (River Ryton at Worksop) higher than the lowest BFI of study sites located in the other regions. The largest range in values occurs in Region 1 with BFIs of between 0.41 (River Churnet at Basford Bridge) and 0.79 (River Dove at Izaak Walton). Conversely, the smallest range occurs in

Region 4, with BFIs between 0.63 (River Ryton at Worksop) and 0.78 (River Idle at Mattersey).

5.5 VARIABILITY IN RUNOFF ACROSS THE TRENT CATCHMENT

The hydrographs illustrated in Figures 5.1 to 5.3 demonstrate the variety of hydrological responses to the 1996 drought by the different tributaries within the Trent catchment.

In order to explore the spatial pattern of flows across the Trent catchment, two basic flow descriptors; mean annual runoff as a percentage of mean annual precipitation and runoff per unit area ($m^3s^{-1}km^{-2}$) were calculated for each of the 31 study sites. Each study site was allocated to one of Pirt's (1983) four discrete regions. Table 5.6 summarises the minimum, maximum, average and standard deviations in the runoff descriptors.

Table 5.6: Variability in runoff across the Trent catchment (*regions based on Pirt 1983 and are summarised in Table 5.5)

Region*	**Minimum Runoff (% Annual Rainfall)** ***($m^3s^{-1}km^{-2}$)***	**Maximum Runoff (% Annual Rainfall)** ***($m^3s^{-1}km^{-2}$)***	**Average Runoff (% Annual Rainfall)** ***($m^3s^{-1}km^{-2}$)***	**Standard Deviation**
1	38.8 *0.010*	68.0 *0.023*	51.5 *0.017*	9.567 *0.004*
2	43.2 *0.011*	45.8 *0.011*	44.7 *0.011*	1.361 *0.000*
3	29.6 *0.007*	74.1 *0.018*	39.4 *0.009*	12.323 *0.003*
4	10.0 *0.002*	34.9 *0.007*	27.4 *0.006*	9.554 *0.002*

Values of mean annual runoff as a percentage of mean annual rainfall were highly variable across the Trent catchment, ranging from between 10.0 per cent (Dover Beck) and 74.1 per cent (River Tame) with an average value of 41.9 per cent. Generally, watercourses with the highest values of annual runoff as a percentage of annual rainfall are located in Region 1. Conversely, watercourses with the lowest values of annual runoff are located in Region 4. In Region 1 annual runoff as a percentage of annual rainfall ranges from between 38.6 per cent (River Derwent at Yorkshire Bridge) and 68.0 per cent (River Manifold) with an average of 51.5 per cent. The low value of annual runoff at Yorkshire Bridge is thought to be a result of the highly regulated nature of the River Derwent downstream of Ladybower Reservoir, and also due to the diversion of flows into adjacent catchments. In Region 2 runoff is remarkably consistent along the length of the main River Trent ranging from between 43.2 per cent (River Trent at Stoke) and 45.8 per cent (River Trent at Colwick) with an average of 44.7 per cent.

In Region 3 runoff ranges from between 29.6 per cent (Meece Brook) and 74.1 per cent (River Tame) with an average of 39.4 per cent. The value for the River Tame is an anomaly as runoff in the adjacent catchment, the River Cole, only represents 31.2 per cent of mean annual rainfall. This irregularity in the results is a reflection of the augmentation of flows within the River Tame by effluent discharges from Minworth WTW. Annual runoff in Region 4 ranges from between 10.0 per cent (Dover Beck) and 34.9 per cent (River Greet) with an average of 27.4 per cent. The low value of runoff within the Dover Beck is thought to be due to a combination of factors including relatively low annual rainfall across the catchment (677 $mmyr^{-1}$), the size of the catchment (69 km^2) and the high baseflow index of 0.76 suggesting that the watercourse has a groundwater dominated flow regime.

A second measure of runoff; average flow (m^3s^{-1}) per unit area (km^{-2}) was also calculated for the 31 study sites, with values ranging from between 0.002 $m^3s^{-1}km^{-2}$ (Dover Beck) and 0.023 $m^3s^{-1}km^{-2}$ (River Dove at Izaak Walton and River Manifold). Average runoff was 0.011 $m^3s^{-1}km^{-2}$ and median runoff 0.010 $m^3s^{-1}km^{-2}$. Generally, watercourses with the highest values of annual runoff per unit area are located in Region 1 and watercourses with the lowest values in Region 4.

In Region 1 values of runoff per unit area range from between 0.010 $m^3s^{-1}km^{-2}$ (River Amber) and 0.023 $m^3s^{-1}km^{-2}$ (River Dove at Izaak Walton and River Manifold) with an average of 0.017 $m^3s^{-1}km^{-2}$. In Region 2 runoff per unit area is consistent along the entire length of the River Trent, with values of 0.011 $m^3s^{-1}km^{-2}$ for each of the three Trent study sites.

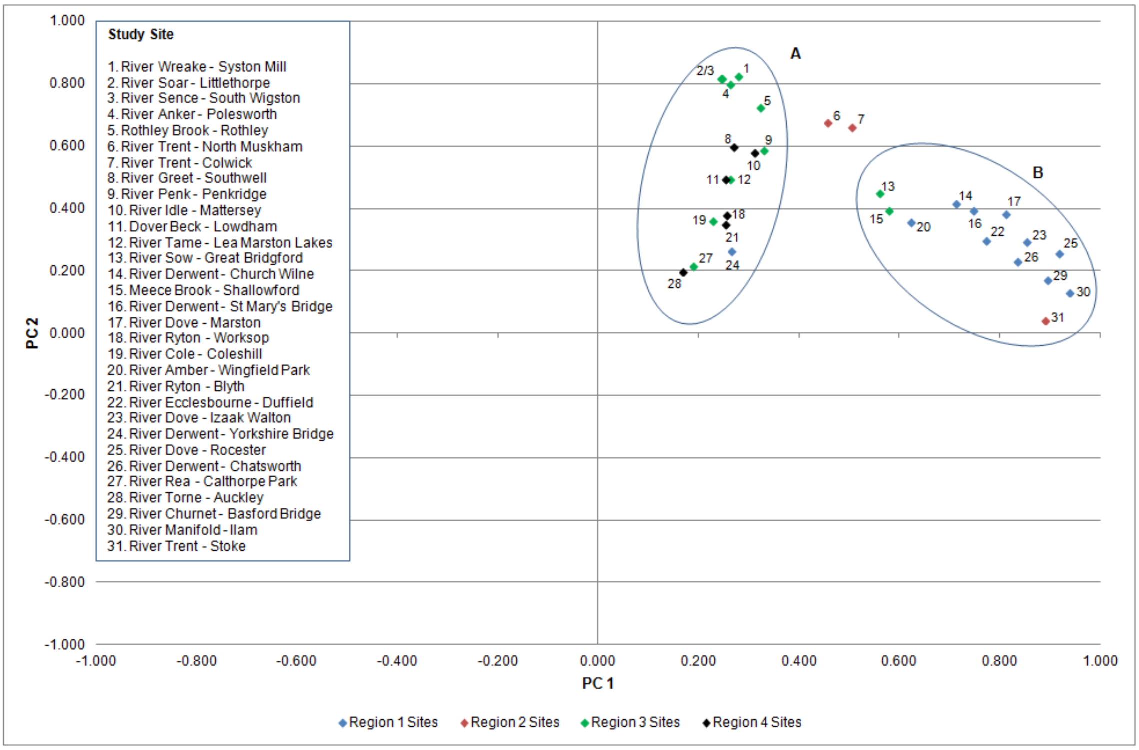
In Region 3 runoff ranges from between 0.007 $m^3s^{-1}km^{-2}$ at four study sites (Rivers Sow, Cole, Soar and Wreake) and 0.018 $m^3s^{-1}km^{-2}$ (River Tame) with an average of 0.009 $m^3s^{-1}km^{-2}$. Runoff in the River Tame is again substantially higher than in other watercourses located within Region 3, reflecting flow augmentation. In Region 4 runoff ranges from between 0.002 $m^3s^{-1}km^{-2}$ (Dover Beck) and 0.007 $m^3s^{-1}km^{-2}$ (River Ryton at Blyth and River Idle) with an average of 0.006 $m^3s^{-1}km^{-2}$. Although runoff within the Dover Beck was again identified as the lowest across the Trent catchment, runoff per unit area was only marginally higher at a number of study sites.

5.6 THE HETEROGENEITY OF FLOWS ACROSS THE TRENT CATCHMENT DURING PERIODS OF BELOW AVERAGE RAINFALL

The results of PCAs that utilised standardised and raw (non-standardised) daily mean flow data were identical indicating that flow magnitude rather than catchment area or the varying temporal and spatial impact of artificial influences controlled the output of each PCA. The first four principal components (PC1, PC2, PC3 and PC4) explained 31.2, 24.1, 21.8 and 12.2 per cent respectively of the total variance in the flow regimes of the 31 study sites. The first two principal components, therefore, explained 55.2 per cent of the variance in the flows recorded during the three driest years in the study period.

The quadrants that each of the 31 study sites lie within, and the distance from the two central axes (x = 0; y = 0), indicate the direction, positive or negative, and the relative strength of the relationship between the study site and PC1 and PC2, respectively (Clausen and Biggs, 2000). In Figure 5.4 each study site is plotted as a function of its rotated loadings for the first two principal components.

Figure 5.4: Rotated plot of loadings of the first two principal components of daily mean flows recorded between January and December inclusive during the 3 driest years in the 20-year study period (31 study sites; River Trent catchment, regions are based on Pirt (1983) and are defined in Table 5.5)



From Figure 5.4 two main clusters of study sites (A and B) may be identified containing 16 and 13 sites respectively. The River Trent at North Muskham (6) and Colwick (7) appear to be outliers from the main clusters. This is thought to be a reflection of the substantial augmentation of low flows and the subsequent creation of anti-drought conditions within the River Trent downstream of the confluence with the River Tame.

Cluster A contains the Rivers Tame (12), Cole (19) and Rea (27); watercourses located within urban catchments with heavily modified, flashy flow regimes. Cluster A also contains the Rivers Wreake (1), Soar (2), Sence (3) and the Rothley Brook (5); all watercourses with surface runoff dominated flow regimes. The watercourses located in Cluster A all display a high degree of flow variability compared to the watercourses in Cluster B.

Cluster B contains a number of watercourses including the River Dove at Marston (17), Izaak Walton (23) and Rocester (25), the Manifold (30) and the Churnet (29). Three of the study sites located along the River Derwent; Church Wilne (14), St Mary's Bridge (16) and Chatsworth (26) plot within Cluster B. This is thought to be a reflection of compensation flows regulating the flow regime of the Derwent and mimicking the provision of baseflows within groundwater-dominated watercourses.

Finally, each of the 31 study sites plotted in the PCA were allocated one of the four regions proposed by Pirt (1983). In Cluster A, nine of the 16 study sites are located within Region 3 (The Uplands to the south of the Trent) and six study sites within Region 4 (The Dukeries and Sherwood Forest). The River Derwent at Yorkshire Bridge (24) is an anomaly and is located within Region 1 (The Uplands of the South Pennines). In Cluster B, 10 of the 13 study sites are located within Region 1, two of the study sites; the River Sow (13) and the Meece Brook (15) are located within Region 3 and one study site, the River Trent at Stoke is located within Region 2 (the Trent Valley and associated terrace).

5.7 VARIABILITY OF LOW-FLOW RESPONSES BETWEEN TRENT SUB-CATCHMENT TYPES: FLOW MAGNITUDE

The spatial diversity of low-flow responses at the 31 study sites is demonstrated in Figure 5.5 which illustrates the number of station days over the study period that daily mean flows were below 20% ADF.

Figure 5.5: Spatial diversity of low-flow response: total days flows fell below 20% ADF (31 study sites; River Trent catchment, regions are defined in Table 5.5)

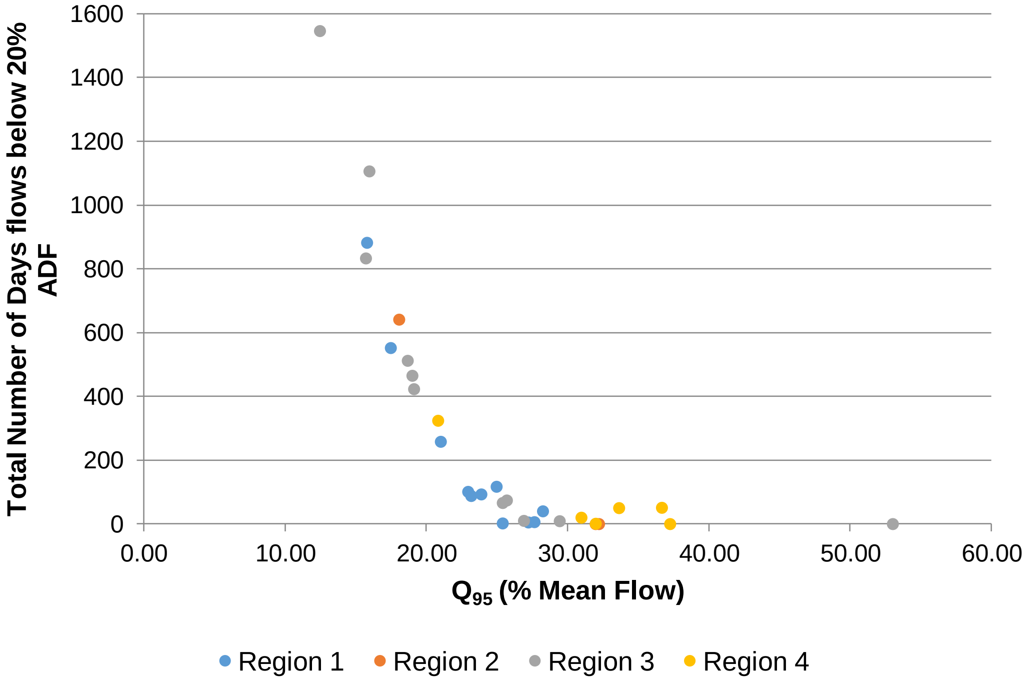
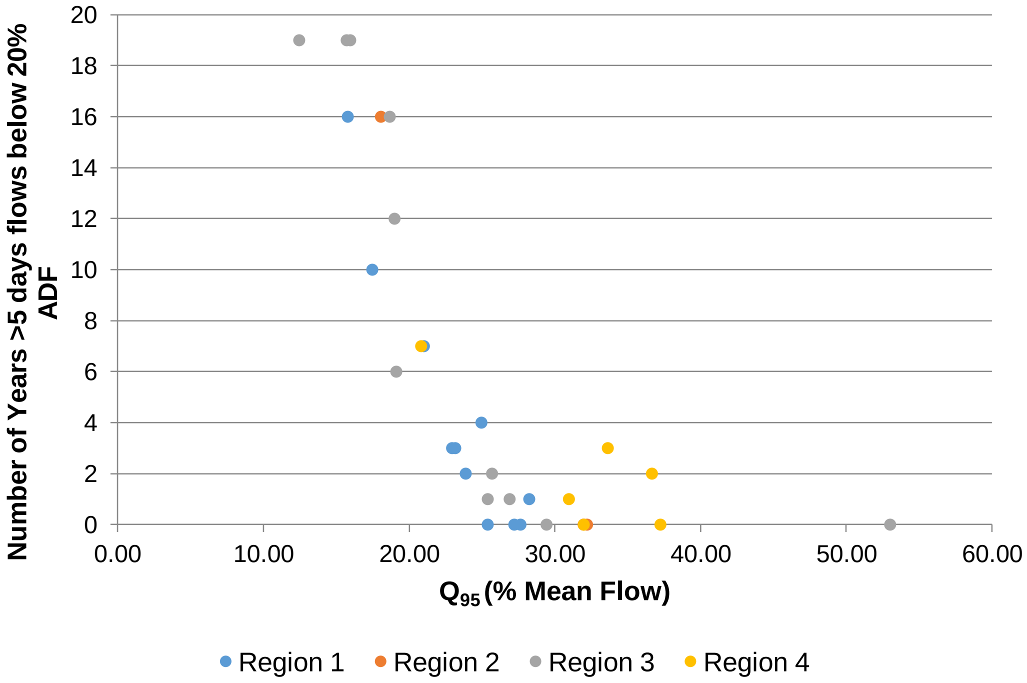


Figure 5.6: Spatial diversity of low-flow response: number of years with five or more consecutive days below 20% ADF (31 study sites; Trent catchment, regions are defined in Table 5.5)



The 20% ADF indicator has been included here as it represents an *e-flow* benchmark proposed by Baxter (1961; 1963) and Tennant (1976) for use in the United Kingdom and America, respectively. Two study sites, the River Wreake and the River Sence recorded more than 1000 days of extreme low flows, and 20 study sites recorded less than 200 days of extreme low flows. Conversely, four study sites; River Tame at Lea Marston Lakes, River Trent at Colwick and North Muskham, and the River Torne recorded none.

In addition, at each study site, the longest consecutive number of days that daily mean flows fell below 20% ADF was identified. The results of this assessment are illustrated in Figure 5.6. This measure of low-flow response was included in order to provide an indication of the spatial diversity of persistent periods of extreme low flows across the Trent catchment.

Eight of the study sites recorded low-flow periods lasting for more than five consecutive days during 10 years or more. The River Wreake and the River Sence recorded low-flow periods lasting more than five consecutive days during 16 of the 20 years investigated. The majority of study sites recorded dry years with a frequency of approximately 1:3 years. 10 study sites, however, recorded no dry years based on this particular definition of low flows.

One of the aims of these flow assessments was to explore the sensitivity of a range of potential hydrological indicators of ecological drought to drought conditions within heavily developed catchments. Figure 5.7 illustrates the total number of station days that daily mean flows fell below four hydrological indicators; the minimum MAM20, the minimum MAM50, 20% ADF, and the long-term annual Q_{95} flow. Additional information on and definitions for these potential ecological drought indicators was provided in Appendix 2.3.

The four indicators illustrated in Figure 5.7 highlight the severe droughts of 1990-1991 and 1995-1996 that were experienced across the Trent catchment. Earlier rainfall assessments indicated that both 1991 and 1996 were one of the 10 driest years in the 1910-2009 period, 100-year Midlands region rainfall record. Indeed, during 1996, daily mean flows fell below the most severe hydrological indicator; the minimum MAM20 flow, on 310 station days, during 1990 on 270 station days and during 1995 on 158 station days. This suggests that severe drought conditions were experienced during 1990, 1995 and 1996 in some areas of the Trent catchment.

Figure 5.7: Drought severity: total station days below four hydrological indicators of ecological drought (31 study sites; River Trent catchment)

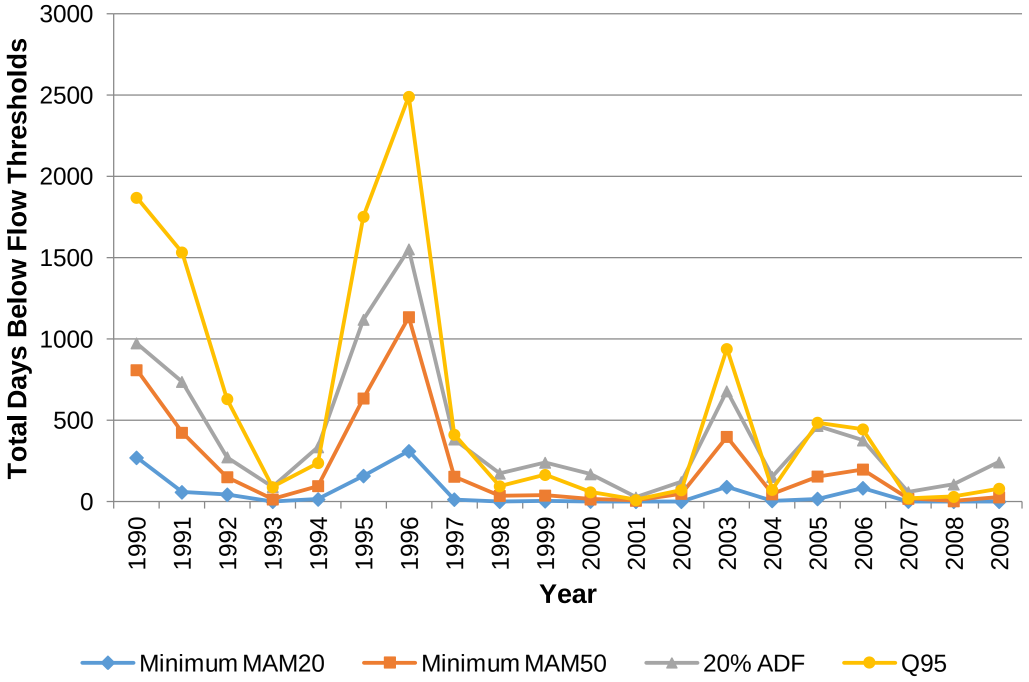
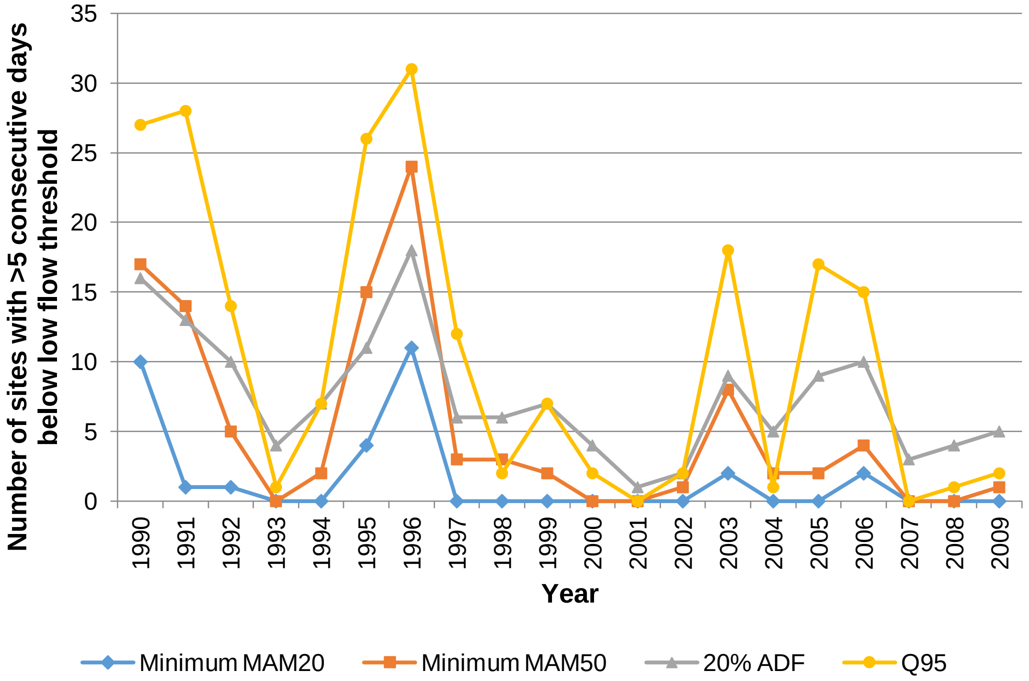


Figure 5.8: Drought severity: number of study sites with five or more consecutive flow days below four hydrological indicators of ecological drought (31 study sites; Trent catchment)

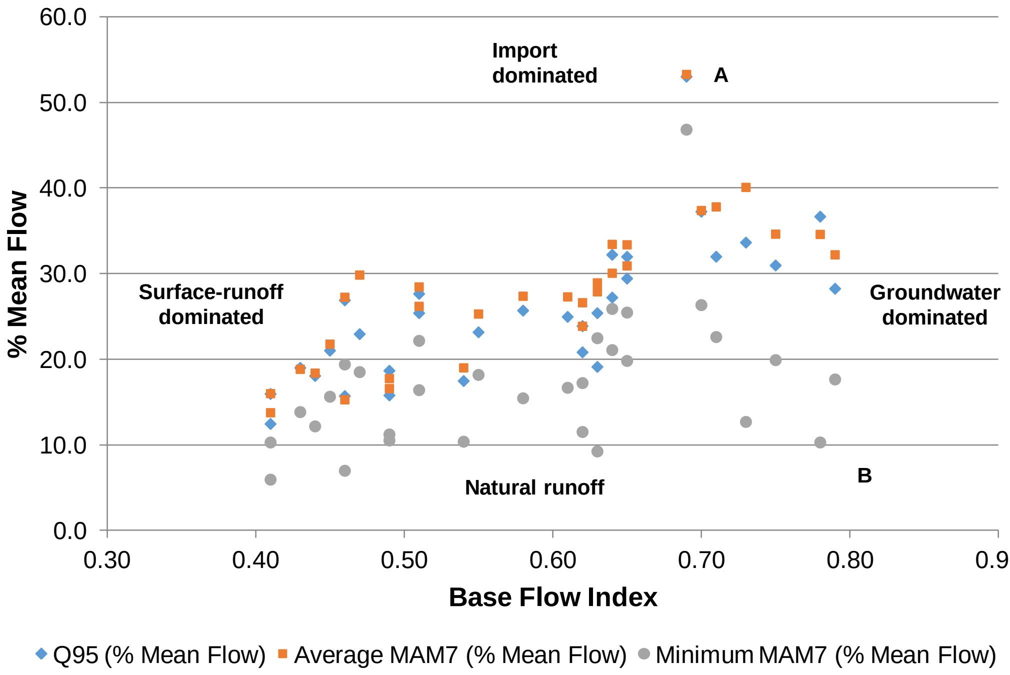


Using the same four hydrological indicators of ecological drought to identify the number of study sites experiencing five or more consecutive days below each threshold; Figure 5.8 demonstrates that the 1990-1991 and 1995-1996 droughts had a large spatial impact across the Trent catchment, with all study sites impacted to some degree. However, the most severe indicator; the minimum MAM20 flow, illustrates that severe drought rarely impacted on more than 10 out of the 31 study sites in any one year. When the minimum MAM50 flow is considered, more than five study sites recorded drought conditions in 15 years during the 20-year study period. There were five years (1993, 2000, 2001, 2007 and 2008) when no study sites recorded drought conditions.

The spatial diversity of low-flow responses at the 31 study sites located across the Trent catchment reflects the variety of sub-catchment conditions; natural and artificial. Figure 5.9 illustrates the spatial diversity of low-flow responses across the Trent catchment.

The plot of BFI; a measure of catchment storage, and three hydrological indicators of ecological drought; the long-term Q_{95}, average MAM7, and minimum MAM7 all standardised by the long-term average flow, illustrates the strong influence of catchment storage.

Figure 5.9: Spatial diversity of low-flow responses across the Trent catchment (31 study sites; River Trent catchment)



Groundwater-dominated watercourses (BFI > 0.70) plot to the right of Figure 5.9, surface-runoff watercourses (BFI < 0.55) to the left, with larger rivers (BFI between 0.55 and 0.70) plotting in the central area. The vertical axis highlights the degree of artificial influence on a sequence from heavily modified by flow augmentation, with the extreme case of the River Tame (A), low degree of flow modification, and study sites with flow regimes influenced by abstractions (for example B).

5.8 VARIABILITY OF LOW-FLOW RESPONSES BETWEEN TRENT SUB-CATCHMENT TYPES: TIMING OF LOW FLOWS

The temporal variability of selected descriptors of ecological drought across the Trent catchment used the Julian dates (timings) of a number of potential descriptors of ecological drought. The results of Spearman's Rank cross correlations are illustrated in Table 5.7. Results indicate that there is a degree of correspondence between these persistent indicators of ecological drought, with all correlations significant at the 0.01 level. The relatively low degree of correspondence between the average of the annual MAM7 series and the average of the annual MAM30, MAM50, and MAM100 series is thought to be a result of these longer duration indicators; the MAM30 essentially represents the driest month in each year and the MAM100 the three driest months, not being directly comparable with the most severe indicator of ecological drought, the average of the annual MAM7 series

Table 5.7: Spearman's rank correlation coefficients – timings of selected potential hydrological indicators of ecological drought (River Trent catchment; 31 study sites)

	Julian Date of Average MAM7	Julian Date of Average MAM20	Julian Date of Average MAM30	Julian Date of Average MAM50	Julian Date of Average MAM100
Julian Date of Average MAM7	-	0.743**	0.684**	0.574**	0.570**
Julian Date of Average MAM20	0.743**	-	0.831**	0.783**	0.664**
Julian Date of Average MAM30	0.684**	0.831**	-	0.913**	0.829**
Julian Date of Average MAM50	0.579**	0.783**	0.913**	-	0.746**
Julian Date of Average MAM100	0.570**	0.664**	0.829**	0.746**	-

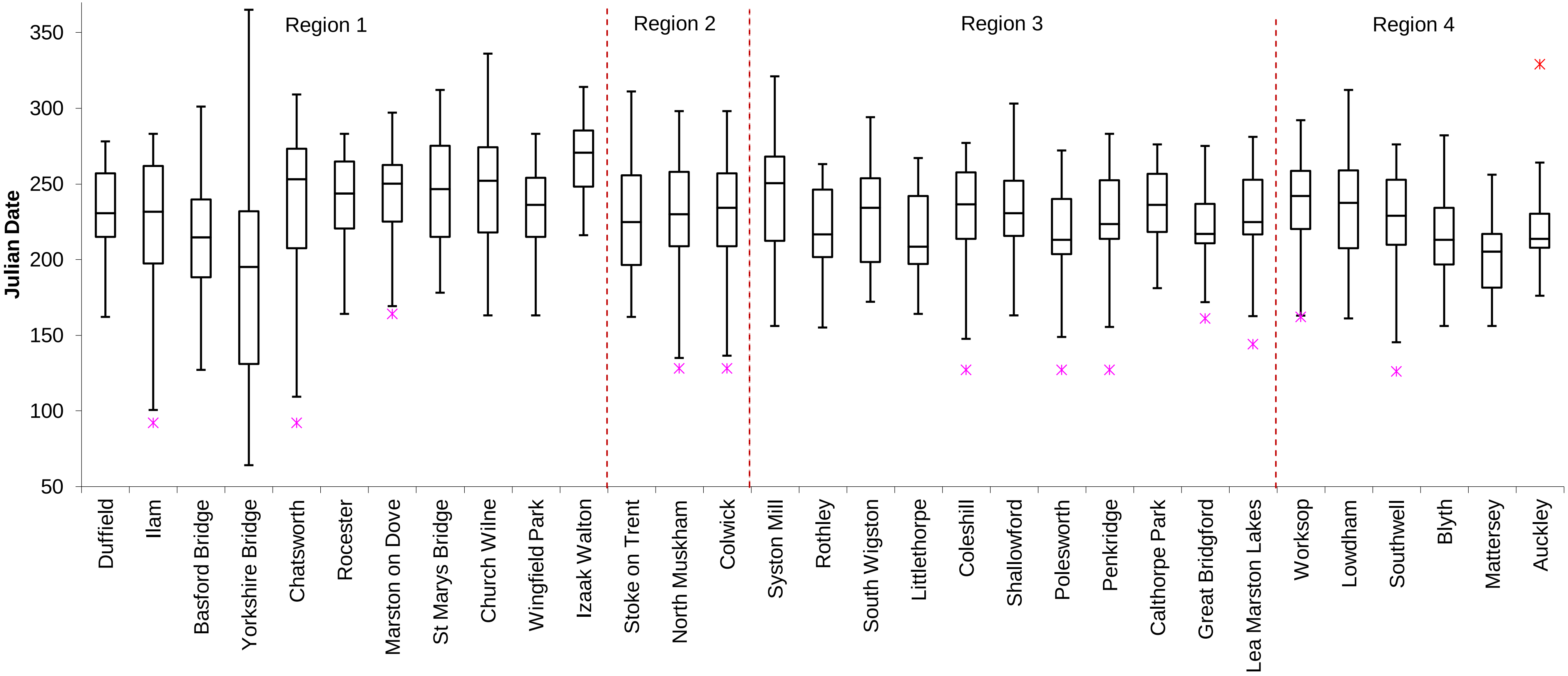
** Correlation is significant at the 0.01 level (2-tailed)

The MAM7 was the hydrological indicator of ecological drought selected to explore the variability in timing of low flows across the 31 study sites in more detail. There are a number of reasons for the selection of this particular hydrological indicator including (1) longer duration MAMs for example the MAM30, 50 and 100 are likely to include (perhaps an extended) period of flow recovery; (2) a seven day period was considered by Hindley (1973) as being sufficiently long enough in duration to not be biased by one or two days artificial interference, important within the heavily modified Trent catchment; and (3) the MAM7 was considered to be more effective at identifying the timing of drought periods than the less severe MAM20, 30, 50 and 100 indicators.

Figure 5.10 illustrates the variability in timings of MAM7 flows across the Trent catchment. Study sites are sorted into Pirt's (1983) four regions; sites within each region are ranked by the ratio of a low-flow index, long-term Q_{95} low-flow to the long-term average daily flow (lowest to highest).

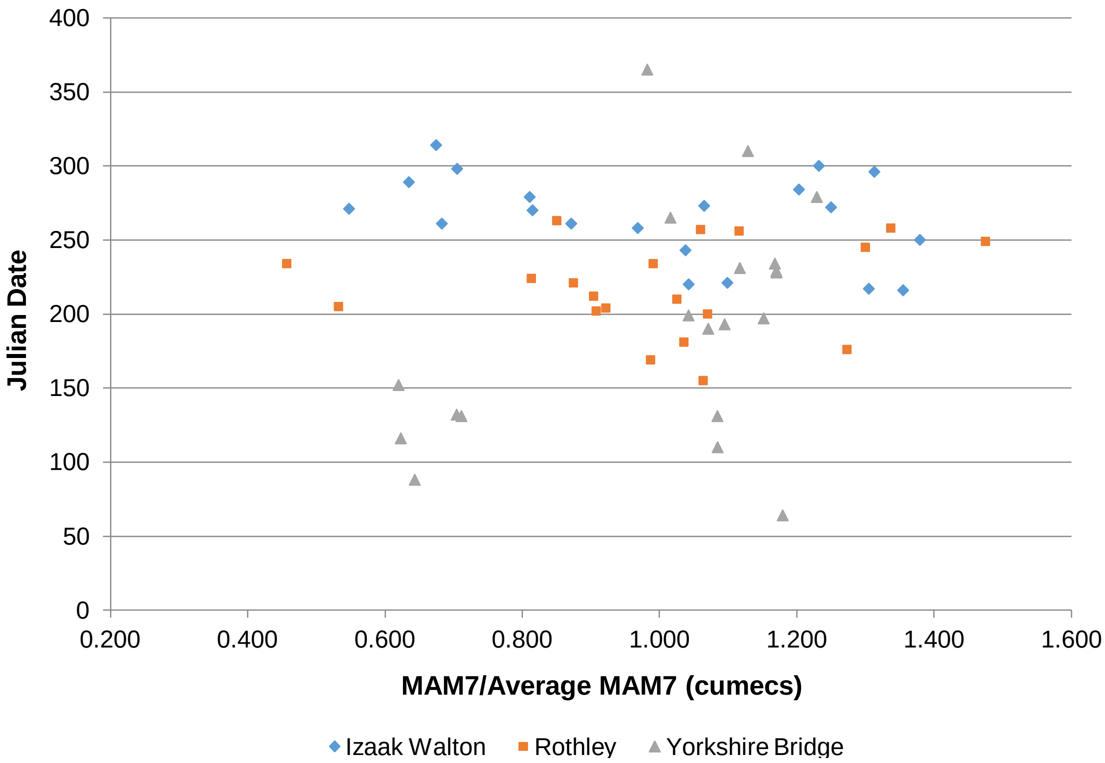
From Figure 5.10 it is immediately apparent that the largest variability in timings in MAM7 flows were experienced within the highly regulated River Derwent at Yorkshire Bridge. Conversely, the lowest variability in timings was experienced within the River Torne at Auckley. The largest variability in timings, as defined using the interquartile range (IQR); a measure of the spread of statistical dispersion, occurred in the timings of MAM7 flows recorded within Region 1; the Uplands of the South Pennines (average IQR of 54.5) and the smallest in Region 4; the Dukeries and Sherwood Forest (average IQR of 38.0). Within each of Pirt's (1983) four regions, the largest variability in timings, again defined using the IQR, occurred at sites with lower ratios of long-term Q_{95} low-flow to long-term average daily flow.

Figure 5.10: Box and whisker plot illustrating the variability in timings of annual 7-day minimum (MAM7) flows across the Trent catchment. Box plots illustrate the range of Julian Days of minimum MAM7 flows for each study site. Sites are sorted into Pirt's (1983) four regions, sites within each region are ranked by Q_{95} (%MF). The boxes enclose the interquartile (IQR) range; the horizontal line within each box indicates the median. The ends of the whiskers are set at 1.5*IQR above the 3rd quartile and 1.5*IQR below the 1st quartile. If the minimum or maximum values are outside this range then they are shown as outliers, only the minimum and maximum outliers are shown.



In order to investigate the variability in low-flow responses between sub-catchment types in more detail, the timings of annual seven-day minimum flows recorded in six contrasting sub-catchments were explored. Figure 5.11 illustrates the annual minimum MAM7 as a function of the average MAM7 flow for the 20-year study period, and the timing (Julian date) of that flow in each year.

Figure 5.11: Variation in annual 7-day minimum (MAM7) timings: three small groundwater dominated, surface-runoff dominated and regulated watercourses



First, when the two relatively natural study sites the River Dove at Izaak Walton and Rothley Brook at Rothley are compared; the groundwater-dominated River Dove experienced later low flows extending though October, than the surface-runoff dominated Rothley Brook where low flows occurred earlier in the year in June, July and August. Figure 5.11 also illustrates the timing of low flows within the heavily regulated River Derwent at Yorkshire Bridge, where low flows defined using the annual MAM7, were recorded in every month with the exception of January.

Figure 5.12 again illustrates the annual minimum MAM7 as a function of the average MAM7 for the 20-year study period, and the timing (Julian date) of that flow in each year for the larger-river and discharge-rich study sites; the River Dove at Marston on

Dove, the River Derwent at St Mary's Bridge, and the River Tame at Lea Marston Lakes.

Figure 5.12: Variation in annual 7-day minimum (MAM7) timings: three large and import-dominated watercourses

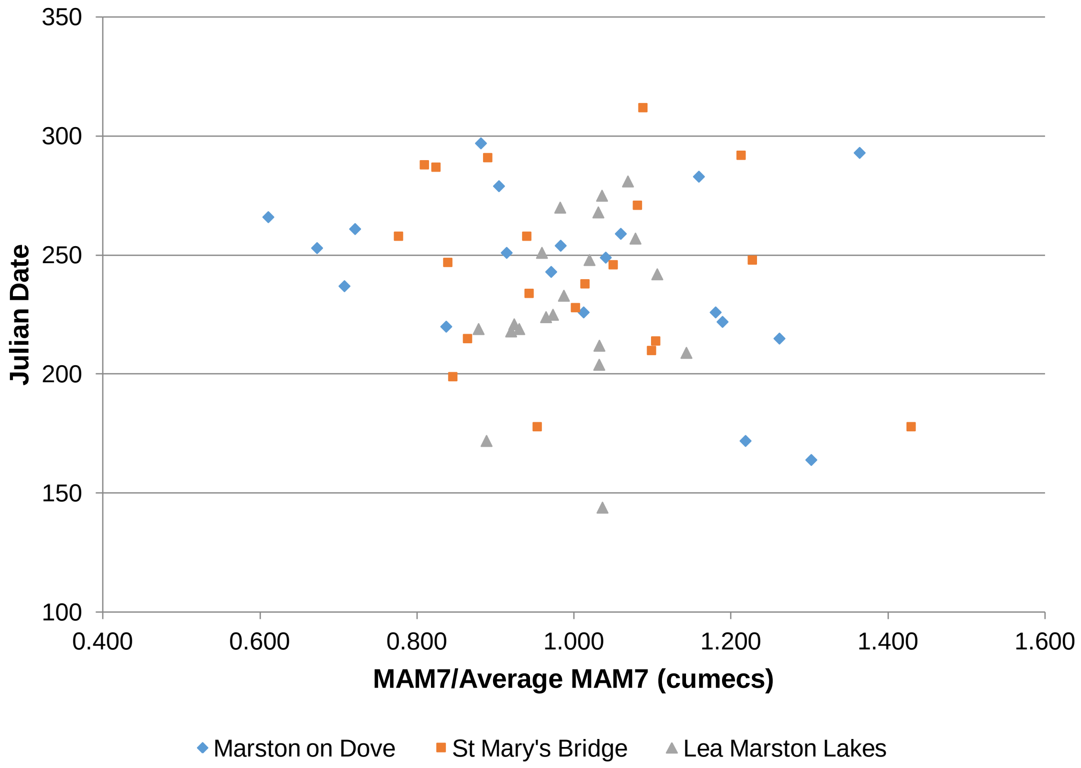
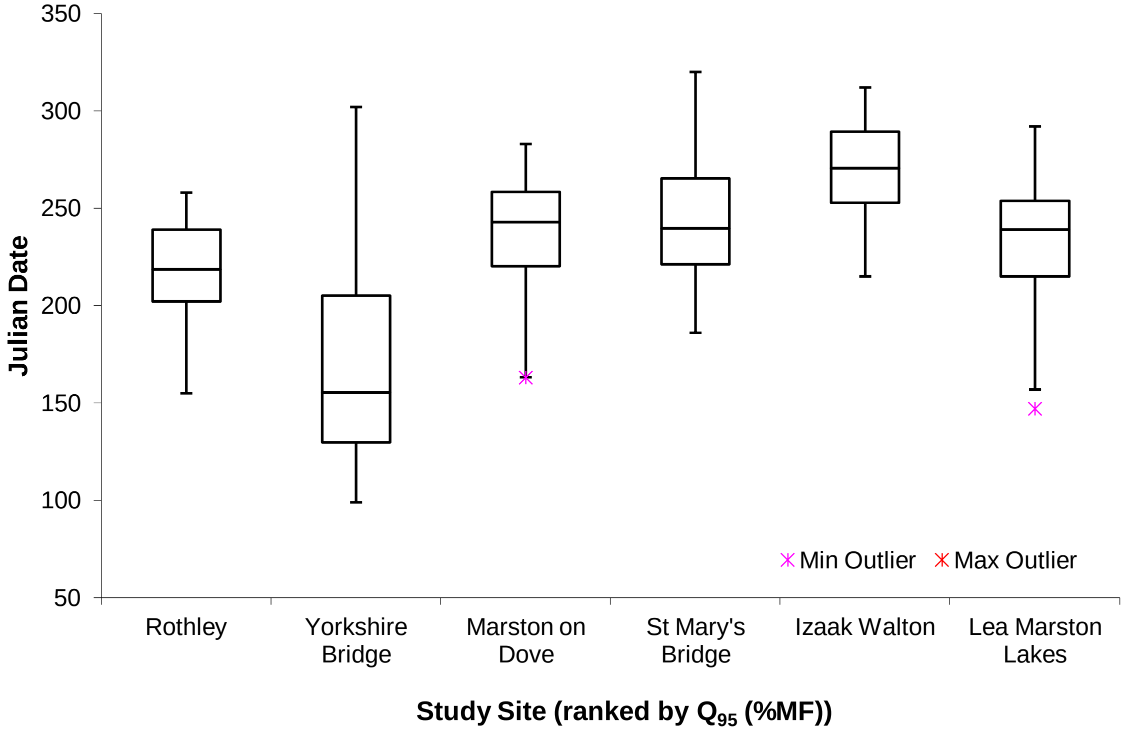


Figure 5.12 demonstrates that the majority of station years plot between June and September, and the narrow range of low-flow values, relative to average flow, throughout the 20-year study period on the River Tame are notable, reflecting the augmentation of low flows by discharges from Minworth WTW.

5.9 TIMING OF RECOVERY FROM LOW-FLOW CONDITIONS ACROSS THE TRENT CATCHMENT

Finally, the variability in timings of the start of the recovery from the annual low-flow conditions in the same contrasting sub-catchments was explored. Figure 5.13 illustrates the variability in the timings, defined using Julian dates, of the end of the annual low-flow period within six contrasting sub-catchments.

Figure 5.13: Variability in timings of the start of recovery from annual low-flow conditions: small groundwater dominated, surface-runoff dominated, regulated and large and import-dominated watercourses



The boxes enclose the interquartile (IQR) range; the horizontal line within each box indicates the median. The ends of the whiskers are set at 1.5*IQR above the 3rd quartile and 1.5*IQR below the 1st quartile. If the minimum or maximum values are outside this range then they are shown as outliers, only the maximum and minimum outliers are shown.

From Figure 5.13 it is clear that the annual low-flow period ended earliest in the River Derwent at Yorkshire Bridge, with a median Julian date of 155, and latest in the River Dove at Izaak Walton, median Julian date of 270.5. The River Derwent at Yorkshire Bridge experienced the largest variability in the timings of the end of the annual low-flow period, IQR of 75.5. Conversely, the surface-runoff dominated Rothley Brook experienced the smallest variability in timings with an IQR of 37. The variation in the timing of the end of the annual low-flow period, and start of flow recovery in the surface-runoff and groundwater-dominated watercourses is likely to have implications when it comes to the determination of *e-flows*, and the protection of watercourses from ecological drought.

5.10 EAST ANGLIA REGION RAINFALL ASSESSMENTS

There is a paucity of reliable long-term flow records available for the Great Ouse catchment with the earliest flow record (Bedford Ouse at Bedford) commencing in

1933. Thus, in order to identify historical low-flow and drought periods, long-term rainfall records (1910-) have been utilised. Rainfall data was downloaded from: http://www.metoffice.gov.uk/climate/uk/datasets/rainfall/data/East_Anglia.txt

5.10.1 Historical rainfall drought within the Great Ouse catchment

Table 5.8 summarises the long-term monthly average rainfall totals and the minimum and maximum monthly rainfall totals for the 100-year East Anglia rainfall record. The long-term average annual rainfall for the 1910 to 2009 inclusive period was 613.1 mm.

Table 5.8: Analysis of historical East Anglia rainfall – monthly average and extreme (minimum and maximum) rainfall totals

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Maximum Rainfall (mm)	Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Maximum Rainfall (mm)
Jan	53.3	**10.7 (1997)**	118.6 (1939)	**Jul**	56.0	7.7 (1955)	115.5 (1936)
Feb	40.0	3.5 (1959)	93.7 (1916)	**Aug**	56.6	4.4 (1947)	177.7 (1912)
Mar	41.7	2.0 (1929)	111.0 (1947)	**Sep**	52.6	1.7 (1959)	127.0 (1918)
Apr	43.1	**1.0 (2007)**	**117.8 (1998)**	**Oct**	57.6	6.0 (1947)	133.8 (1939)
May	45.9	**9.6 (1989)**	**118.0 (2007)**	**Nov**	62.1	18.5 (1945)	154.5 (1940)
Jun	47.9	5.6 (1962)	**129.5 (1997)**	**Dec**	56.3	12.5 (1932)	145.7 (1914)

Annual rainfall totals were ranked (lowest to highest) to identify the 10 driest and the 10 wettest years (Table 5.9)

.

Table 5.9: Analysis of historical East Anglia rainfall – the 10 driest and wettest years in the 1910-2009 inclusive 100-year period based on annual rainfall totals

Dry Year	Annual Rainfall (mm)	Percentage of 1910-2009 long-term average[1]	Wet Year	Annual Rainfall (mm)	Percentage of 1910-2009 long-term average)[1]
1921	346.5	56.5	**2001**	**779.8**	**127.2**
1996	**461.5**	**75.3**	**2000**	**778.8**	**127.0**
1933	472.2	77.0	1912	776.9	126.7
1972	475.6	77.6	1960	768.7	125.4
1991	**478.6**	**78.1**	1939	758.6	123.7
1959	481.2	78.5	1916	749.2	122.2
1990	**482.4**	**78.7**	1937	749.0	122.2
1943	483.9	78.9	1927	748.1	122.0
1964	490.3	80.0	1958	745.5	121.6
1949	490.3	80.0	1951	733.3	119.6

[1] The 1910-2009 long-term average rainfall was 613.1 mm

The results in Table 5.9 illustrate that three of the driest years (1996, 1991 and 1990) fall within the last two decades with two years (2001 and 2000) experiencing the highest annual rainfall totals. 1921 was the driest year with only 56.5 per cent of the long-term average annual rainfall (613.1 mm) recorded. It is worth noting that 1921 was also identified as the driest year from an analysis of equivalent rainfall data for the Midlands region, with 68.9 per cent of the long-term average annual rainfall (785.4 mm) recorded.

In 1996, 1991 and 1990 only 75.3, 78.1 and 78.7 per cent respectively of the long-term average annual rainfall was recorded. With two consecutive years, 1990 and 1991 experiencing below average annual rainfall, prolonged drought conditions were experienced across the catchment.

5.10.2 East Anglia region rainfall during critical ecological periods

The historical occurrence of periods of below average rainfall during the critical ecological periods of spring (April – June) and autumn (October and November) were identified. An initial assessment compared the rainfall recorded during the critical ecological periods in each year with the long-term average annual rainfall total for each critical ecological period. Long-term average rainfall totals were 136.9 mm, 165.2 mm and 119.7 mm for the spring, summer and autumn ecological periods respectively.

Table 5.10: Analysis of historical East Anglia rainfall – the 10 lowest annual rainfall totals experienced during the spring, summer and autumn ecological periods

Year	Rainfall during Spring[1] (mm)	Percentage of 1910-2009 LTA[2] (%)	Year	Rainfall during Summer[3] (mm)	Percentage of 1910-2009 LTA[4] (%)	Year	Rainfall during Autumn[5] (mm)	Percentage of 1910-2009 LTA[6] (%)
1996	**45.8**	**33.5**	1964	73.2	44.3	1978	29.0	24.2
1976	54.8	40.0	1947	80.8	48.9	1947	37.0	30.9
1995	**69.6**	**50.9**	**2003**	**81.7**	**49.5**	1920	42.4	35.4
1921	71.6	52.3	**1990**	**83.1**	**50.3**	**1995**	**45.6**	**38.1**
1938	80.1	58.5	1911	84.2	51.0	1922	58.9	49.2
1923	80.2	58.6	1921	84.5	51.2	1972	64.4	53.8
1960	81.4	59.5	1955	87.3	52.9	1985	65.6	54.8
1940	81.9	59.8	**1997**	**93.9**	**56.9**	1973	65.8	55.0
1974	82.6	60.3	1979	97.2	58.9	**1989**	**69.8**	**58.3**
1957	85.1	62.2	1959	98.8	59.8	1931	70.5	58.9

[1] Spring critical ecological period is defined as April, May and June

[2] The 1910-2009 long-term spring average rainfall is 136.9 mm

[3] Summer ecological period is defined as July, August and September

[4] The 1910-2009 long-term summer average rainfall is 165.2 mm

[5] Autumn critical ecological period is defined as October and November

[6] The 1910-2009 long-term autumn average rainfall is 119.7 mm

Table 5.10 (on the previous page) summarises the 10 driest years in the East Anglia rainfall record based on rainfall recorded during the three ecological periods. Below average rainfall totals over the 100-year record were experienced in 50 and 49 years in spring and autumn respectively. Rainfall totals recorded during each of the three ecological periods were subsequently ranked (lowest to highest totals) and the 10 driest years based on these assessments in the East Anglia district rainfall record identified.

Table 5.10 illustrates that 1996 experienced the lowest rainfall during the spring critical ecological period in the 100-year rainfall record, with only 33.5 per cent of the long-term spring average rainfall recorded. In addition, only 50.9 per cent of the long-term average spring rainfall was recorded in 1995. Rainfall recorded during the 2003, 1990 and 1997 summer ecological period represented three of the lowest summer rainfall totals experienced in the 100-year rainfall record, with only 49.5, 50.3 and 56.9 per cent respectively of the long-term summer average rainfall. Finally, two years experienced dry autumns with rainfall totals representing only 38.1 and 58.3 per cent of the long-term average autumn rainfall in 1995 and 1989 respectively. The sequence of dry critical periods (spring 1995, autumn 1995 and spring 1996) is particularly notable in terms of ecological drought.

5.10.3 Identification of the driest years in East Anglia in the 1981-2010 study period

Rainfall data was analysed in order to identify the years experiencing the lowest annual rainfall totals in the 30-year study period. Table 5.11 summarises the 1981-2010 annual rainfall totals and is included here as it provides an indication of whether there was a surplus or deficit of rainfall in comparison with the 1981 to 2010 long-term average annual rainfall (624.0 mm). Deficit years are highlighted in red.

Fourteen of the 30 years in the study period experienced a deficit in annual rainfall. The three years experiencing the largest annual rainfall were 1996 with 74.0 per cent, 1991 with 76.7 per cent and 1990 with 77.3 per cent of the 1981-2010 long-term average rainfall recorded. Interestingly there were several clusters of years experiencing below average annual rainfall particularly 1989 to 1991 (-374 mm) and 1994 to 1997 (-230 mm). According to data obtained from the Met Office, the long-term average annual East Anglia rainfall is increasing slightly with the 1961-1990 long-term average recorded as 601.3 mm, the 1971-2000 long-term average as 605.8 mm, and the most recent 1981-2010 long-term average as 624.0 mm.

Table 5.11: Comparison of annual rainfall totals for East Anglia with 1981-2010 long-term average rainfall

Year	Annual Rainfall (mm)	Surplus/ Deficit (mm)	Annual Total (% LTA)	Year	Annual Rainfall (mm)	Surplus/ Deficit (mm)	Annual Total (% LTA)
1981	649.8	25.8	104.1	**1996**	461.5	-162.5	74.0
1982	655.0	31.0	105.0	**1997**	534.1	-89.9	85.6
1983	564.1	-59.9	90.4	**1998**	713.6	89.6	114.4
1984	636.6	12.6	102.0	**1999**	671.2	47.2	107.6
1985	579.7	-44.3	92.9	**2000**	778.8	154.8	124.8
1986	636.9	12.9	102.1	**2001**	779.8	155.8	125.0
1987	701.4	77.4	112.4	**2002**	708.4	84.4	113.5
1988	625.2	1.2	100.2	**2003**	517.6	-106.4	82.9
1989	537.0	-87.0	86.1	**2004**	677.5	53.5	108.6
1990	482.4	-141.6	77.3	**2005**	530.7	-93.3	85.0
1991	478.6	-145.4	76.7	**2006**	610.0	-14.0	97.8
1992	696.8	72.8	111.7	**2007**	690.3	66.3	110.6
1993	718.6	94.6	115.2	**2008**	685.0	61.0	109.8
1994	621.2	-2.8	99.6	**2009**	599.4	-24.6	96.1
1995	553.3	-70.7	88.7	**2010**	585.3	-38.7	93.8

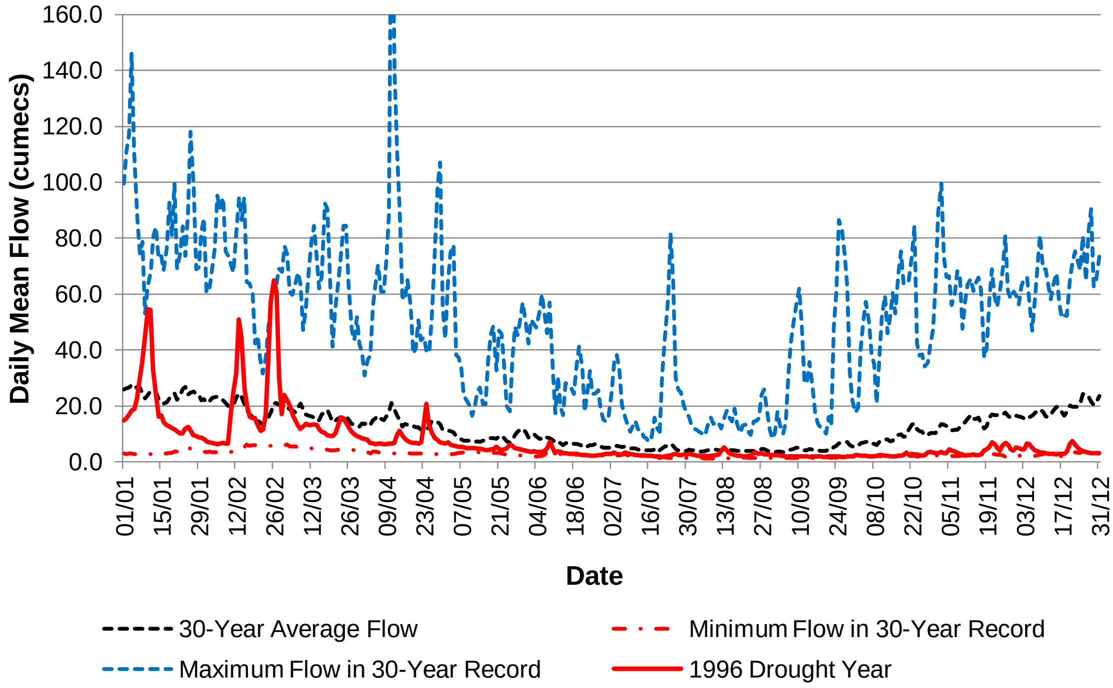
The 1981-2010 long-term average rainfall was 624 mm

5.11 GREAT OUSE FLOWS DURING THE 1996 DROUGHT

The assessment of annual rainfall totals (Table 5.11) indicated that 1996 experienced the largest rainfall deficit, receiving only 74.0 per cent of the long-term average annual rainfall. In order to explore the impact that this rainfall deficit had on river flows, a series of hydrographs were plotted using daily mean flows recorded within three watercourses with contrasting flow regimes and complete flow records for 1996; the Bedford Ouse, the River Hiz and the River Tove. The hydrographs in Figures 5.14 to 5.16 illustrate the average, minimum and maximum daily mean flows recorded in the 1981 to 2010 inclusive study period and also daily mean flows recorded during 1996.

Figure 5.14 illustrates hydrographs for the Bedford Ouse at Bedford, the largest study site with a catchment area of 1460 km^2. The catchment has a predominantly clay geology with a BFI of 0.53 (Marsh and Hannaford, 2008). The 30-year average daily mean flow hydrograph demonstrates that low flows occur between July and September, and that sustained flow recovery from the summer low-flow period commences towards the end of September.

Figure 5.14: Hydrographs illustrating the average, minimum and maximum daily mean flows in the 1981-2010 study period and the 1996 drought: Bedford Ouse at Bedford*

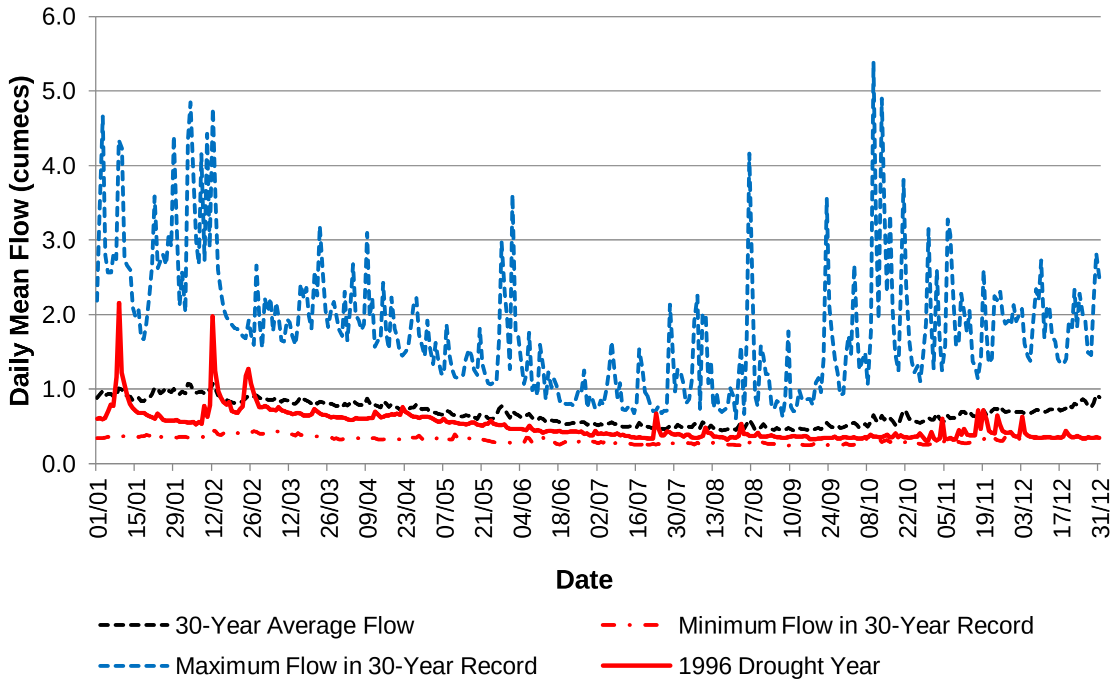


*Please note that a maximum flow of 219.100 cumecs was recorded on 11/04/1998

Flows experienced during 1996 were higher than the 30-year average flow on a number of occasions between January and April, with one flow peak in February approaching the maximum flow in the 30-year study period. From the end of April onwards, however, flows within the Bedford Ouse remained below the 30-year average flow, and during parts of June, July, September and October, represented the lowest flow in the 30-year flow record. Finally, from Figure 5.14 it is immediately apparent that, there was no recovery of flows during the autumn and winter recharge period in 1996. This in combination with continued below average rainfall, would have impacted flows during the spring and summer of 1997.

Figure 5.15 illustrates hydrographs for the River Hiz at Arlesey, a small (catchment area 108 km^2) predominantly chalk catchment with a BFI of 0.85. The 30-year average daily mean flow hydrograph illustrates the lack of flow variability within the River Hiz, with flows ranging between 0.447 and 1.073 cumecs. The 30-year average daily flow hydrograph suggests that low flows within the River Hiz occur between July and September, with recovery from the low-flow period not commencing until the beginning of October.

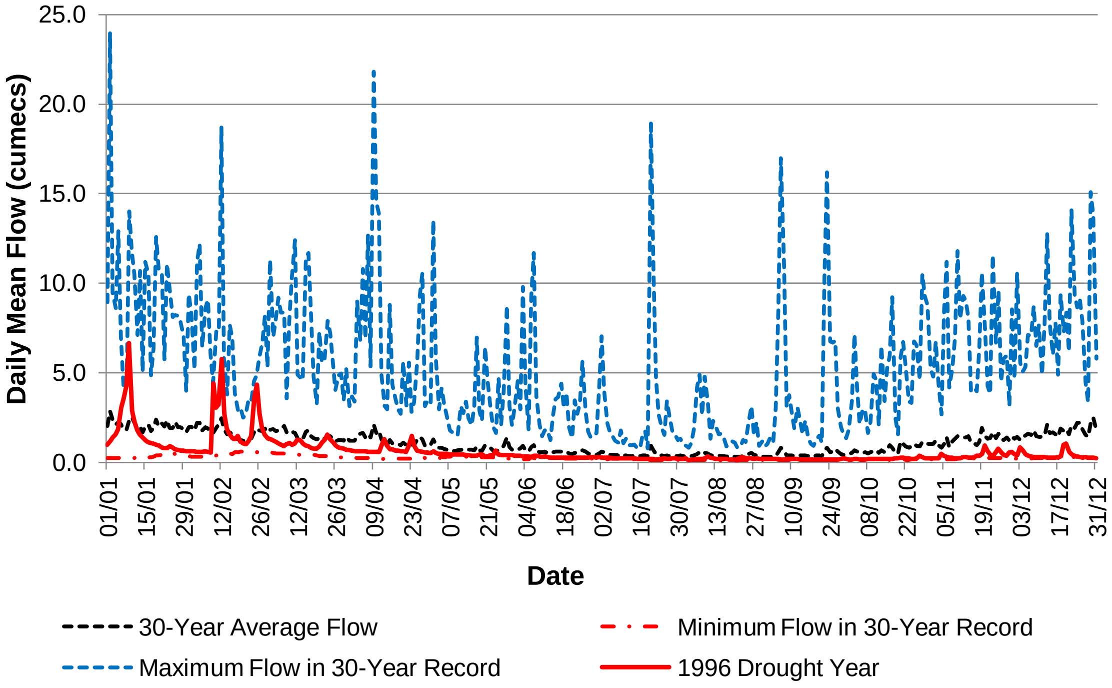
Figure 5.15: Hydrographs illustrating the average, minimum and maximum daily mean flows in the 1981-2010 study period and the 1996 drought: River Hiz at Arlesey



Flows experienced during 1996 were at times higher than the 30-year average daily flow in January, February, July, August and November. 1996 flows remained below the 30-year average flow from the end of April until the middle of July. The 1996 drought year hydrograph illustrates flow peaks in July and August, presumably in response to intensive summer rainfall events or as a result of a reduction in groundwater abstraction for public water supply, described as having a significant impact on flows. From late August up to the start of November, flows in 1996 remained well below the 30-year average flow. Throughout November a series of peaks in the hydrograph suggest that there was a degree of flow recovery, however, in December 1996, flows represented the lowest flows in the 30-year flow record. The lack of flow recovery during 1996 again suggests that spring and summer flows within the River Hiz in 1997 would have been impacted.

Finally, Figure 5.16 illustrates hydrographs for the River Tove at Cappenham Bridge, a small (catchment area 138.1 km^2) responsive catchment with a BFI of 0.54. The 30-year average daily mean flow hydrograph indicates that low flows within the River Tove occur between June and September and that on average, recovery from the summer low-flow period commences at the beginning of October.

Figure 5.16: Hydrographs illustrating the average, minimum and maximum daily mean flows in the 1981-2010 study period and the 1996 drought: River Tove at Cappenham Bridge



Flows experienced during 1996 were higher than the 30-year average flow on several occasions between January to April inclusive, with flow peaks in January and February approaching the maximum flow in the 30-year flow record. From May onwards, however, flows in 1996 remained consistently below the 30-year average daily flow, and for the majority of the year represented the lowest flow in the 30-year flow record. Again from Figure 5.16 it is clear that there was no recovery of flows during the autumn and winter recharge period.

The most notable contrast between the Great Ouse and Trent is the impact of the 1996 drought on the autumn critical ecological period with severe low flows on the former extending through to the winter with the failure of the normal autumn flow recovery. All three examples from the Ouse catchment also experienced below average flows in the spring of 1996, reflecting the low rainfalls during the autumn of 1995 and the failure of catchment storage to recover over the winter of 1995-96.

5.12 GREAT OUSE CATCHMENT CLASSIFICATION

Each study site was allocated to one of the seven contrasting sub-catchments defined by the Environment Agency (2010a); Table 5.12 illustrates the distribution of the 17 study sites across the sub-catchments.

Table 5.12: Distribution of study sites across seven contrasting sub-catchments defined by the Environment Agency (2010a)

Sub-catchment	Area (km^2)	Major Watercourses	Study Sites within sub-catchment
Upper Bedford Ouse	1444	River Great Ouse, River Ouzel, River Tove	River Tove – Cappenham Bridge
Lower Bedford Ouse	1569	River Great Ouse, River Ivel, River Kym, Alconbury Brook	Bedford Ouse – Bedford River Ivel – Blunham River Hiz – Arlesey River Kym – Meagre Farm River Flit - Shefford
River Cam Catchment	804	River Cam, River Rhee, River Granta, Bin Brook, Bourne Brook	River Cam – Dernford River Rhee – Burnt Mill River Granta – Linton
Fens – Middle Level	1098	Tidal River Great Ouse/100ft, River Delph, Counter Drain, Middle Level Main Drain (non-Main River)	No study sites
Fens – South Level	1259	Ely Ouse, Soham Lode, Cottenham Lode lower reaches of the River Cam, River Lark, River Little Ouse River Wissey	No study sites
Eastern Rivers	1661	River Lark, River Little Ouse, River Wissey, River Kennet River Thet	River Thet – Melford Bridge River Little Ouse – Knettishall River Wittle – Quidenham River Stringside – Whitebridge River Lark – Temple
North West Norfolk	760	River Heacham, River Gaywood, River Ingol, River Babingley River Nar	River Heacham – Heacham River Babingley – Castle Rising River Nar - Marham

Table 2.2 in Section 2.3.4 provided information on the characteristics of each of the 17 Great Ouse study sites. BFI values range from between 0.26 for the extremely flashy River Kym to 0.96 for the River Heacham, a high baseflow catchment where the topographical catchment area substantially exceeds the contributing area by a factor of about two (Marsh and Hannaford, 2008). The average BFI across the 17 study sites in the Great Ouse catchment was calculated as 0.71.

5.13 VARIABILITY IN RUNOFF ACROSS THE GREAT OUSE CATCHMENT

In order to explore the spatial pattern of flows across the Great Ouse catchment, two basic flow descriptors; mean annual runoff as a percentage of mean annual rainfall, and runoff per unit area ($m^3s^{-1}km^{-2}$) were calculated for the study sites.

The spatial variability in the basic flow descriptors across the contrasting sub-catchments identified by the Environment Agency (2010a) was investigated in order to determine whether runoff varied across the sub-catchments. Table 5.13 provides information on the minimum, maximum and average values of the two basic flow descriptors of runoff.

Table 5.13: Variability in runoff across the Great Ouse catchment (sub-catchments based on Environment Agency (2010a) and are summarised in Table 5.12)

Sub-catchment	Minimum Runoff (% Annual Rainfall) *($m^3s^{-1}km^{-2}$)*	Maximum Runoff (% Annual Rainfall) *($m^3s^{-1}km^{-2}$)*	Average Runoff (% Annual Rainfall) *($m^3s^{-1}km^{-2}$)*
Upper Bedford Ouse[1]	35.5 *0.008*	35.5 *0.008*	35.5 *0.008*
Lower Bedford Ouse	23.1 *0.004*	37.0 *0.008*	31.0 *0.006*
River Cam Catchment	16.5 *0.003*	25.5 *0.004*	21.3 *0.004*
Eastern Rivers	24.1 *0.005*	30.0 *0.006*	25.6 *0.005*
North West Norfolk	16.4 *0.004*	47.8 *0.010*	33.0 *0.007*

[1] This sub-catchment contains one site; the River Tove at Cappenham Bridge

Values of the first flow descriptor mean annual runoff as a percentage of mean annual rainfall ranged from between 16.4 per cent (River Heacham) and 47.8 per cent (River) with an average value of 28.3 per cent. Only one study site, the River Tove, is located within the Upper Bedford Ouse sub-catchment.

Within the Lower Bedford Ouse sub-catchment (5 study sites) annual runoff as a percentage of annual rainfall ranges between 23.1 per cent (River Kym) and 37.0 per cent (River Flit) with an average value of 31.0 per cent. The low value of annual runoff within the River Kym is thought to be due to a combination of relatively low annual rainfall (606 mm pa) and agricultural and industrial abstractions. Within the River Cam sub-catchment (3 study sites) annual runoff ranges from between 16.5 per cent (River Granta) and 25.5 per cent (River Cam) with an average value of 21.3 per cent. The relatively low value of runoff within the River Granta is thought to be a legacy of a combination of factors including relatively low annual rainfall across the catchment (620 mm pa), the size of the catchment (59.8 km^2) and abstraction.

Within the Eastern Rivers sub-catchment (5 study sites) annual runoff ranges from between 24.1 per cent (River Little Ouse) and 30.0 per cent (River Thet) with an average value of 25.6 per cent. With the exception of the River Thet, annual runoff is remarkably consistent. The slightly higher runoff within the River Thet is thought to be a result of the augmentation of river flows by effluent returns.

Finally, within the North West Norfolk sub-catchment (3 study sites) annual runoff ranges from between 16.4 per cent (River Heacham) and 47.8 per cent (River Babingley) with an average value of 33.0 per cent. The extremely low value of runoff within the River Heacham, the lowest across the 17 study sites is thought to be due to a combination of low annual rainfall, agricultural abstractions, and the small catchment area of 59 km^2. The topographical catchment area upstream of the River Heacham is thought to considerably exceed the true contributing area by a factor of approximately two (Marsh and Hannaford, 2008).

Interestingly, the study site with the highest value of annual runoff, the River Babingley is also located within the North West Norfolk sub-catchment. The Babingley is described by Marsh and Hannaford (2008) as a high baseflow catchment (BFI 0.95) with a groundwater catchment area that exceeds the topographic divide.

Values of a second basic flow descriptor, runoff per unit area ($m^3s^{-1}km^{-2}$) ranged from between 0.003 $m^3s^{-1}km^{-2}$ (River Granta) and 0.010 $m^3s^{-1}km^{-2}$ (River Babingley) with an average of 0.006 $m^3s^{-1}km^{-2}$. Generally, watercourses with the highest values of annual runoff per unit area are located within the Upper Bedford Ouse and North West Norfolk sub-catchments and watercourses with the lowest values of runoff per unit area in the River Cam sub-catchment.

Within the Lower Bedford Ouse sub-catchment (5 study sites) runoff per unit area varies from between 0.004 $m^3s^{-1}km^{-2}$ (River Kym) and 0.008 $m^3s^{-1}km^{-2}$ (Bedford Ouse and River Flit) with an average value of 0.006 $m^3s^{-1}km^{-2}$. The relatively high value of runoff per unit area within the Bedford Ouse is thought to be due to a combination of relatively high annual rainfall (654 mm pa) and the augmentation of flows by effluent discharge from Milton Keynes sewage treatment works. Similarly, the relatively high value of runoff per unit area within the River Flit at Shefford is thought to be due to the augmentation of flows by effluent discharge from Luton sewage treatment works.

Within the River Cam sub-catchment (3 study sites) runoff per unit area varies from between 0.003 $m^3s^{-1}km^{-2}$ (River Granta) and 0.004 $m^3s^{-1}km^{-2}$ (Rivers Cam and Rhee) with an average value of 0.004 $m^3s^{-1}km^{-2}$. Within the Eastern Rivers sub-catchment (5 study sites) runoff per unit area varies from between 0.005 $m^3s^{-1}km^{-2}$ (Rivers Little Ouse, Wittle, Stringside and Lark) and 0006 $m^3s^{-1}km^{-2}$ (River Thet) with an average value of 0.005 $m^3s^{-1}km^{-2}$. Finally, within the North West Norfolk sub-catchment (3 study sites) runoff per unit area varies from between 0.004 $m^3s^{-1}km^{-2}$ (River Heacham) and 0.010 $m^3s^{-1}km^{-2}$ (River Babingley) with an average value of 0.007 $m^3s^{-1}km^{-2}$. A possible explanation for the apparently high value of runoff within the River Babingley was provided on page 163.

5.14 THE HETEROGENEITY OF FLOWS ACROSS THE GREAT OUSE CATCHMENT DURING PERIODS OF BELOW AVERAGE RAINFALL

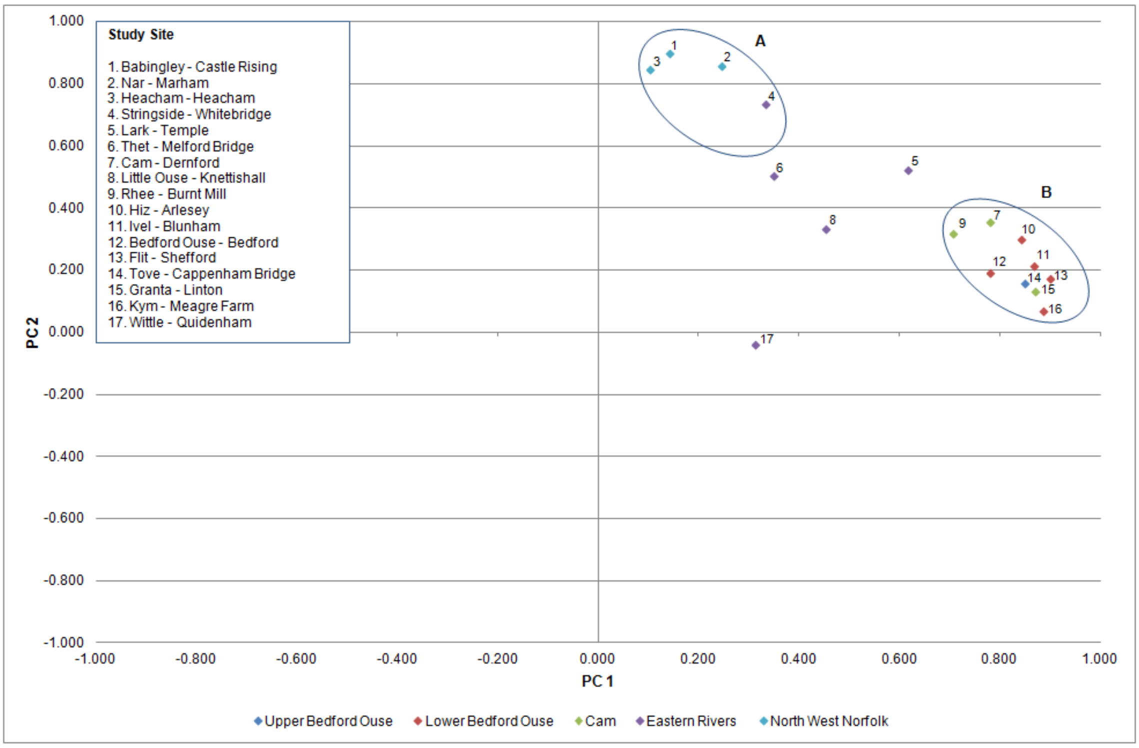
In order to investigate the heterogeneity of flows during periods of below average rainfall, a PCA with varimax rotation was performed using daily mean flows recorded across the 17 study sites during the three driest years in the 30-year study period standardised by the 30-year average flow. January to December inclusive, flows recorded during 1996, 1991 and 1990, the three driest years in the study period, were used in the PCA.

The results of the PCAs that utilised standardised and raw (non-standardised) daily mean flow data were identical indicating that flow magnitude rather than catchment area or the varying temporal and spatial impact of artificial influences controlled the output of each PCA. The first three principal components (PC1, PC2, and PC3) explained 42.7, 23.1, and 20.3 per cent respectively of the total variance in the flow regimes of the 17 study sites. The first two principal components, therefore, explained approximately 65.7 per cent of the total variance in the flows recorded during the three driest years.

The quadrants that each of the 17 study sites lie within, and the distance from the two central axes ($x = 0$; $y = 0$), indicate the direction, positive or negative, and the relative strength of the relationship between the study site and PC1 and PC2. In Figure 5.17 each study site is plotted as a function of its rotated loadings for the first two principal components.

From Figure 5.17, two clusters ‘A’ containing four study sites and ‘B’ containing nine study sites may be identified. Cluster A contains small watercourses with groundwater dominated flow and Cluster B larger sized watercourses. The proximity of the nine sites in Cluster B to each another within the rotated PCA plot suggests that the hydrological characteristics and flow regimes of the sites are similar during periods of below average annual rainfall. The PCA in Figure 5.17 illustrates that anthropogenic influences are overriding geographical patterns across the Great Ouse catchment.

Figure 5.17: Rotated plot of loadings of the first two principal components of daily mean flows recorded between January and December inclusive during the 3 driest years in the 30-year study period (17 study sites, River Great Ouse catchment, sites classified according to the sub-catchments defined by the Environment Agency (2010a) see Table 5.12)



Study sites 1 (River Babingley), 2 (River Nar) and 3 (River Heacham) are located within the North West Norfolk sub-catchment. The proximity of these three sites within the rotated PCA plot suggests that they have similar hydrological characteristics and flow regimes.

Four sites; study site 4 (River Stringside), 5 (River Lark), 6 (River Thet) and 8 (River Little Ouse) plot in a similar area of the rotated PCA. All four sites are located within the Eastern Rivers sub-catchment and are likely to have similar hydrological characteristics and flow regimes. Interestingly, one study site, the River Wittle, appears to be an outlier from the remainder of the Eastern Rivers study sites. This perhaps indicates that the hydrological characteristics and flow regime of the River Wittle differs from the rest of the Eastern Rivers study sites.

5.15 VARIABILITY OF LOW-FLOW RESPONSES BETWEEN GREAT OUSE SUB-CATCHMENT TYPES: FLOW MAGNITUDE

The spatial diversity of low-flow responses across the 17 study sites is demonstrated in Figure 5.18.

Figure 5.18: Spatial diversity of low-flow response: total days flows were equal to or lower than 20% ADF (River Great Ouse catchment; 17 study sites, sub-catchments are defined in Table 5.12)

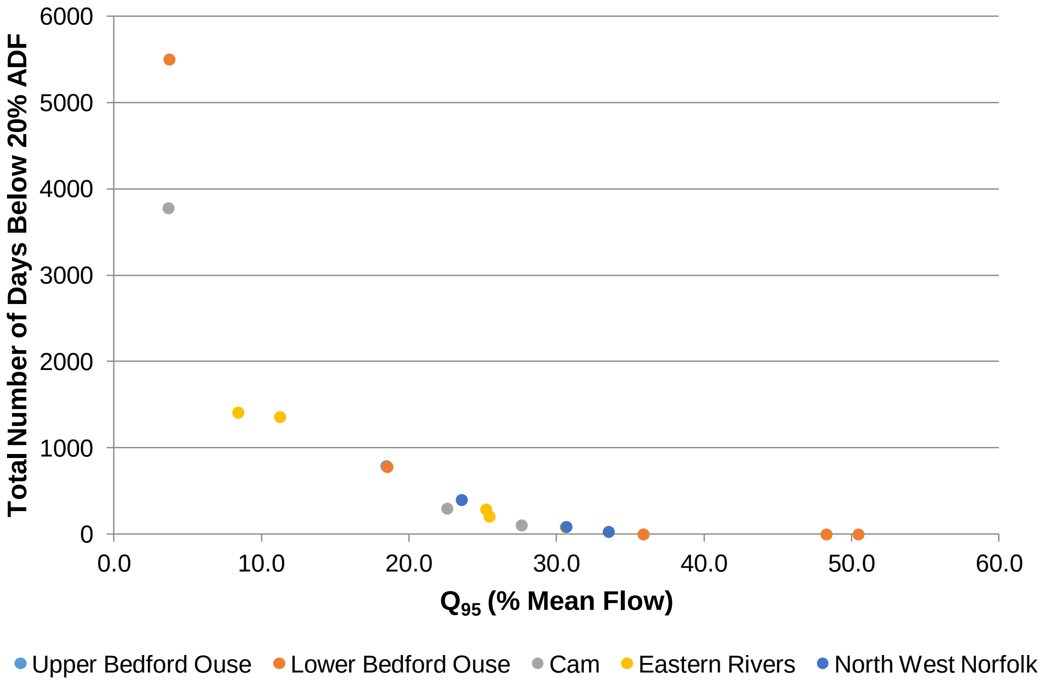
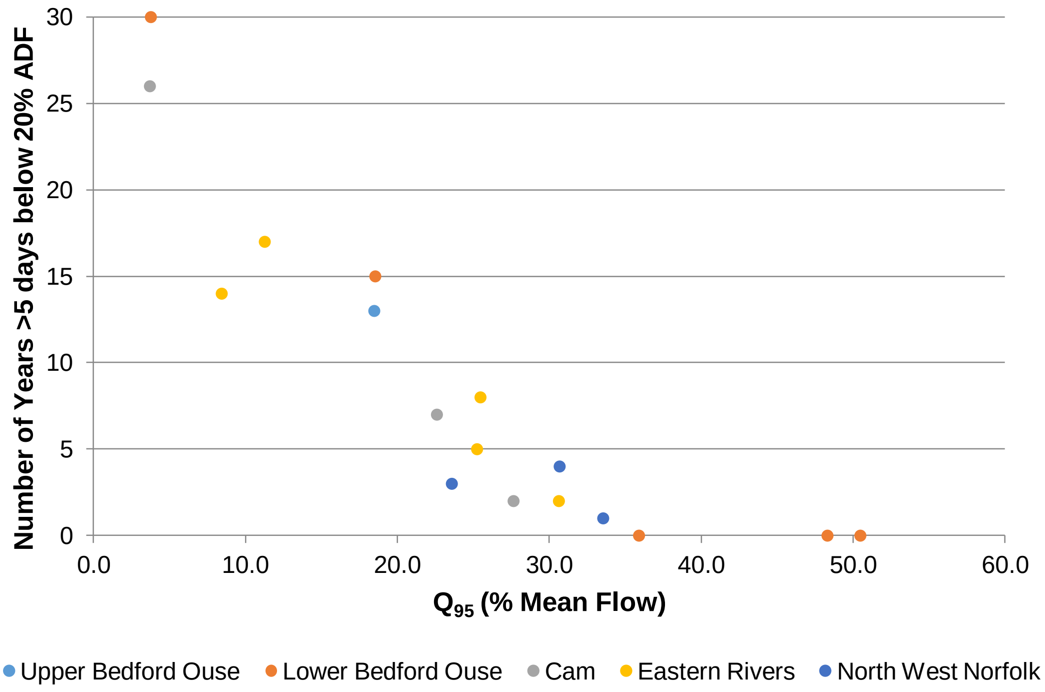


Figure 5.18 illustrates the total number of station days over the 30-year study period that daily mean flows were equal to or below a low-flow indicator, 20% ADF. This low-flow indicator has been included here as it represents an *e-flow* benchmark proposed for some watercourses within both the United Kingdom and United States, by Baxter (1961; 1963) and Tennant (1976), respectively.

Two study sites; the River Kym (5500 days) and the River Granta (3778 days) recorded more than 3000 days in total and more than 100 days per year on average of extreme low flows. In addition, two study sites; the River Stringside (1411 days) and the River Wittle (1360 days) recorded more than 1000 days of extreme low flows. Conversely, seven study sites recorded less than 200 days of extreme low flows, with both the Rivers Flit and Hiz recording no days of flows below 20% ADF.

In addition, the longest consecutive number of days that daily mean flows were equal to or fell below 20% ADF was identified. The results of this assessment are illustrated in Figure 5.19. This measure of low-flow response was included in order to provide an indication of the spatial diversity of persistent periods of extreme low flows.

Figure 5.19: Spatial diversity of low-flow response: number of years with five or more consecutive days below 20% ADF (River Great Ouse catchment; 17 study sites, sub-catchments are defined in Table 5.12)



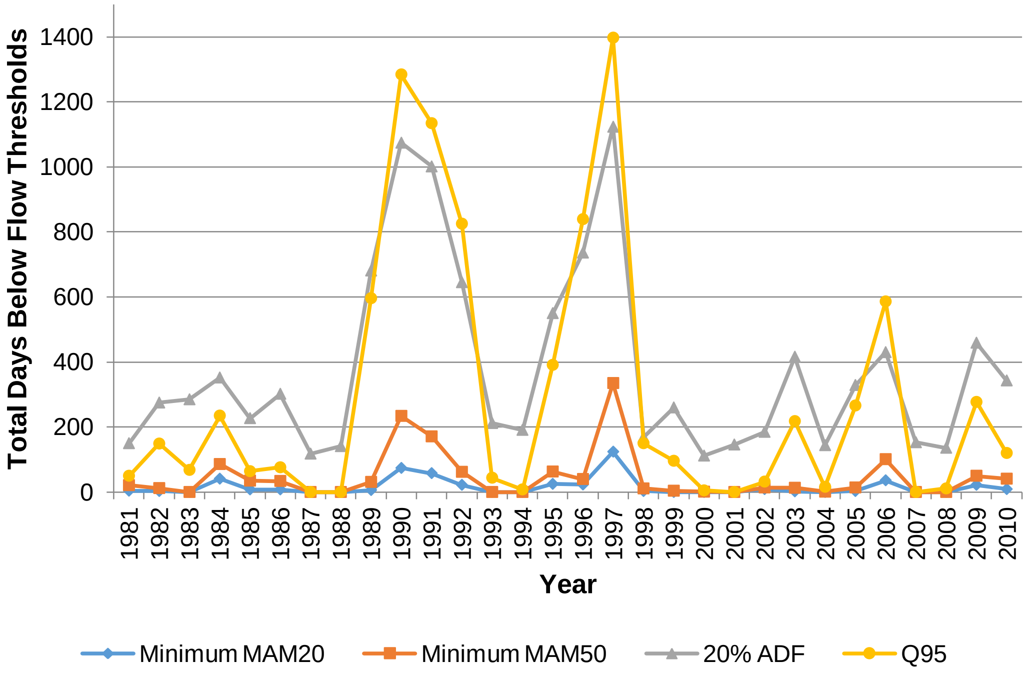
Six study sites recorded low-flow periods lasting for more than five consecutive days during 10 years or more. Based on this particular descriptor of low-flow, the River Kym recorded low-flow periods lasting more than five consecutive days during each of the 30 years forming the basis of the study period. In addition, three sites, the River Granta (26 years), River Wittle (17 years) and the Bedford Ouse (15 years) recorded low-flow periods lasting more than five consecutive days in more than half of the years investigated. Based on this definition of low flows three sites (the Rivers Ivel, Flit and Hiz) recorded no dry years.

One of the main aims of these assessments was to explore the sensitivity of a range of potential hydrological indicators of ecological drought to drought and low-flow conditions within the Great Ouse catchment. The Great Ouse is a large and diverse catchment, and the PCA demonstrated that watercourses located within the Great

Ouse catchment have contrasting flow regimes. In addition, the flow regimes of watercourses located within the Great Ouse catchment are impacted by a different range of artificial influences, particularly abstraction for spray irrigation during periods of below average rainfall.

Figure 5.20 illustrates the total number of station days that daily mean flows were equal to or lower than four hydrological indicators; (1) the minimum value of the series of annual MAM20 flows (Minimum MAM20), (2) the minimum value of the series of annual MAM50 flows (Minimum MAM50), (3) 20% ADF, and (4) the long-term annual Q_{95}.

Figure 5.20: Drought severity: total station days equal to or below four hydrological indicators of ecological drought (River Great Ouse catchment; 16 study sites*)

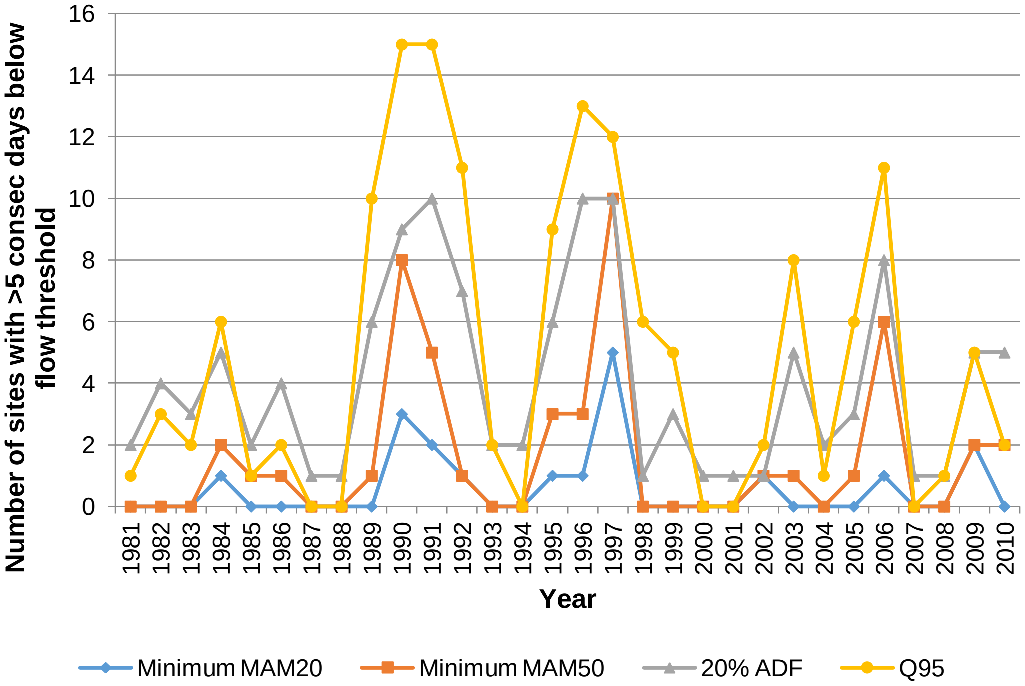


*Please note that results for the River Granta at Linton are not included due to issues surrounding the large number of zero flows in the flow record and the resulting minimum MAM20 and MAM50 values of 0.000 m^3s^{-1}

The four hydrological indicators illustrated in Figure 5.20 highlight the severe droughts of 1989-1992, 1995-1997, and also the less severe drought of 2005-2006 experienced across the Great Ouse catchment. Earlier rainfall assessments indicated that based on annual rainfall deficiencies, 1996, 1991 and 1990 were one of the 10 driest years in the 1910-2009 inclusive, 100-years East Anglia region rainfall record. When the most severe hydrological indicator, the minimum MAM20 is, however, used to define drought and low-flow periods across the Great Ouse catchment, 1997 experienced 124 station days below the minimum MAM20 whereas 1996 experienced only 23 station days below the minimum MAM20 flow.

This illustrates one of the issues surrounding the use of rainfall records to identify historical drought periods across a spatially diverse catchment. This may also, however, simply be a reflection of groundwater storage within the catchment maintaining flows during the summer period, or a result of flow augmentation by effluent discharges or by groundwater support schemes.

Figure 5.21: Drought severity: number of study sites with more than five consecutive flow days equal to or below four hydrological indicators of ecological drought (River Great Ouse catchment; 16 study sites*)



*Please note that results for the River Granta at Linton are not included due to issues surrounding the large number of zero flows in the flow record and the resulting minimum MAM20 and MAM50 values of 0.000 m^3s^{-1}

Using the same four potential indicators of ecological drought to identify the number of study sites experiencing more than five consecutive days equal to or below each threshold, Figure 5.21 demonstrates that the 1990-1991, 1995-1997 and to an extent the 2006 drought had a large spatial impact across the Great Ouse catchment, with the majority of sites impacted to some degree. The most severe indicator, the minimum MAM20 flow, however, illustrates that severe drought only impacted on more than two of the 16 study sites assessed here in two years (1990 and 1997) with a maximum of five sites (Rivers Tove, Rhee, Cam, Ivel and Hiz) experiencing more than five consecutive days of flows equal to or lower than the minimum MAM20 flow during 1997. When the annual Q_{95} is, however, used to identify drought periods, seven years in the 30-year study period (1989, 1990, 1991, 1992, 1996, 1997 and 2006) experienced persistent low flows across a large spatial area with 10 or more study sites experiencing prolonged low-flow conditions.

Figure 5.22: Spatial diversity of low-flow responses across the Great Ouse catchment (River Great Ouse catchment; 17 study sites)

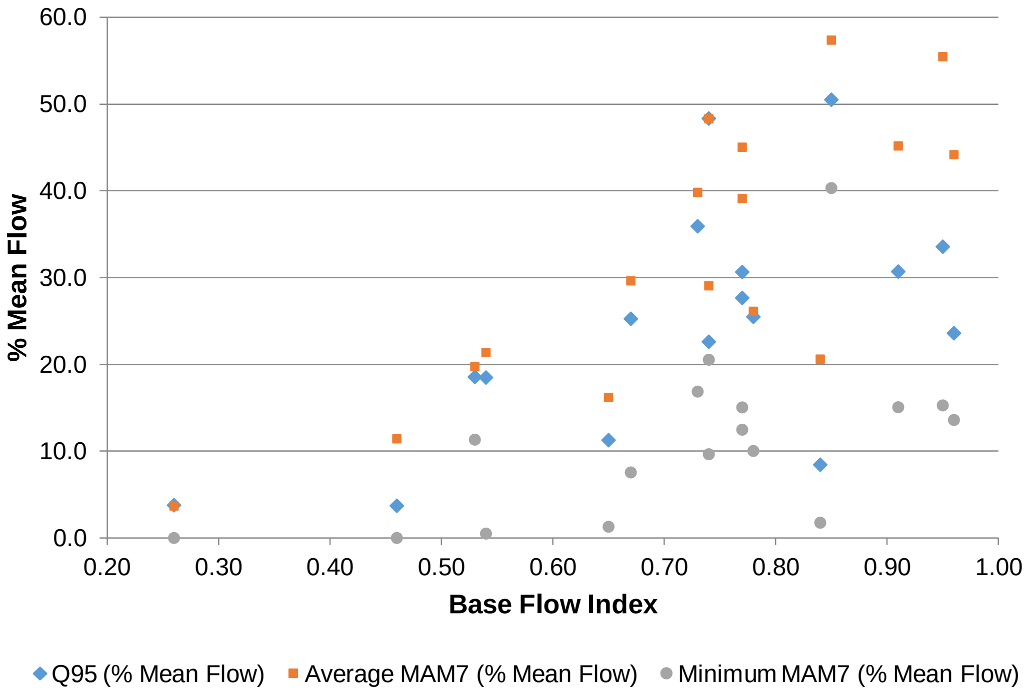


Figure 5.22 illustrates the plot of BFI a measure of catchment storage, and three potential hydrological indicators of ecological drought; (1) the long-term annual Q_{95}, (2) average MAM7 and (3) minimum MAM7 all standardised by the long-term mean flow, demonstrates the influence of catchment storage. The vertical axis highlights the degree of artificial influence. Values of the first hydrological indicator, Q_{95} as a percentage of the long-term mean flow, varied from between 3.7 per cent (River Granta) and 50.5 per cent (River Hiz). Generally, study sites with high values of Q_{95} as a percentage of mean flow have higher BFI values, suggesting that the catchment response is predominantly due to baseflow and is, therefore, dominated by groundwater.

Study sites with lower values of Q_{95} as a percentage of mean flow generally have lower BFI values, indicating that the catchments have flashy flow regimes with the low-flow response mainly due to surface water runoff, an exception to this is the River Stringside (BFI: 0.84; Q_{95} (% Mean Flow): 8.4).

When the second hydrological indicator, the average MAM7 as a percentage of the long-term mean flow is considered, study sites with higher BFI values (i.e. sites with groundwater-dominated flow regimes) generally have higher values of average MAM7 as a percentage of long-term mean flow. When the final, most severe hydrological indicator, the minimum MAM7 as a percentage of the long-term mean flow is considered, a much lower variability in low-flow response across the 17 study sites is evident.

5.16 VARIABILITY OF LOW-FLOW RESPONSES BETWEEN GREAT OUSE SUB-CATCHMENT TYPES: TIMING OF LOW FLOWS

In order to quantify the temporal variability of selected low-flow indicators across the Great Ouse catchment, the concept of Julian dates was again employed in this Chapter. Julian dates represent calendar dates with integer values, which starts with 1 on January 1st and end with 366 on December 31st.

Annual Julian dates (timings) of a number of potential descriptors of ecological drought were identified using the 1981 to 2010 inclusive, daily mean flow records available for the 17 study sites; the annual minimum flow, MAM7 flow, MAM10 flow, MAM30 flow and MAM50 flow.

The average annual timing of each potential descriptor of ecological drought at each study site was calculated, these values were used to perform Spearman Rank cross correlations. The results of these correlations are summarised (Table 5.14).

The results in Table 5.14 indicate that there is a high degree of correspondence between these potential indicators of ecological drought, with all correlations significant at the 0.01 level. The slightly lower degree of correspondence between the average of the annual minimum flow series and the average of the annual MAM30 and MAM50 flow series is thought to be a result of these slightly longer duration indicators; for example the MAM30 essentially represents the driest month in each year, not being directly comparable with the most severe potential indicators of ecological drought, the annual minimum flow and the average of the MAM7 flow series.

Table 5.14: Spearman Rank correlation coefficients – timings of selected potential hydrological indicators of ecological drought (River Great Ouse catchment; 17 study sites)

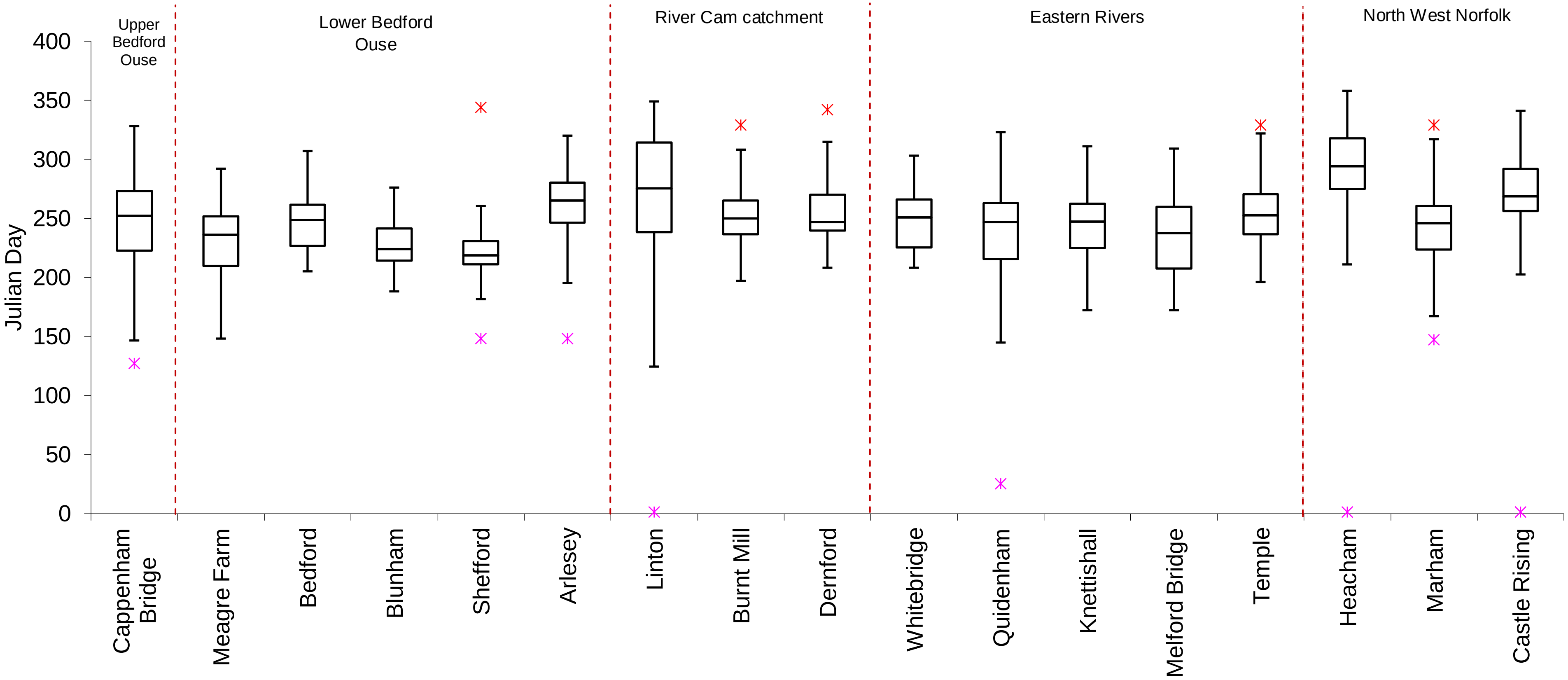
	Julian Date of Average Annual Min	Julian Date of Average MAM7	Julian Date of Average MAM10	Julian Date of Average MAM30	Julian Date of Average MAM50
Julian Date of Average Annual Min	-	0.966	0.969	0.897	0.808
Julian Date of Average MAM7	0.966	-	0.975	0.941	0.863
Julian Date of Average MAM10	0.969	0.975	-	0.938	0.845
Julian Date of Average MAM30	0.897	0.941	0.938	-	0.911
Julian Date of Average MAM50	0.808	0.863	0.845	0.911	-

(All correlations are significant at the 0.01 level (2-tailed))

The annual MAM7 flow was selected to explore the variability in the timing of low flows across the study sites in more detail. There are a number of reasons for this including (1) longer duration MAMs for example the MAM30 and MAM50 are likely to include (perhaps an extended) period of flow recovery, (2) a seven day period was identified by Hindley (1973) as being sufficiently long enough in duration to not be biased by one or two days interference, this was considered important due to the degree of modification to flows within the Great Ouse catchment, (3) the annual MAM7 flow was considered to be more effective at identifying the timing of drought and low-flow periods than the less severe MAM10, MAM30 and MAM50 indicators, and (4) the annual MAM7 flow was used to explore the temporal variability of low flows across the Trent catchment.

Figure 5.23 on the next page illustrates the variability in timings of the annual MAM7 flows across the Great Ouse catchment.

Figure 5.23: Box and whisker plots illustrating the variability in timings of annual 7-day minimum (MAM7) flows across the Great Ouse catchment. Box plots illustrate the range of Julian Days of minimum MAM7 flows for each study site. Sites are sorted into the sub-catchments defined by the Environment Agency (2010a), sites within each sub-catchment are ranked by Q95 (%MF). The boxes enclose the interquartile (IQR) range; the horizontal line within each box indicates the median. The ends of the whiskers are set at 1.5*IQR above the 3rd quartile and 1.5*IQR below the 1st quartile. If the minimum or maximum values are outside this range they are shown as outliers, only the minimum and maximum outliers are shown.



Study sites are sorted into the sub-catchments proposed by the Environment Agency (2010a); sites within each sub-catchment are ranked by the ratio of a low-flow index, long-term annual Q_{95} to the long-term average daily flow (lowest to highest). From the box and whisker plots it is immediately apparent that the largest variability in timings of annual MAM7 flows during the study period was experienced within the River Granta, and the lowest variability within the River Flit.

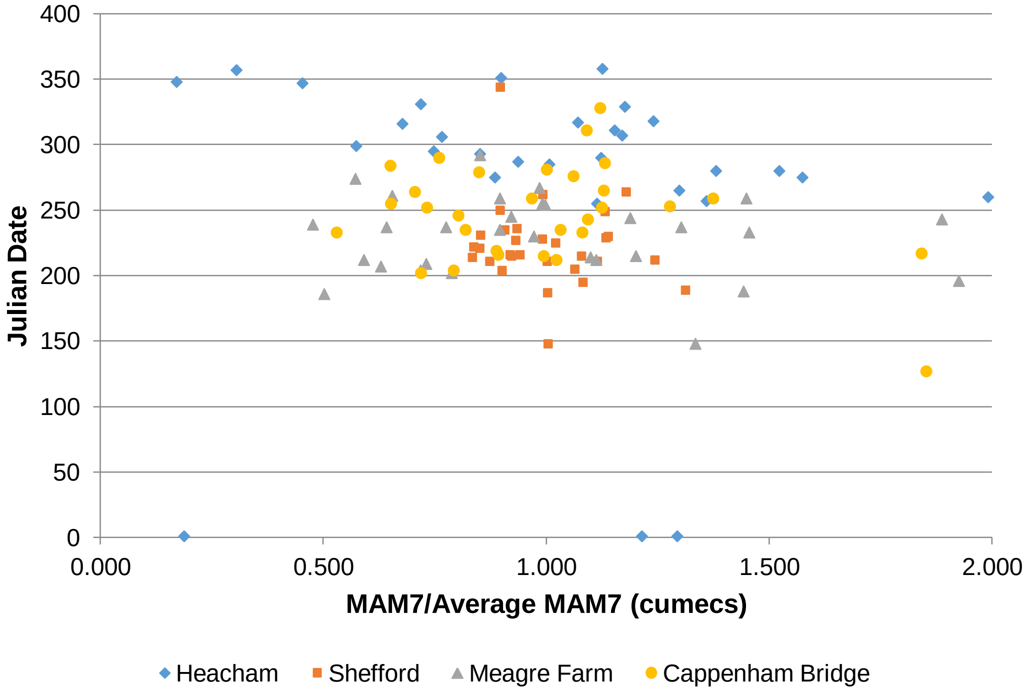
The largest variability in timings, as defined using the interquartile range (IQR); a measure of the spread of statistical dispersion, occurred in the timings of annual MAM7 flows recorded within the Lower Bedford Ouse sub-catchment (average IQR of 31.1) and the lowest variability in timings in the Upper Bedford Ouse sub-catchment (average IQR of 50.8). Study sites located within the River Cam and Eastern Rivers sub-catchments recorded very similar variability in annual MAM7 timings with average IQR values of 42.2 and 42.3 respectively.

In order to investigate the variability in low-flow responses between sub-catchment types in more detail, the timings of the annual MAM7 flows recorded in eight watercourses with contrasting flow regimes and characteristics was explored. Figure 5.24 illustrates the annual MAM7 flow as a function of the 30-year average MAM7 flow, and the timing (Julian date) of the MAM7 flow in each year of the 30-year 1981 to 2010 inclusive study period.

In Figure 5.24, the annual MAM7 flow timings for four smaller study sites, the River Heacham at Heacham (catchment area 59 km^2), the River Flit at Shefford (catchment area 119.6 km^2), the River Kym at Meagre Farm (catchment area 137.5 km^2), and the River Tove at Cappenham Bridge (catchment area 138.1 km^2) are illustrated.

When the first two study sites are compared, the groundwater-dominated River Heacham experienced later MAM7 low flows between mid-September and extending through November and December, than the surface-runoff dominated River Flit, where annual MAM7 flows generally occurred earlier in each year. The average Julian Day timings of annual MAM7 flows was 273 (29th September) River Heacham and 223 (9th August) River Flit.

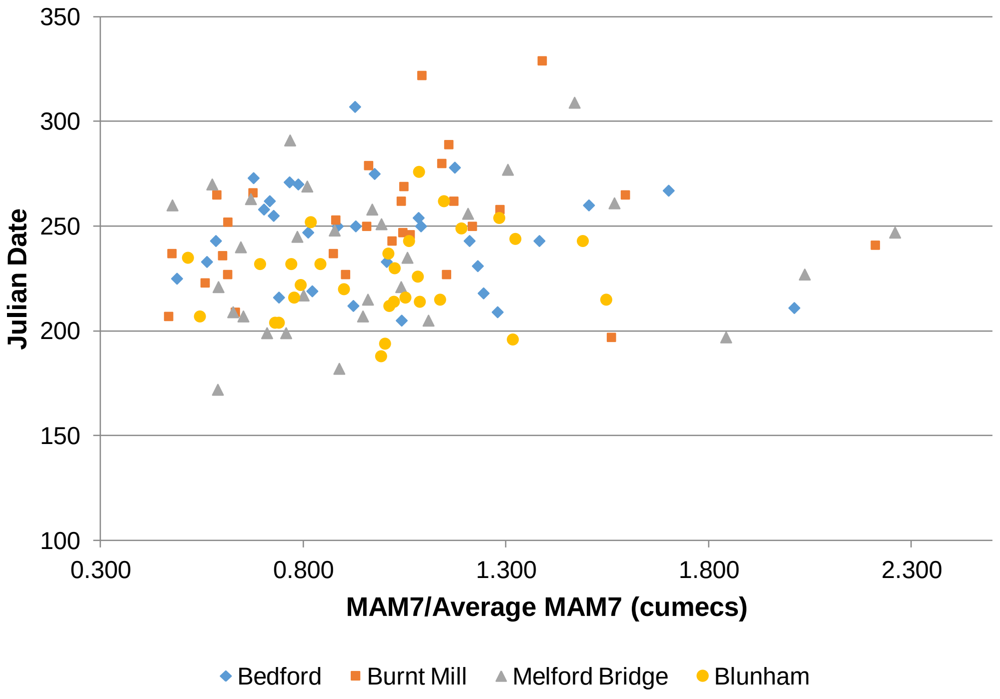
Figure 5.24: Variation in annual 7-day minimum (MAM7) timings: four smaller catchments that are either groundwater or surface-runoff dominated



From Figure 5.24, the narrow range of low-flow values relative to the average flow throughout the 30-year study period on the River Flit is notable; this is thought to be a reflection of the augmentation of low flows by discharges from Luton STW. Figure 5.24 also illustrates annual MAM7 low-flow timings for the surface-runoff dominated River Kym, a watercourse which is described as having a flashy flow regime by Anglian standards, and the River Tove, another surface-runoff dominated watercourse which generally experiences a small range of annual MAM7 low-flow timings.

Figure 5.25 again illustrates the annual MAM7 low-flow as a function of the average MAM7 flow and the timing (Julian date) of the MAM7 flow in each year. In Figure 5.25 data from four larger study sites; the Bedford Ouse at Bedford (catchment area 1460 km^2), the River Rhee at Burnt Mill (catchment area 303 km^2), the River Thet at Melford Bridge (catchment area 316 km^2), and the River Ivel at Blunham (catchment area 541 km^2) are illustrated.

Figure 5.25: Variation in annual 7-day minimum (MAM7) timings: four larger catchments that are import-dominated



Flows within all of the watercourses illustrated within Figure 5.25 are known to be augmented by either effluent discharges or artificially maintained by groundwater sources during low flows. The majority of station years plot between July and August, with the earlier timing of annual MAM7 flows a reflection of the artificial augmentation of flows. The Bedford Ouse and the River Ivel experienced the lowest variability in annual MAM7 timings across the 17 study sites explored in this Chapter, again thought to be a reflection of the augmentation of low flows by effluent discharges and the resulting reduction in flow variability.

5.17 THE DIMENSIONS OF ECOLOGICAL DROUGHT ACROSS THE GREAT OUSE CATCHMENT

Before any attempt is made to establish flow rules to manage abstractions, it is important to understand the dynamics of ecological drought. Both the onset and end of droughts are, however, difficult to determine, the impacts of a drought event may increase slowly, often accumulating over a considerable period of time, and lingering for years after termination (Mishra and Singh, 2010).

Dracup *et al*. (1980a; 1980b) identified five main components of a drought event; (1) drought initiation time, the start of the water shortage period, (2) drought termination time, the time when the water shortage becomes sufficiently small so that drought conditions no longer persist, (3) drought duration, the period of time a drought parameter is continuously below the critical level, (4) drought severity which indicates a cumulative deficiency of a drought parameter below the critical level, and (5) drought intensity; the average value of a drought parameter below the critical level.

Here the aim is to demonstrate the nature of drought response diversity across the Great Ouse catchment. Investigations focus on drought duration (days) and frequency of occurrence, rather than on the magnitude of individual drought events, as from an ecological perspective these parameters are considered more significant. From an ecological perspective, one measure of drought impact is the rate of recovery. Drought impacts will be most severe when coincident with the spring (April to June inclusive) and autumn (October and November) critical ecological periods, as a result, the date of drought end is considered to be more significant than the start date of the drought period.

5.17.1 Drought duration

5.17.1.1 Most extreme drought events in the 30-year study period

Detailed information on the most severe drought events experienced is provided in Appendix 5.1. The most severe drought events were identified using the absolute minimum flow recorded in each of the 30-year daily mean flow records. Three flow thresholds; (1) 20% ADF, (2) the annual Q_{95} flow, and (3) the average MAM7 flow were used to identify the start date, end date and duration of each drought event. The start date represents the earliest date that daily mean flows fell below each flow threshold, and the end date the earliest date that daily mean flows crossed back above each flow threshold. Each drought event is the number of days that flows were consecutively lower than each flow threshold, i.e. the duration between the start and end date.

From Appendix 5.1, the large variability in the timings of the lowest flow on record is evident, with the lowest flow in the 30-year study period recorded in nine different years. The month that the minimum flow was recorded in was, however, more consistent, with the majority of minimum flows occurring in August and September. Two sites, the Rivers Kym and Rhee experienced earlier minimum flows in June 1986 and July 2006, respectively. Three sites, the Rivers Tove, Wittle and Heacham experienced later minimum flows in October 1990, November 1990 and December 1991, respectively.

In addition, it is evident that the flow threshold used to identify droughts clearly influences the timings and duration of each drought event. When a flow threshold of 20% ADF was used to identify the most extreme drought experienced within the River Heacham, flows remained continuously below the flow threshold for 102 days. However, when the annual Q_{95} and average MAM7 flow thresholds were used, drought conditions persisted for a duration of 199 days and 549 days respectively. Drought duration and, therefore, drought severity varies considerably depending on the flow threshold used, due to the variability in low-flow response across the catchment. This is also a reflection of the spatial and temporal variability in the artificial influences located across the Great Ouse catchment. A number of study sites have low flows that are augmented by either effluent discharges or artificially maintained by groundwater sources during drought events.

Initial assessments demonstrated the variability in low-flow response and in the dimensions of the most extreme drought events experienced across the Great Ouse catchment, and also in the need to manage low flows at the individual, sub-catchment scale. From an ecological perspective, drought impacts will be most severe when coincident with the spring (April to June inclusive) and autumn (October and November) critical ecological periods. The most extreme droughts coincided with at least one critical ecological period, with the most severe droughts persisting throughout both the autumn and following spring, critical ecological periods. Few of the most severe drought events, however, persisted for more than 100 days; therefore, due to the resilience of riverine ecosystems, it is unlikely that even these extreme events would have had a significant impact from an ecological perspective.

5.17.1.2 Drought events during an individual year of below average annual rainfall

In order to investigate the degree of variability in the dynamics of drought events during a period of below average rainfall, the assessments described in the previous section were repeated using daily mean flows recorded during 1990. Information on the timings and duration of drought events and low-flow periods during 1990 is provided in Appendix 5.2 1990 was identified as representing the third driest year in the study period, receiving 77.3 per cent of the 1981-2010 long-term average rainfall. Although both 1996 (74.0 per cent long-term average rainfall) and 1991 (76.7 per cent long-term average rainfall) were drier, periods of missing flow data identified during 1991 and

1996 would have made accurately determining the timings and the duration of drought events virtually impossible.

From Appendix 5.2, the variability in the month that minimum flows occurred in during 1990 is immediately evident. During 1990, more than half of the study sites experienced minimum flows in either August or September. Three sites, the Rivers Kym, Rhee and Thet experienced minimum flows in July. Conversely, three sites, the Rivers Granta, Tove and Wittle experienced minimum flows in October and November, i.e. during the autumn critical ecological period. Two sites, the Rivers Heacham and Cam experienced minimum flows in December.

In addition, it is again evident that the flow threshold used to identify droughts in 1990 influences both the timings and the duration of each drought event. For example, when a flow threshold of 20% ADF is used to identify the duration of the drought experienced during 1990 within the River Kym, flows remained continuously below the flow threshold for 230 days. However, when the annual Q_{95} and average MAM7 flow thresholds are used to determine the duration of the same drought event, drought conditions only persisted for a duration of 18 and 14 days, respectively.

Results in Appendix 5.2 demonstrate an apparent limitation in using the absolute minimum flow to identify the most extreme drought events. For example, when results for the River Stringside are explored in more detail, it is evident that irrespective of the flow threshold employed to define the drought period, the duration of the drought in 1990 was longer than the drought in 1995, the year which experienced the absolute minimum flow.

From the results for 1990, potential issues surrounding the variation in the sensitivity of the three flow thresholds and potential hydrological indicators of ecological drought are highlighted. When both 20% ADF and the annual Q_{95} flow are used to define drought events, only three study sites experienced droughts of equal to or in excess of 100 days duration. When the average MAM7 flow, however, is used to define drought events, seven of the sites experienced droughts in excess of 100 days duration. This illustrates that due to the diversity of drought response, low-flow management across the Great Ouse catchment should take place at a local, sub-catchment scale.

5.17.2 Frequency of occurrence

In order to understand the dynamics of ecological drought, it was also considered important to understand the frequency of occurrence of drought and low-flow events. Assessments also aimed to investigate the predictability of the spatial variability in droughts and low-flow events.

Table 5.15 summarises the number of years in the 30-year study period that daily mean flows fell below the three flow thresholds previously used to identify drought events; 20% ADF, the annual Q_{95} flow, and the average MAM7 flow for more than five consecutive days. Although a period of five or more consecutive days of low flows clearly doesn't constitute a drought event, the data in Table 5.15 provides an indication of the spatial diversity of low-flow/drought events across the catchment.

Table 5.15: Years with more than five consecutive days of flows equal to or below three low-flow thresholds (1981-2010) (River Great Ouse catchment; 17 study sites)

Study Site	Number of years below 20% ADF	Number of years below Q_{95}	Number of years below MAM7	Days below 20% ADF	Days below Q_{95}	Days below MAM7
Granta – Linton	26	6	16	3778	562	1563
Kym – Meagre Farm	30	16	15	5500	621	531
Stringside – Whitebridge	14	7	16	1411	548	1459
Wittle – Quidenham	17	10	15	1360	579	997
Tove – Cappenham Bridge	13	11	14	791	564	970
Bedford Ouse - Bedford	15	13	13	781	560	706
Rhee – Burnt Mill	7	9	14	299	552	1437
Heacham – Heacham	3	4	13	399	548	1972
Little Ouse – Knettishall	5	10	15	289	552	1022
Thet – Melford Bridge	8	15	17	207	551	597
Cam- Dernford	2	7	15	105	555	1915
Lark – Temple	2	5	15	85	546	1665
Nar – Marham	4	7	14	87	550	1496
Babingley – Castle Rising	1	5	13	30	553	1798
Ivel – Blunham	0	10	11	1	551	842
Flit – Shefford	0	13	14	0	548	548
Hiz - Arlesey	0	7	14	0	559	1471

When 20% ADF was used to define low-flow and drought events, four sites; the Rivers Granta, Kym, Wittle and the Bedford Ouse recorded more than five consecutive days of low flows in 15 or more years. Conversely, three sites; the Rivers Ivel, Flit and Hiz recorded no drought or low-flow events when a flow threshold of 20% ADF was used to define low-flow events.

When the annual Q_{95} flow was used to define low-flow and drought events, all of the Great Ouse study sites experienced low-flow periods of five or more consecutive day's duration in at least four years. When the final flow threshold, the average MAM7 flow was used to define low-flow and drought events, all sites recorded low flows lasting more than five consecutive days in 11 or more years.

The results summarised in Table 5.15 provide an initial indication of both the spatial and temporal diversity of low-flow events across the Great Ouse catchment. An additional assessment of the occurrence of more prolonged low-flow events, with a duration of at least 100 consecutive days (approximately 3 months) may provide a more meaningful indication of the variability in frequency of occurrence of low-flow and drought events across the catchment.

5.18 DISCUSSION

This chapter aimed to illustrate the potential ecological significance of low-flow variability across the contrasting heavily developed River Trent and the highly regulated, lowland Great Ouse catchments. Initial assessments aimed to explore the heterogeneity of flows across both catchments during historical periods of below average annual rainfall. Before considering how artificial influences may be directly contributing to the variability of low flows across both catchments, it was considered important to consider the range of natural factors which influence the low-flow regime of a watercourse. According to Smakhtin (2001), these natural factors include the distribution and infiltration characteristics of soils, the hydraulic characteristics and extent of aquifers, the rate, frequency and amount of recharge, evapotranspiration rates from the catchment, topography, climate and the distribution of vegetation types. It is clear, therefore, that even in the absence of any anthropogenic influences, low flows would be highly variable across the catchment.

The flow regimes of the majority of watercourses located within the Trent and Great Ouse catchment are not natural, and are modified by varying degrees by a range of anthropogenic impacts including surface and groundwater abstractions, inter-basin transfer schemes, for example the Trent-Witham-Ancholme scheme, and flow regulation downstream from impoundments. The augmentation of low flows within the River Tame and the River Trent downstream of the River Tame confluence by treated sewage effluent discharge and the subsequent creation of 'discharge-rich' conditions is, however, perhaps the most important artificial influence from the perspective of ecological drought within the heavily developed River Trent catchment. This augmentation of low flows has resulted in the elimination of natural periods of low flows during the summer, the homogenisation of flows (Naiman *et al*., 2008) and the creation of anti-drought (Bunn *et al*., 2006) conditions.

The Great Ouse catchment is located within one of the driest regions of the United Kingdom and has a long history of human intervention aiming to secure reliable water supplies. Although the influence of effluent discharges is not as significant within the Great Ouse catchment as it is within the Trent catchment, the augmentation of flows by river support schemes is considered to be potentially significant. According to the Environment Agency (2012), flows within the Rivers Hiz, Rhee, Cam, Snail, Little Ouse and Thet are augmented by river support schemes during periods of low flows and drought. Such schemes are likely to result in the elimination of natural low-flow periods, in the homogenisation of flows (Naiman *et al*., 2008) and in the creation of anti-droughts. From an ecological drought perspective, river support schemes are perhaps potentially more damaging than surface water abstractions which theoretically will not be operational during periods of extreme low flows and droughts due to abstraction controls.

We unfortunately currently have a poor understanding of the ecological ramifications of the ‘anti-drought’ flows (Bond *et al*., 2008) that tend to elevate low flows in discharge-rich watercourses such as the Rivers Tame and Trent. The loss of low flows and droughts, both of which are important components of the natural flow regime, combined with the creation of more stable hydraulic conditions (Bond *et al*., 2008) is, however, likely to have a negative impact on riverine biota.

This Chapter also aimed to identify a range of potential hydrological indicators of drought severity that may be used to derive *e-flows* across the Trent and Great Ouse catchments and other similar heavily developed and highly regulated, lowland catchments. As a result, the utility of a selection of potential descriptors of ecological drought were explored. These descriptors included the annual Q_{95} flow duration statistic currently employed across England, a range of percentages of the long-term ADF based on recommendations made by Baxter (1961; 1963), and finally, a range of persistent hydrological indicators, for example the minimum value of the 30-year series of annual 7-day minimum and 10-day minimum flows were explored.

5.19 CONCLUSIONS

This initial examination of low-flow and drought characteristics across the heavily developed Trent catchment and the highly regulated, lowland Great Ouse catchment has highlighted a wide variety of low-flow responses in terms of flow magnitude, timing and duration. Using a selection of potential hydrological indicators of ecological drought, this Chapter demonstrated that across both the Trent and the Great Ouse catchments, catchment-wide droughts are rare.

The most severe indicator; the minimum MAM20 flow, illustrated that severe drought rarely impacted on more than 10 out of the 31 Trent study sites, and on more than two of the 17 Great Ouse study sites in any one year. In addition, the timing of extreme low flows varies widely between the sub-catchments, with the severest ecological droughts occurring in October and even early November on groundwater-dominated watercourses.

Although the Trent and Great Ouse catchments have contrasting flow regimes, the results of the flow assessments are comparable and demonstrate that no single hydrological indicator of low flows and drought is suitable for all river types and that due to the wide variety of low-flow responses that smarter solutions may require *e-flow* determination at the local, sub-catchment scale. The next Chapter uses river flow data from both the Trent and the Great Ouse catchments to create a regional dataset to explore the application of hydrological approaches to setting *e-flows*.

CHAPTER 6: FROM ECOLOGICAL DROUGHT TO ENVIRONMENTAL FLOWS

6.1 INTRODUCTION

The previous Chapter analysed 20 and 30-year low-flow records from 31 and 17 gauging stations across two contrasting catchments, the heavily developed River Trent and the highly regulated, lowland Great Ouse respectively. These analyses highlighted a range of low-flow responses in terms of flow magnitude, timing and duration. In addition, assessments using a selection of potential indicators of ecological drought demonstrated that across both stream networks, catchment-wide droughts are rare. Furthermore, flow assessments determined that no single hydrological indicator of ecological drought was most suitable for all river types, and that due to the wide variety of low flows responses, smarter solutions may require *e-flow* determination at the local, sub-catchment scale.

This Chapter focuses on the application of hydrological approaches to setting *e-flows.* First, the utility of Baxter's (1961) principles for managing low flows and ecological drought at the regional scale, combining the Trent and Great Ouse catchments is explored. Secondly, flows recorded within a reduced set of watercourses with contrasting flow regimes are analysed to examine the practice of using the Q_{95} flow as the basis for managing abstractions and compensation flows below impoundments. Finally, the Chapter investigates Baxter's (1961) assertion that the adoption of a more complex approach saves water thus benefitting both riverine ecology and abstractors in a future of increasing hydrological uncertainty.

6.2 METHODS

The methodology follows the approach outlined in Section 2.3.5. Combining the two catchments to generate a regional dataset required a reassessment of the flow records to optimise the number of stations, and record length and integrity. Gauged flows from 38 gauging stations (21 located across the Trent and 17 across the Great Ouse catchment) for a 25-year period (1988-2012) were considered (Appendix 6.1). Information on flow data availability for each of the 38 gauging stations is provided in Appendix 6.2. Eleven of the 38 flow records were incomplete, with missing data ranging from between two days (River Rhee at Burnt Mill) to a maximum of 87 consecutive days (River Torne at Auckley).

The second objective involved a reduced number of 10 study sites with contrasting flow regimes that were selected to avoid issues relating to missing flow data during periods of low flows and the calculation of low-flow metrics (e.g. Marsh, 2002). The 10 study sites had 25-year daily mean flow records with no periods of missing data. Basic information on the 10 study sites is provided in Table 6.1, more detailed information is provided in Appendices 6.1 and 6.2.

Table 6.1: Study sites selected to explore more complex approaches to setting *e-flows* across the River Trent and River Great Ouse catchments (study sites ranked by Q_{95} per cent mean flow lowest to highest)

Watercourse	Station Name	Basin	Catchment Area (km^2)	BFI
River Kym	Meagre Farm	Great Ouse	137.5	0.26
River Manifold	Ilam	Trent	148.5	0.53
River Tove	Cappenham Bridge	Great Ouse	138.1	0.54
Bedford Ouse	Bedford	Great Ouse	1460.0	0.53
River Derwent	Yorkshire Bridge	Trent	126.0	0.47
River Dove	Izaak Walton	Trent	83.0	0.79
River Sow	Great Bridgford	Trent	163.0	0.65
River Trent	North Muskham	Trent	8231.0	0.65
River Hiz	Arlesey	Great Ouse	108.0	0.85
River Tame	Lea Marston Lakes	Trent	799.0	0.68

The third objective used selected hydrologic metrics to test Baxter's (1961) premise that smarter low-flow management results in more water available for the riverine environment. Additionally, whenever appropriate, each flow management approach aimed to meet two fundamental principles: (1) to mimic natural flow variations, and (2) to minimise the degree of hydrological alteration.

The ten study sites were classified as rivers with (a) natural/semi-natural flow regimes or (b) modified flow regimes. Long-term gauged Q_{95} and mean flow statistics were calculated using the 1988-2012 inclusive 25-year daily mean flow record for each study site. Naturalised Q_{95} and mean flow statistics were estimated using Low Flows Enterprise (information on the science behind the Low Flows software is provided in Young *et al*., 2000, Holmes *et al*., 2002, Young *et al*., 2003 and Holmes *et al*., 2005). Table 6.2 summarises selected flow duration statistics and provides an indication of the degree of flow modification at each study site.

The influence that the effluent discharge from Minworth WTW has had on the flow regime of the River Tame is demonstrated in Table 6.2. The naturalised Q_{95} of the River Tame was estimated as 1.199 m^3s^{-1} whereas the gauged Q_{95} was calculated as 7.453 m^3s^{-1} illustrating that low flows within the River Tame during the study period were more than six times higher than they would have been naturally. Similarly, the River Trent experiences Q_{95} low flows that are double the estimated naturalised low-flow. Although the majority of the study sites appear to experience slightly higher than naturalised Q_{95} and mean flows (indicated by a ratio of >1.0) the Rivers Kym and Sow experience slightly lower Q_{95} flows, and the Rivers Derwent and Sow lower mean flows than they would have done in the absence of artificial influences.

Table 6.2: Selected statistics relating to gauged and naturalised Q_{95} and mean flows

Watercourse	**Gauged Data**			**Naturalised Data**[1]			**Ratio 1**	**Ratio 2**
	Q_{95} (m^3s^{-1})	**Mean Flow (m^3s^{-1})**	**Q_{95} (% Mean Flow)**	**Q_{95} (m^3s^{-1})**	**Mean Flow (m^3s^{-1})**	**Q_{95} (% Mean Flow)**	**GQ_{95}: NQ_{95}**	**GMF: NMF**
River Kym	0.023	0.595	3.8	0.062	0.559	11.1	0.37	1.07
River Manifold	0.594	3.529	16.8	0.540	3.118	17.3	1.10	1.13
River Tove	0.185	1.066	17.4	0.164	0.905	18.1	1.13	1.18
Bedford Ouse	2.262	12.143	18.6	1.131	8.669	13.0	2.00	1.40
River Derwent	0.467	2.080	22.4	0.427	4.025	10.6	1.09	0.52
River Dove	0.521	1.903	27.4	0.497	1.785	27.8	1.05	1.07
River Sow	0.325	1.168	27.8	0.432	1.259	34.3	0.75	0.93
River Trent	27.339	87.148	31.4	13.520	79.570	17.0	2.02	1.10
River Hiz	0.328	0.667	49.1	0.243	0.528	46.0	1.35	1.26
River Tame	7.453	14.109	52.8	1.199	7.769	15.4	6.22	1.82

[1] Naturalised long-term Q_{95} and mean flow estimates were provided by the Environment Agency and were obtained from Low Flows Enterprise.

The ratios of GQ_{95}:NQ_{95} and G_{MEAN}:N_{MEAN} were used to classify the 10 study sites as rivers with either (a) natural/semi-natural flow regimes or (b) modified flow regimes. For a watercourse to be classified as having a natural/semi-natural flow regime, both ratios reported in Table 6.2 had to be lower than 1.20. In addition, information contained within the UK Hydrometric Register was used to classify the 10 study sites. Following this classification five watercourses; the Rivers Kym, Manifold, Tove, Dove and Sow were classified as having natural or semi-natural flow regimes. Assessments of the impact that the adoption of the alternative flow management scenarios had on flows initially focused on these study sites.

6.3 RESULTS (1): FLOW MANAGEMENT AT THE REGIONAL SCALE

Previous Chapters explored the information gained from employing 26 hydrologic metrics as indicators of ecological drought (Appendix 6.3). Following consideration of statistical redundancy, these were classified into the key components of the flow regime as recommended by Richter *et al*. (1996) and Poff *et al*. (1997). Using the consolidated database of 38 stations with 25-year flow series across the combined Trent-Ouse catchments, 37 hydrologic metrics were input to a PCA (Appendix 6.4). Again, two dominant clusters defined flow variability and flow magnitude. The former included 20% ADF and the second included the Q_{95}, MAM7 and the 3- and 5-year MAM10.

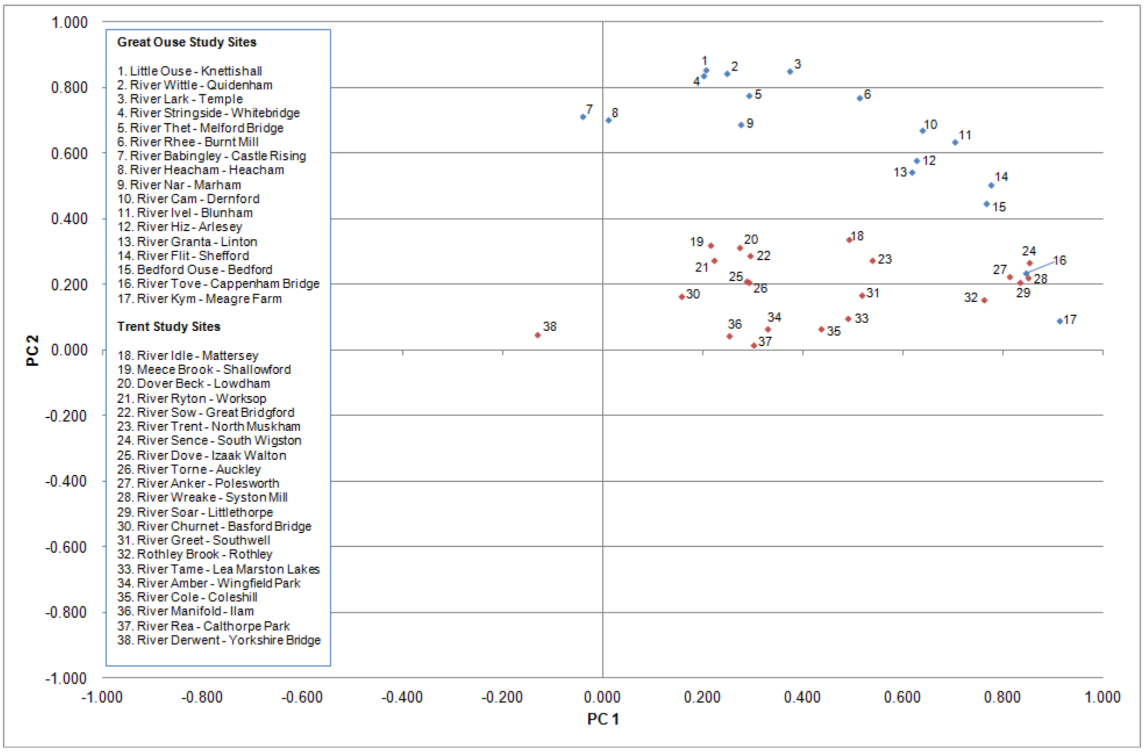
In order to explore the development of more complex flow rules, this study focused on the annual Q_{95}, 20% ADF, 5-year MAM10 and 3-year MAM10, and the total number of days that daily mean flows were equal to or lower than each metric. The MAM10 provides a strong discriminator of ecological drought and was selected to explore the variability in timing of low flows from a management perspective because (1) longer duration MAMs are likely to include (perhaps an extended) period of flow recovery; (2) a 10 day period avoids issues surrounding the 7-day week and the varying temporal impact of artificial influences; important within the heavily developed Trent and Great Ouse catchments; (3) the MAM10 was identified as being effective at discriminating between wet and dry years and between the contrasting sub-catchments, and (4) it is less likely to be affected by weekly operational flow patterns than the MAM7.

6.3.1 The heterogeneity of flows across the Trent and Great Ouse catchments during periods of below average rainfall

The results of PCAs that utilised standardised and raw (non-standardised) daily mean flow data were identical indicating that flow magnitude rather than catchment area or the varying temporal and spatial impact of artificial influences controlled the output of each PCA. The first four principal components (PC1, PC2, PC3 and PC4) explained 27.4, 22.4, 18.7 and 10.7 per cent respectively of the total variance in the flow regimes of the 38 study sites. The first two principal components, therefore, explained 49.8 per cent of the variance in the flows recorded during the two driest years in the 25-year study period. In Figure 6.1 each study site is plotted as a function of its rotated loadings for the first two principal components. Red markers delineate study sites located within the Trent catchment and blue markers study sites located within the Great Ouse catchment.

The PCA plot demonstrates the variability across the study catchments in flow magnitude during two years experiencing below average annual rainfall. The distance between two study sites located in the Great Ouse catchment; the River Babingley (7) and the River Kym (17) suggests that these sub-catchments have contrasting flow regimes. Interestingly, the River Babingley (7) plots in a different quadrant to the remainder of the Great Ouse study sites. Similarly the River Derwent (38) plots in a different quadrant to the main cluster of Trent study sites, an indication that the flow regime of the Derwent differs from the rest of the Trent study sites. During both 1996 and 2011, releases from Ladybower Reservoir significantly increased flows within the River Derwent, with peak daily mean flows of 13.930, 16.600 and 38.800 m^3s^{-1} recorded in December 1996, December 2011 and February 2011, respectively. In addition, the River Tove (16) plots within a cluster of Trent study sites comprised of the Rivers Sence (24), Anker (27) Wreake (28) and Soar (29). This suggests that the River Tove has a similar flow regime during periods of lower than average rainfall to four study sites located in the Trent catchment. The River Tove has a BFI of 0.54; this is comparable to the Rivers Sence, Anker, Wreake and Soar. In addition, flows within all five study sites are substantially augmented by effluent discharges.

Figure 6.1: Rotated plot of loadings of the first two principal components of daily mean flows recorded between January and December inclusive during 2011 and 1996 the 2 driest years in the 25-year study period (38 study sites; River Trent and Great Ouse catchments)

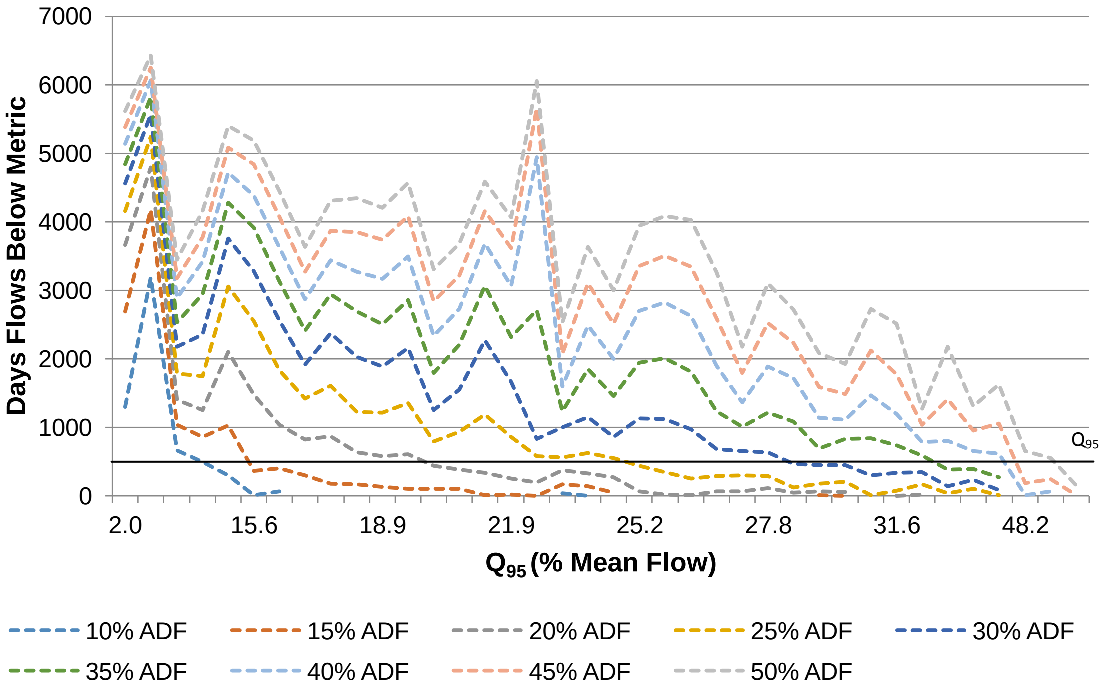


This initial assessment of flows recorded within 38 study sites located across the Trent and Great Ouse catchments supports a key finding made in Chapter 5. The PCA plot demonstrated that during periods of below average rainfall, flow magnitude varied across the 38 study sites. In addition, the flow regimes of the study sites located within the heavily developed River Trent generally differed from the study sites located within the highly regulated, lowland Great Ouse. This initial assessment of flow magnitude has demonstrated that due to the heterogeneity of flows across both catchments during periods of below average rainfall, flow management at a regional scale may not be appropriate. Using the same regional dataset, the next section focuses on the use of proportions of the long-term ADF as the basis of flow assessments.

6.3.2 Using proportions of the long-term average daily flow as the basis of flow assessments

One of the aims of this Chapter was to explore the utility of Baxter's (1961; 1963) approach to managing low flows across the contrasting study catchments. Baxter advocated the use of the ADF as the basis of flow assessments. Unfortunately the limited availability of flow data in the 1960s combined with concerns surrounding the accuracy of low flows prevented the implementation of his proposals. Figure 6.2 illustrates the diversity of low-flow magnitude across the 38 study sites. Daily mean flows would be expected to fall below the annual Q_{95} (the current *e-flow* approach) on approximately 456 days in total during the 25-year study period.

Figure 6.2: Spatial diversity of low flows: total number of days that flows were equal to or lower than 10, 15, 20, 25, 30, 35, 40, 45 and 50% ADF (38 study sites; River Trent and Great Ouse catchments)



20% ADF was suggested by Baxter (1961; 1963) to provide an index of ecological degradation, an assertion later supported by Tennant (1976) for USA rivers. Figure 6.2 demonstrates that flows in a number of study sites have fallen below this metric on a regular basis. Conversely, at six study sites, flows never fell below 20% ADF. Eight study sites experienced flows lower than an even more extreme metric; 10% ADF, with the River Kym experiencing more than 3000 days of exceptionally low flows. When less extreme metrics were explored; 40%, 45% and 50% ADF, the potential unsuitability of these metrics for allocating flows and protecting low flows is clear. For example, flows within the River Kym were equal to or lower than 40% ADF on more than 6000 days. Conversely, three study sites; the Rivers Flit, Hiz and Tame experienced less than 100 days of flows equal to or lower than 40% ADF.

In order to further explore the utility of Baxter's approach to determining *e-flows*, the number of study sites experiencing flows equal to or lower than each hydrologic metric was determined (Table 6.3).

Table 6.3: Days flows were equal to or lower than selected hydrologic metrics in the 25-year study period (38 study sites River Trent and Great Ouse catchments)

		Flow Metric								
		10% ADF	**15% ADF**	**20% ADF**	**25% ADF**	**30% ADF**	**35% ADF**	**40% ADF**	**45% ADF**	**50% ADF**
Number of study sites with flows below-flow threshold	**0-499 days**	35	33	26	18	12	6	3	3	1
	500-999 days	1	1	5	7	7	5	4	1	2
	1000-1499 days	1	2	4	5	4	6	5	4	2
	1500-1999 days				4	4	4	4	3	2
	2000-2499 days			1		6	4	3	3	3
	2500-2999 days		1		1	1	7	6	4	5
	3000-3499 days	1			1	1	2	6	6	4
	3500-3999 days			1		1	1	2	6	4
	4000-4499 days		1		1		1	1	3	8
	4500-4999 days			1		1	1	2	1	2
	5000-5499 days				1			1	2	2
	5500-5999 days					1	1		1	1
	6000 + days							1	1	2

This additional assessment has been included to further illustrate some of the issues surrounding the use of proportions of the long-term ADF as the basis of flow assessments. Table 6.3 indicates that flows were equal to or lower than 20% ADF on more than 500 days at 12 study sites, with one site recording more than 4500 days of extreme low flows. The majority of study sites, however, recorded less than 500 days of extreme low flows. The relative rarity of severe low-flow events when the average daily flow is used as the basis of flow assessments is thought to be due to a combination of flow augmentation by effluent discharge in some areas of the Trent catchment, and by low-flow support schemes in parts of the Great Ouse catchment. Conversely, when the occurrence of flows below 50% ADF is explored, only one study site experienced less than 500 days of flows equal to or lower than the least severe hydrologic metric.

These initial assessments illustrated the issues surrounding the implementation of Baxter's approach across the two contrasting catchments. Hydrologic metrics calculated from average daily flows in both discharge-rich rivers and in rivers with artificially augmented low flows are unsuitable as measures of low-flow impact. Although the results from these initial assessments are important from a flow management perspective, they do not provide an indication of the inter-annual variability of low flows experienced across the 38 study sites during the 25-year study period.

Chapter 5 considered the inter-annual variability of the occurrence of flows below a range of potential indicators of ecological drought. These assessments illustrated the spatial diversity and inter-annual variability of low flows, but it was important to use a statistical test to explore the inter-annual variability of a range of hydrologic metrics. In addition, it was considered essential that the hydrologic metrics could not only discriminate between wet and dry years, but also between the contrasting sub-catchments identified by the PCA.

6.3.3 Application of standard hydrological metrics across large catchments

A second tenet of Baxter's (1961; 1963) approach was to use standardised hydrological metrics at least at the regional scale. Spearman's Rank correlations were calculated using outputs from the assessments of the inter-annual variability in the occurrence of flows equal to or below selected hydrologic metrics. Four hydrologic metrics; the annual Q_{95}, the average MAM10, 20% ADF and 30% ADF were investigated. In addition, statistical analyses aimed to determine the degree of hydrological dependency across the River Trent and River Great Ouse study sites and also the similarity in hydrological behaviour year on year (Appendices 6.5 and 6.6). Hydrological dependence between study sites was considered to be statistically significant when the Spearman's Rank correlation coefficient was > 0.700.

The diversity of low-flow response between the study sites is immediately evident. When the annual Q_{95} was used to define low flows, the degree of correspondence ranges from no other study sites (Rivers Sence, Amber and Rea) to 15 other sites (River Anker). Similarly, when the average MAM10 is used to define low-flow periods, the degree of correspondence between the 38 study sites ranges from between no study sites (River Amber) and 25 sites (River Anker). The degree of correspondence between the study sites appears to be weaker when low-flow periods are defined using the 20% ADF and 30% ADF.

Correlation matrices for 20% ADF and 30% ADF (Appendix 6.6) were included in order to explore the potential utility of Baxter's approach. From Appendix 6.6 the importance of selecting appropriate hydrologic metrics to define low-flow periods is evident. When low flows are defined using 20% ADF, the degree of hydrological dependence between the 38 study sites is lower than when the other hydrologic metrics are used to define low-flow periods. The degree of correspondence between the study sites ranges from between no sites (eight study sites) and 11 sites (River Tove). This apparent low degree of hydrological dependence, which is not demonstrated when the other hydrologic metrics are used to define low-flow periods, is thought to be a direct reflection of the rare occurrence of flows of such a low magnitude across the region. This is supported when the less extreme hydrologic metric, 30% ADF is considered. Finally, when 30% ADF is used to define low-flow periods the degree of hydrological dependency ranges from between no sites (Rivers Derwent, Amber, Rea, Nar and Dover Beck) and 17 sites (River Stringside).

One of the aims of this Chapter is to identify hydrologic metrics to derive *e-flow* management approaches for application across the River Trent and River Great Ouse catchments. The results illustrated in Appendices 6.5 and 6.6 suggest that the degree of hydrological dependence across the study sites is greatest when the inter-annual variability of low flows is defined using the average MAM10. Although no hydrologic metric effectively discriminates between dry and wet periods across all of the study sites, the average MAM10 appears to be the most effective metric at discriminating between wet and dry years and between the contrasting sub-catchments. Assessments of hydrological dependency demonstrated the inter-annual variability in hydrological behaviour across the 38 study sites, the variability of “in year” timings of low flows are, however, not illustrated.

6.3.4 Variability in annual MAM10 flows across the 38 study sites

Figure 6.3 illustrates the variability in timings of annual MAM10 flows as a percentage of the long-term mean flow across the 38 study sites. In Figure 6.3 the study sites are ranked according to BFI, from low BFI values (surface-runoff dominated flow regimes) to high BFI values (groundwater-dominated flow regimes). The variability in annual MAM10 flows is generally less pronounced in study sites with surface-runoff flow regimes than in sites with groundwater dominated flow regimes. The River Kym (BFI 0.26) displays the lowest variability (2.2 to 7.5 per cent) and the River Heacham the highest variability (8.1 to 92.4 per cent) in MAM10 flows as a percentage of the long-term average daily flow. The reason for the higher variability in annual MAM10 flows in the majority of study sites with groundwater-dominated flow regimes is not fully understood.

Some of the study sites appear to be outliers, for example the River Granta (BFI 0.45) displays a greater degree of variability in MAM10 flows compared to the rest of the surface runoff dominated sites. This is thought to be largely due to the occurrence of prolonged periods of zero flows within the Granta resulting in low MAM10 values. The River Wittle (BFI 0.65) is thought to display a large degree of variability in annual MAM10 flows for a similar reason. Conversely, the River Tame (BFI 0.68) and the River Flit (BFI 0.73) experienced a lower level of variability in annual MAM10 flows compared to study sites with comparable BFIs. This is thought to be due to the augmentation of flows by effluent discharges. Flow augmentation can result in the loss of natural low-flow periods, a reduction in flow variability and the creation of anti-drought conditions. Finally, from Figure 6.3 the River Stringside also appears to be an outlier, with annual MAM10 flows representing a lower proportion of the long-term average daily flow than study sites with comparable BFIs.

6.3.5 Variability in the timings of annual MAM10 flows during the 25-year study period

Figure 6.4 illustrates the variability in the timings of annual MAM10 flows during the 25-year study period. The box plots show the range of Julian dates of annual MAM10 flows recorded across the 38 study sites in each year. The PCA and additional flow assessments demonstrated the variability in low-flow magnitude and timings across the 38 study sites. Sub-catchments with contrasting low-flow regimes are, therefore, expected to experience low flows during different months, with surface-runoff dominated sites experiencing earlier low flows than groundwater-dominated sites. However, the narrow range in the timings of annual MAM10 flows across the majority of the 38 study sites during 1991, 1993, 1995, 1998, 2008 and 2009 is striking. Possible reasons for the limited variability in MAM10 timings in these six years are explored using the relevant UK Hydrological Reviews produced by the Centre for Ecology and Hydrology.

The period between the spring of 1990 and the summer of 1992 was identified by Marsh *et al*. (1997) as representing one of the major droughts experienced in England. Although there was a significant improvement in drought conditions across eastern, central and southern England during the first half of 1991, dry conditions prevailed from August onwards, and the drought re-intensified into the winter of 1991/92. Similarly, the limited variability in the timings of annual MAM10 flows recorded in 1995 is also a direct consequence of severe drought conditions. The main hydrological feature of 1995 was a transformation from an exceptionally wet winter, to severe and widespread drought conditions by the late summer.

Figure 6.4 also illustrates the notable lack in variability in the timings of MAM10 flows experienced across the Trent and Great Ouse study sites in 1993. The River Manifold, however, experienced MAM10 flows at the beginning of April, the reason for this anomaly is not clear. In 1993, a wet April heralded a very protracted wet phrase which extended into 1994; the autumn of 1993 was especially wet. Similarly, 1998, 2008 and 2009 were notably wet years experiencing higher than average rainfall totals. The lack of variability in the timings of MAM10 flows during years experiencing higher than average rainfall totals and flooding reflects the homogenisation of flow conditions experienced during high flows.

Finally, the dramatic shift from drought to flood conditions in 2012 (Kendon *et al*., 2013; Parry *et al*., 2013) is illustrated in Figure 6.4. Although dramatic terminations of prolonged periods of drought have occurred before, for example the 1975-76 drought was abruptly terminated during September and October 1976, a distinguishing characteristic of the 2010-2012 drought was its termination during the April to July period (Parry *et al*., 2013). Drought conditions had been declared across large areas of central and eastern England in early July 2011, and by March 2012 the area was extended to cover most of central, southern and south-east England. However, in April 2012 the majority of England and Wales received more than twice the monthly average rainfall; indeed it was the wettest April in the United Kingdom in a series commencing in 1910 (Parry *et al*., 2013). Although rainfall totals were unremarkable in May, June saw a return to exceptionally wet weather with the majority of the United Kingdom receiving well over twice the monthly average rainfall (Parry *et al*., 2013). The record rainfall brought the 2010-2012 drought to an abrupt end.

These initial assessments demonstrated the potential unsuitability of Baxter’s approach in watercourses with discharge-rich flow regimes, for example the River Tame, and also in watercourses with low-flow support schemes, for example the River Hiz. The average MAM10 hydrologic metric was identified as potentially the most useful in explaining the patterns of flow variability present across the 38 study sites located across the region.

Figure 6.3: Box and whisker plot illustrating the variability in annual 10-day minimum (MAM10) flows (% mean flow) experienced during the 25-year study period. Sites are ranked by BFI lowest to highest. The boxes enclose the interquartile (IQR) range; the horizontal line within each box indicates the median. The ends of the whiskers are set at 1.5*IQR above the 3rd quartile and 1.5*IQR below the 1st quartile. If the minimum or maximum values are outside this range they are shown as outliers, only the minimum and maximum outliers are shown.

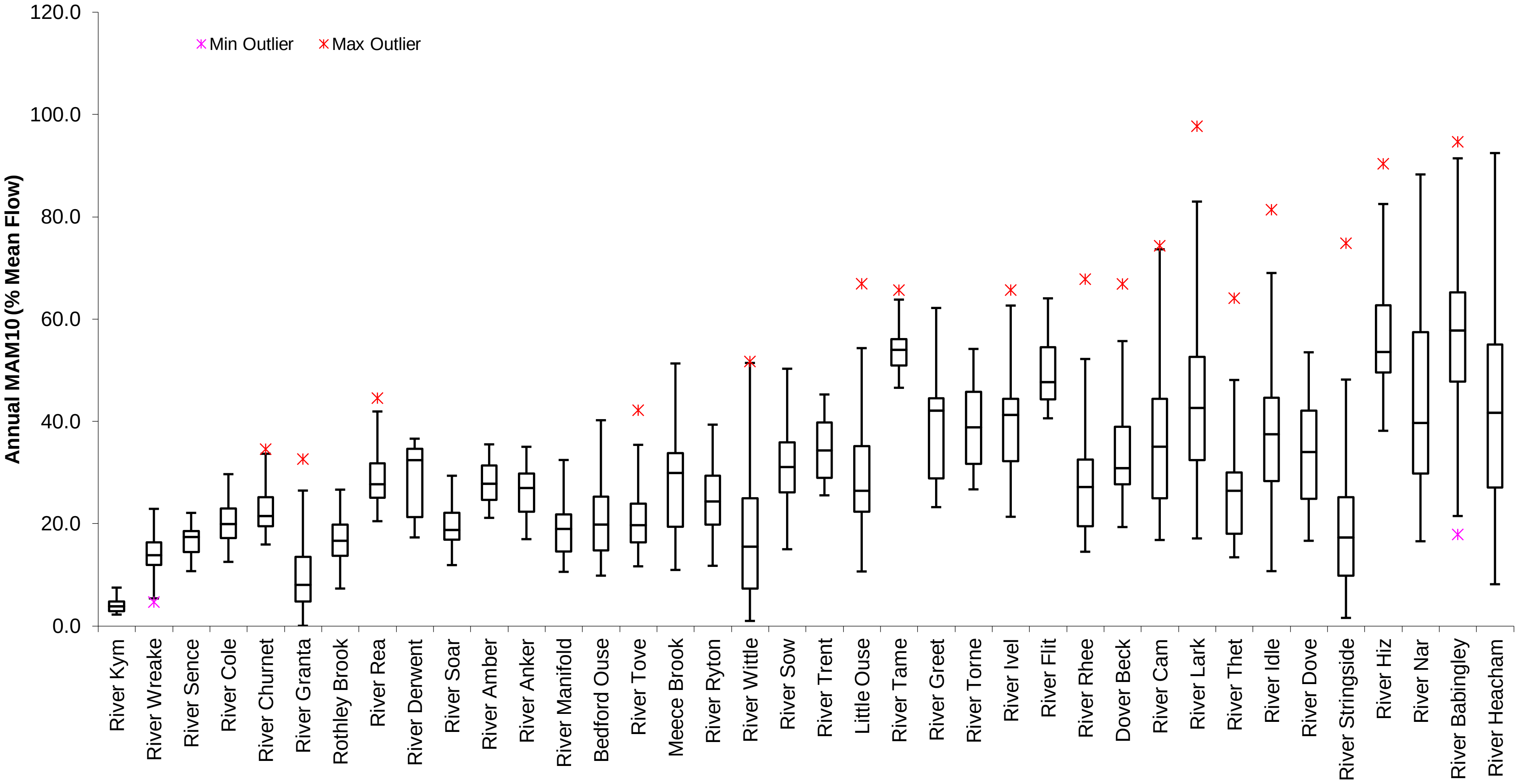
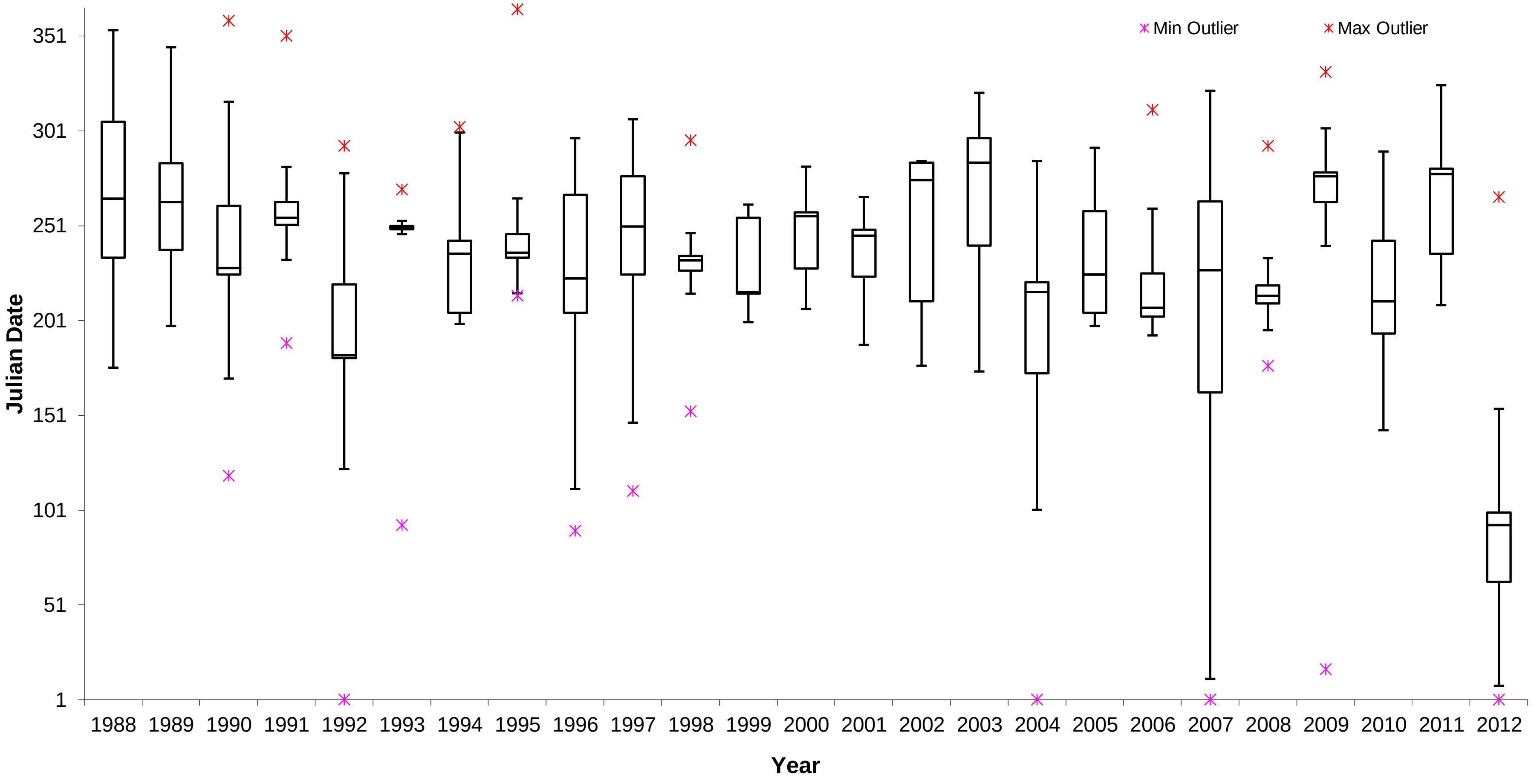


Figure 6.4: Box and whisker plot illustrating the inter-annual variability in timings of annual 10-day minimum (MAM10) flows. Box plots illustrate the range of Julian Dates of annual MAM10 flows for each year. The boxes enclose the interquartile (IQR) range; the horizontal line within each box indicates the median. The ends of the whiskers are set at 1.5*IQR above the 3rd quartile and 1.5*IQR below the 1st quartile. If the minimum or maximum values are outside this range they are shown as outliers, only the minimum and maximum outliers are shown.



6.4 RESULTS (2): APPLICATION OF MORE COMPLEX FLOW RULES

At the centre of Baxter's (1961; 1963) approach was the belief that more complex flow rules would increase the water available for abstraction and provide added protection for the environment in general and fish in particular. The review of historical and current low-flow management approaches identified that in the majority of cases, the annual Q_{95} flow duration statistic is used to determine HOFs at abstractions and compensation flows below impoundments. Arguably, this has resulted in more water than necessary being allocated during the summer period when riverine biota are adapted to low-flow conditions, in all but the most extreme drought years and even then recovery can be rapid, in ecological timescales of evolution and adaptation. Furthermore, the approach appears to be inadequate in protecting flows during the spring (May and June) and autumn (October and November) critical ecological periods. In addition, the use of the annual Q_{95} as an *e-flow* overlooks the importance for riverine biodiversity and resilience of ensuring that a degree of inter-annual flow variability is maintained.

Table 6.4 illustrates some of the potential issues surrounding the adoption of Baxter's 20% ADF to manage low flows and ecological drought.

Table 6.4: Diversity of low flows: total number of days that flows were equal to or lower than four hydrologic metrics (10 study sites; River Trent and River Great Ouse catchments)

Watercourse	Station Name	Q_{95}	20% ADF	5-year MAM10	3-year MAM10
River Kym	Meagre Farm	524	4789	104	145
River Manifold	Ilam	459	823	108	460
River Tove	Cappenham Bridge	468	869	254	436
Bedford Ouse	Bedford	455	633	134	256
River Derwent	Yorkshire Bridge	461	195	202	881
River Dove	Izaak Walton	458	66	174	398
River Sow	Great Bridgford	460	110	189	494
River Trent	North Muskham	461	0	118	297
River Hiz	Arlesey	467	0	389	587
River Tame	Lea Marston Lakes	454	0	175	320

Although one study site, the River Kym recorded more than 4500 days of flows lower than 20% ADF, three study sites; the Rivers Trent, Hiz and Tame recorded no days of flows lower than this metric. There was, however, far less variability in the occurrence of flows equal to or lower than the 5-year and the 3-year MAM10 metrics during the 25-year study period.

6.4.1 Temporal patterns of variability

From a practical flow management perspective, a persistent low-flow is more significant than the one-day minima. Tables 6.5 to 6.8 illustrate the number of years in the 25-year study period that the April to November inclusive flow management period experienced 10 or more consecutive days of flows equal to or lower than the annual Q_{95}, 20% ADF, the 3-year MAM10 and the 5-year MAM10.

Table 6.5 illustrates that annual Q_{95} flows with a 10-day duration rarely occur earlier than July and rarely occur in November; the exception is the highly regulated River Derwent where low flows were previously identified as occurring in every month of the year. Prolonged periods of flows equal to or lower than the annual Q_{95} generally occurred during August and September, with four study sites; the Rivers Manifold, Bedford Ouse, Dove and Trent recording September flows lasting 10 or more consecutive days equal to or lower than the annual Q_{95} flow in six years in the 25-year study period.

Table 6.5: Number of years in the 25-year study period (1988-2012) experiencing 10 or more consecutive days of flows equal to or lower than the annual Q_{95}

Month	**River Kym**	**River Man-ifold**	**River Tove**	**Bed-ford Ouse**	**River Der-went**	**River Dove**	**River Sow**	**River Trent**	**River Hiz**	**River Tame**
May					4				1	
Jun		1			3		1	1	2	
Jul	**5**	2	2	3	**5**	2	3	3	2	1
Aug	4	5	4	4	2	4	**4**	5	**3**	**3**
Sep	4	**6**	**5**	**6**		**6**	3	**6**	**3**	2
Oct	2	2	4			4	2	2	2	1
Nov		1			1	1	1		2	1
Total	**15**	**17**	**15**	**13**	**15**	**17**	**14**	**17**	**15**	**8**

Although the issues surrounding the use of 20% ADF to manage low flows and ecological drought were demonstrated in Table 6.3, the results in Table 6.6 were included to facilitate the comparison of the occurrence of persistent periods of flows below a range of potential flow metrics.

The River Kym recorded 10 or more consecutive days of flows equal to or lower than 20% ADF in May, October and November in more than 10 years in the 25-year study period, and 10 or more consecutive days of flows equal to or lower than 20% ADF between June and September inclusive in 20 or more years. Indeed, the River Kym experienced persistent low flows in 144 months in total during the 25-year study period. Conversely, three study sites; the Rivers Trent, Hiz and Tame recorded no prolonged periods of flows equal to or lower than 20% ADF. The results of this and of previous assessments appear to indicate that Baxter's approach may be restricted by the variety of flow regime types studied and may not be transferable outside of hard rock, upland catchments.

Table 6.6: Number of years in the 1988-2012 inclusive 25-year study period experiencing 10 or more consecutive days of flows equal to or lower than 20% ADF

Month	River Kym	River Man-ifold	River Tove	Bed-ford Ouse	River Der-went	River Dove	River Sow	River Trent	River Hiz	River Tame
May	17				**2**					
Jun	23	3	1		1					
Jul	22	8	6	3	**2**					
Aug	23	**10**	**8**	**7**			**1**			
Sep	**25**	7	**8**	**7**		**2**	**1**			
Oct	18	5	7	1		1	**1**			
Nov	16	1	1							
Total	**144**	**34**	**31**	**18**	**5**	**3**	**3**	**0**	**0**	**0**

The results in Table 6.5 on the previous page illustrated that with the exception of the discharge-rich River Tame, the total number of years in the 25-year study period that experienced persistent low flows during the May to November regulation period was consistent. When 20% ADF was, however, used to define low flows, the number of months experiencing persistent low flows ranged from between zero months (Rivers Trent, Hiz and Tame), and 144 months (River Kym). The results in Tables 6.5 and 6.6 clearly illustrate that the annual Q_{95} flow with a 10-day duration provided better flow protection during the summer and autumn periods than the 20% ADF with a 10-day duration.

Table 6.7 illustrates that flows equal to or lower than the 3-year MAM10 low-flow metric rarely occur earlier than July, the exception is the highly regulated River Derwent which experiences low flows throughout the year. Low-flow events lasting more than 10 consecutive days generally occurred during July, August and September.

Two study sites; the Rivers Derwent and Sow recorded July flows equal to or lower than the 3-year MAM10 for 10 or more consecutive days in four years, four sites; the Rivers Manifold, Derwent, Sow and Hiz recorded August flows equal to or lower than the 3-year MAM10 for 10 or more consecutive days in four years. Finally, five sites; the Rivers Manifold, Tove, Bedford Ouse, Dove and Sow recorded 10 or more consecutive days of September flows equal to or lower than the 3-year MAM10 in four or more years. Although the 3-year MAM10 flow with a 10-day duration appears to provide a degree of protection during the summer and autumn periods, with the exception of the River Hiz, spring flows would seemingly not be protected.

Table 6.7: Number of years in the 1988-2012 inclusive 25-year study period experiencing 10 or more consecutive days of flows equal to or lower than the 3-year MAM10

Month	River Kym	River Manifold	River Tove	Bedford Ouse	River Derwent	River Dove	River Sow	River Trent	River Hiz	River Tame
May					**5**		1		1	
Jun		1			**5**		1		2	
Jul	**2**	2	2	1	**5**	2	4	1	2	
Aug		5	3	3	4	3	**5**	**3**	**4**	1
Sep		**6**	**5**	**4**	1	**4**	4	**3**	3	**2**
Oct		2	3		2	**4**	2	1	2	1
Nov		1			3	1	1		2	1
Total	**2**	**17**	**13**	**8**	**25**	**14**	**18**	**8**	**16**	**5**

Although the 3-year MAM10 flow with a 10-day duration apparently provided a degree of protection during the summer and autumn periods flows during the critical spring ecological period were generally not protected. The results in Table 6.7 illustrate that when compared to the annual Q_{95} flow (Table 6.5), the 3-year MAM10 flow was influenced by the contrasting flow regimes of the 10 study sites to a greater extent. For example, when the annual Q_{95} flow was used to define persistent low-flow events, the River Kym experienced persistent low flows during July to October inclusive, however, when the 3-year MAM10 flow was used to define low flows, only July experienced persistent low flows.

Table 6.8 illustrates that periods of 10 or more consecutive days of flows equal to or lower than the most severe metric explored here, the 5-year MAM10, were recorded in a maximum of three years during August and September. With the exception of the highly regulated River Derwent and the heavily modified River Hiz, spring flows would not be protected by the 5-year MAM10. In addition, it is unlikely that the adoption of the 5-year MAM10 flow would provide adequate protection of flows during the critical spring period.

The 5-year MAM10 flow would have provided a lower degree of flow protection during the summer and autumn periods than both the annual Q_{95} flow (Table 6.5) and the 3-year MAM10 flow (Table 6.7). From Table 6.8 it is clear that the 5-year MAM10 flow would have provided less flow protection during the critical spring period than both the annual Q_{95} flow and the 3-year MAM10 flow.

Table 6.8: Number of years in the 1988-2012 inclusive 25-year study period experiencing 10 or more consecutive days of flows equal to or lower than the 5-year MAM10

Month	River Kym	River Man-ifold	River Tove	Bed-ford Ouse	River Der-went	River Dove	River Sow	River Trent	River Hiz	River Tame
May					**2**				1	
Jun					1				1	
Jul	**2**		1	1	**2**		1		2	
Aug		1	**3**	**3**		**2**	**2**	**1**	2	**1**
Sep		**3**	**3**	2		**2**	**2**	**1**	**3**	
Oct			1			**2**	1		2	**1**
Nov						1	1		2	
Total	**2**	**4**	**8**	**6**	**5**	**7**	**7**	**2**	**13**	**2**

Unfortunately, in the majority of cases the four hydrologic metrics explored here do not appear to provide adequate protection during the critical spring (May and June) ecological period. The results in Table 6.5, however, illustrated that the adoption of the annual Q_{95} flow with a 10-day duration provides a novel perspective on the application of the current Q_{95} approach, and appears to provide the best flow protection during the summer (July to September inclusive) and autumn (October and November) periods. The results in Tables 6.5 to 6.8 indicate that the adoption of seasonal or even monthly flow metrics may be required to adequately protect flows during the critical spring ecological period. Selected monthly flow metrics are considered in the next section which explores the application of the current annual Q_{95} approach and a range of alternative *e-flow* scenarios.

6.5 ALTERNATIVE ENVIRONMENTAL FLOW SCENARIOS

Using daily mean flow data from the 10 study sites, comprising five semi-natural and five modified rivers, summarised in Table 6.1, the remainder of this Chapter investigates the impact that the application of a range of alternative flow management scenarios would have had on flows during dry years. The current hydrological *e-flow* approach, the annual Q_{95}, was previously identified as allocating insufficient water during both the spring and autumn critical ecological periods, when the water requirements of the riverine biota are higher, and too much water during the summer.

By employing the annual Q_{95} approach as a baseline, assessments aimed to determine whether more complex hydrological *e-flow* approaches are not only capable of offering better environmental protection but also capable of allocating more water for abstraction.

Assessments of the flow surplus and deficits resulting from the adoption of alternative flow management scenarios aimed to determine:

(a) How much water above the annual Q_{95} (the current hydrological *e-flow* approach) would be available for abstraction.
(b) Whether it is possible to allocate a higher hands-off flow during the spring and autumn critical ecological periods and to still make more water available for abstraction by reducing the hands-off flow during the summer period.

Assessments also explored whether the application of the hydrological *e-flow* approaches at more complex temporal resolutions (annual vs. seasonal vs. month) summarised in Table 6.9, saves water and protects the environment.

Table 6.9: Flow management scenarios used to explore the application of a range of alternative hydrological approaches to setting environmental flows

Flow Management Scenario	**Spring**		**Summer**			**Autumn**	
	May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Annual Q_{95} (the current approach)	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}
Month Q_{95} (mimics natural flows)	May Q_{95}	Jun Q_{95}	Jul Q_{95}	Aug Q_{95}	Sep Q_{95}	Oct Q_{95}	Nov Q_{95}
Month Q_{84} and Month Q_{95}	May Q_{84}	Jun Q_{84}	Jul Q_{95}	Aug Q_{95}	Sep Q_{95}	Oct Q_{84}	Nov Q_{84}
20% - 30% ADF (included to test Baxter's proposals)	30% ADF	30% ADF	20% ADF	20% ADF	20% ADF	30% ADF	30% ADF
20% - 40% ADF (included to test Baxter's proposals)	40% ADF	30% ADF	20% ADF	20% ADF	20% ADF	30% ADF	40% ADF
Month Q_{84} and 5-year MAM10	May Q_{84}	Jun Q_{84}	5-year MAM10	5-year MAM10	5-year MAM10	Oct Q_{84}	Nov Q_{84}
30% ADF and 5-year MAM10	30% ADF	30% ADF	5-year MAM10	5-year MAM10	5-year MAM10	30% ADF	30% ADF

In order to explore the potential utility of the flow management scenarios summarised in Table 6.9, the four driest years in the 25-year study period were determined by calculating and subsequently ranking (lowest to highest value) the annual MAM10 flow series for each of the study sites (Table 6.10).

Monthly daily mean flows for the summer regulation period were subsequently calculated using daily mean flows recorded between May and November inclusive during each of the four driest years summarised in Table 6.10.

Table 6.10 The four driest years in the 1988-2012 inclusive study period (10 study sites River Trent and River Great Ouse catchments)

Watercourse	Station Name	1st Driest Year	2nd Driest Year	3rd Driest Year	4th Driest Year
River Kym	Meagre Farm	2009	2010	2002	2011
River Manifold	Ilam	1996	1989	1991	1995
River Tove	Cappenham Bridge	1997	2011	1990	1991
Bedford Ouse	Bedford	1990	1997	1995	1991
River Derwent	Yorkshire Bridge	1988	1992	1996	1990
River Dove	Izaak Walton	2011	1996	1991	1995
River Sow	Great Bridgford	2011	1990	1996	1991
River Trent	North Muskham	1989	1990	2011	1995
River Hiz	Arlesey	1997	2006	2011	1998
River Tame	Lea Marston Lakes	2011	1990	2004	2006

The variability in the timings of the four driest years in the 25-year daily flow records of each study site is clearly demonstrated in Table 6.10. This highlights the importance of using local and not regional determination of lowest flow years.

6.5.1 Assessment of the surplus/deficit in monthly daily mean flows resulting from the application of the current and alternative environmental flow approaches – natural and semi-natural watercourses

Before the impact of the adoption of the alternative flow management scenarios (Table 6.9) was quantified, schematics were plotted for each study site (Figures 6.5 to 6.9). Each schematic illustrates the May to November inclusive monthly daily mean flows experienced during one of the four driest years in the 1988-2012 inclusive study period, the current annual Q_{95} *e-flow* and each of the alternative flow management scenarios. Each schematic was subsequently used to identify unsuitable alternative flow management scenarios.

Taking Figure 6.5 which illustrates the second driest year in the River Kym at Meagre Farm as an example, it is clear that flow management scenarios utilising 20% ADF to 30% ADF and also 20% ADF to 40% ADF to allocate *e-flows* could not be adopted as alternative flow management approaches. Both allocate higher flows than the annual Q_{95} during the summer period when the aim is to allocate lower flows.

Figure 6.5: Schematic illustrating the monthly daily mean flow recorded during 2010 the second driest year, the annual Q_{95} and a range of alternative flow management scenarios - River Kym at Meagre Farm

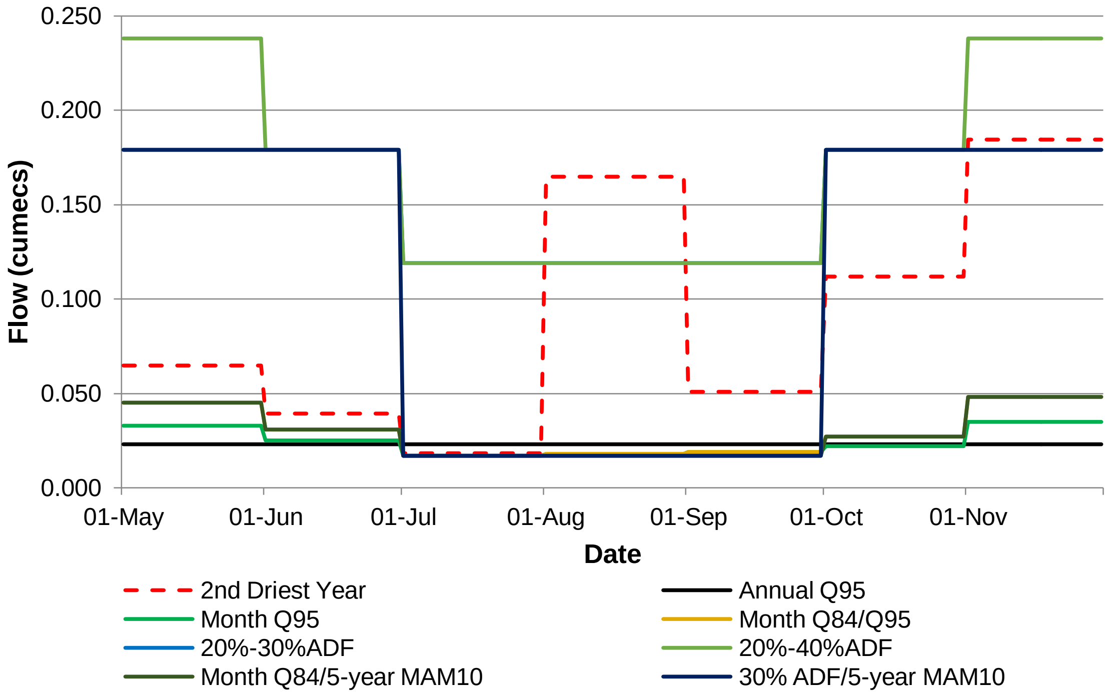


Figure 6.6: Schematic illustrating the monthly daily mean flow recorded during 1995 the fourth driest year, the annual Q_{95} and a range of alternative flow management scenarios - River Manifold at Ilam

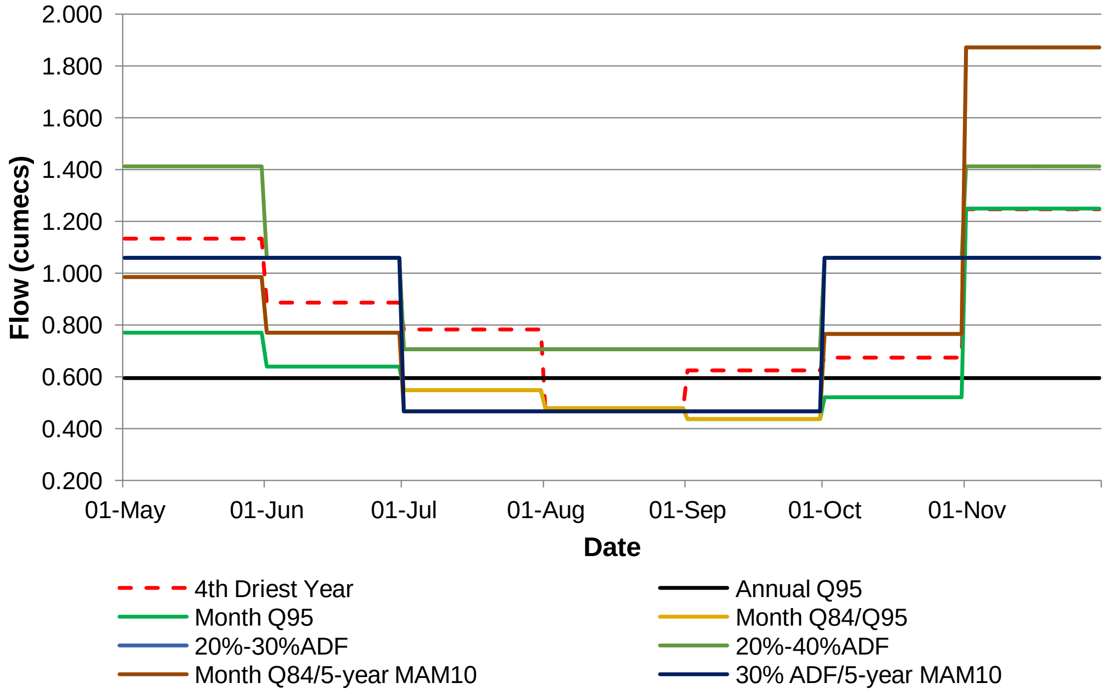


Figure 6.7: Schematic illustrating the monthly daily mean flow recorded during 1990 the third driest year, the annual Q_{95} and a range of alternative flow management scenarios - River Tove at Cappenham Bridge

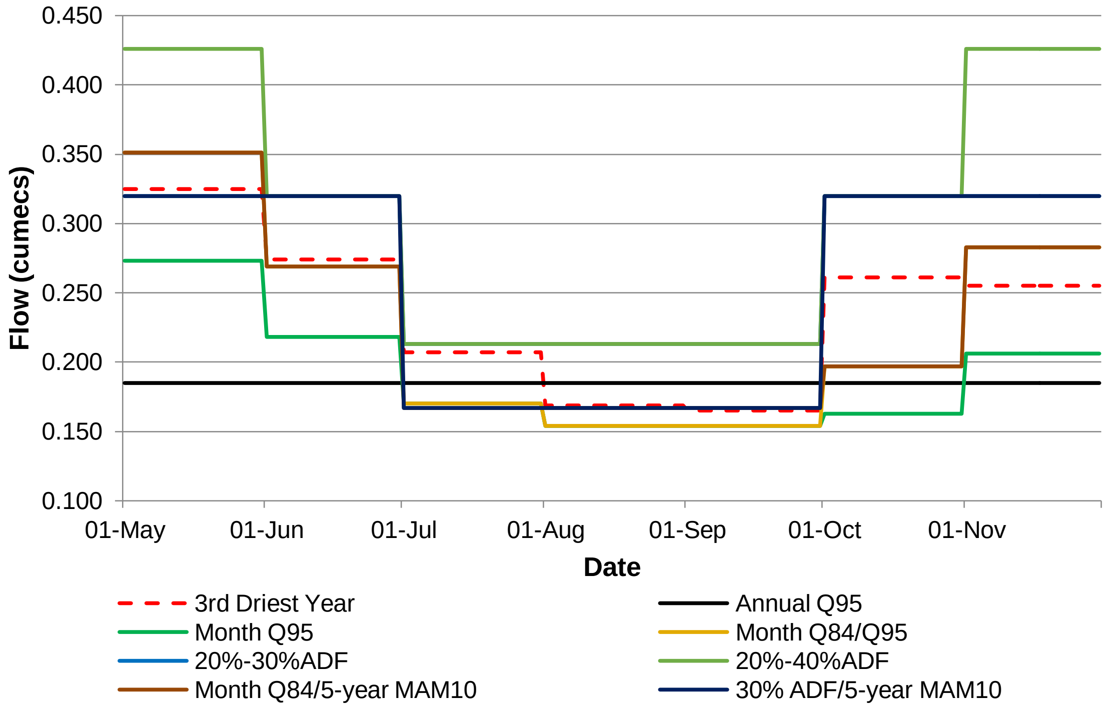


Figure 6.8: Schematic illustrating the monthly daily mean flow recorded during 1991 the third driest year, the annual Q_{95} and a range of alternative flow management scenarios - River Dove at Izaak Walton

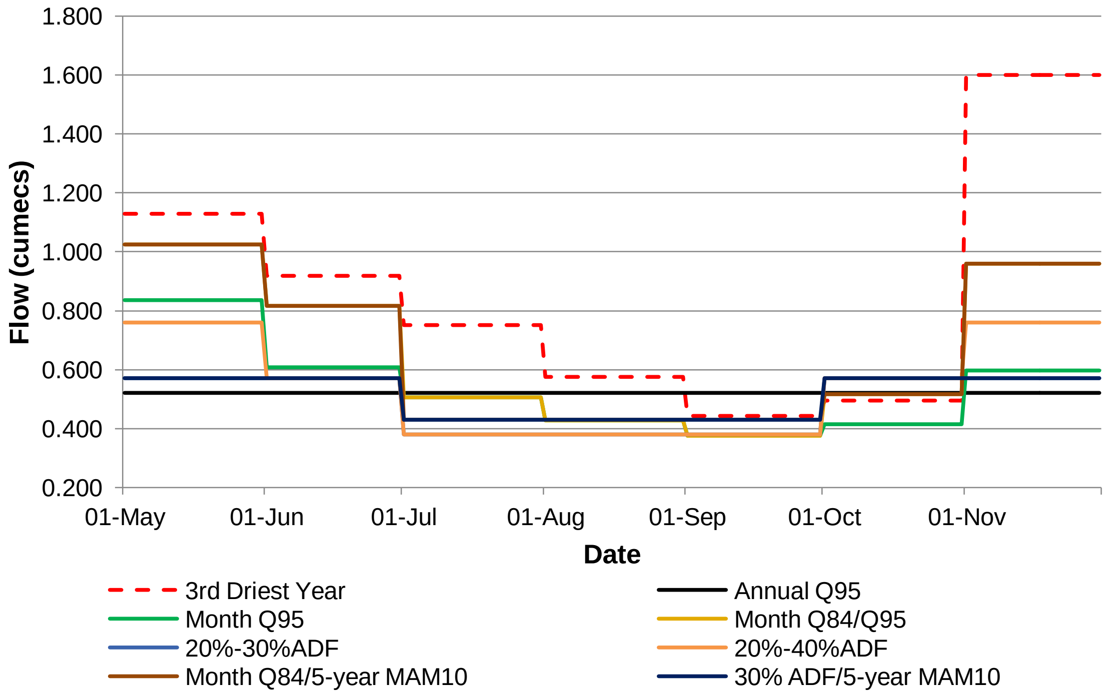
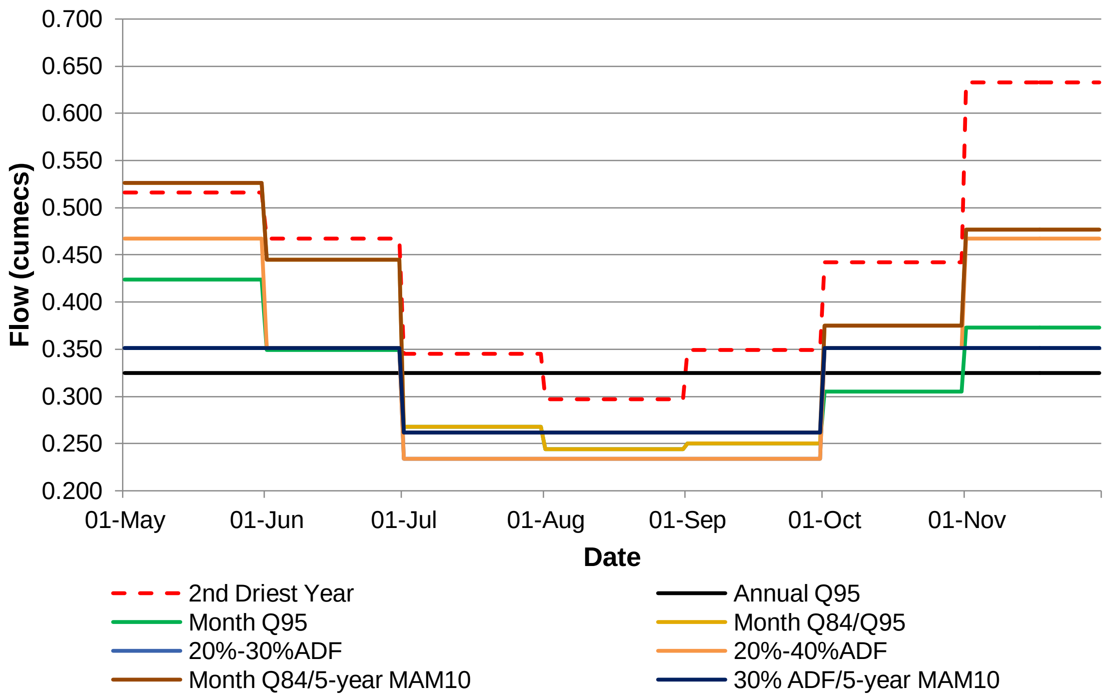


Figure 6.9: Schematic illustrating the monthly daily mean flow recorded during 1990 the second driest year, the annual Q_{95} and a range of alternative flow management scenarios - River Sow at Great Bridgford



In the next section, a range of alternative flow management scenarios are evaluated. Throughout the flow assessments the annual Q_{95} is used as a baseline. Flow management scenarios that would result in the allocation of substantially lower flows than the annual Q_{95} during the spring and autumn critical ecological periods, and substantially higher flows than the Q_{95} during the summer period were discounted at this stage.

Table 6.11 summarises the flow management scenarios that were identified as being potentially unsuitable at this stage. Assessments indicated that the adoption of the month Q_{95} would have resulted in the allocation of lower October flows in four of the watercourses with semi-natural and natural flow regimes. The month Q_{95} flow metric was, however, included in the more detailed flow assessments as its adoption resulted in a higher degree of inter-annual flow variability than the other alternative flow management scenarios.

Table 6.11: Summary of the potential utility of the range of alternative flow management scenarios – natural and semi-natural watercourses

Watercourse	Flow Management Scenario					
	Month Q_{95}	Month Q_{84}/Q_{95}	20%-30% ADF	20%-40% ADF	Month Q_{84}/5year MAM10	30%ADF/ 5year MAM10
River Kym	✓	✓	x[1]	x[1]	✓	x[1]
River Manifold	x[2]	✓	x[1]	x[1]	✓	✓
River Tove	x[2]	✓	x[1]	x[1]	✓	✓
River Dove	x[2]	✓	✓	✓	✓	✓
River Sow	x[2]	✓	✓	✓	✓	✓

✓ Flow management scenario identified as potentially representing a suitable alternative to the annual Q_{95}
x Flow management scenario identified as representing an unsuitable alternative to the annual Q_{95}

[1] Application of alternative flow management scenario would result in the allocation of higher flows than the Q_{95} approach during the summer ecological period. In addition, the allocation of flows within the River Kym was unrealistic.
[2] Application of alternative flow management scenario would result in the allocation of lower flows than the Q_{95} approach during October, the first month of the autumn critical ecological period.

Following the identification that the month Q_{95} may not allocate adequate flows during October, an additional flow assessment was undertaken. The IHA Software was used to calculate detailed annual and monthly flow exceedence probabilities and the equivalent flows for the five study sites with natural and semi-natural flow regimes. The May to November inclusive monthly flow exceedence probabilities that were equivalent to the long-term annual Q_{95} were subsequently determined (Table 6.12).

Table 6.12: Monthly flow exceedence probabilities that are equivalent to the long-term annual Q_{95} natural and semi-natural watercourses

Study Site	May	Jun	Jul	Aug	Sep	Oct	Nov
River Kym (Q_{95} 0.023 m^3s^{-1})	$Q_{99.9}$	$Q_{96.9}$	$Q_{82.9}$	$Q_{83.2}$	$Q_{83.2}$	$Q_{91.5}$	$Q_{99.0}$
River Manifold (Q_{95} 0.594 m^3s^{-1})	$Q_{99.9}$	$Q_{97.5}$	$Q_{91.6}$	$Q_{82.7}$	$Q_{79.4}$	$Q_{90.1}$	$Q_{98.0}$
River Tove (Q_{95} 0.185 m^3s^{-1})	$Q_{99.9}$	$Q_{98.4}$	$Q_{91.4}$	$Q_{84.9}$	$Q_{78.8}$	$Q_{88.6}$	$Q_{97.8}$
River Dove (Q_{95} 0.521 m^3s^{-1})	$Q_{99.9}$	$Q_{99.6}$	$Q_{94.5}$	$Q_{85.8}$	$Q_{77.7}$	$Q_{83.7}$	$Q_{99.0}$
River Sow (Q_{95} 0.325 m^3s^{-1})	$Q_{99.0}$	$Q_{96.5}$	$Q_{87.6}$	$Q_{82.8}$	$Q_{87.6}$	$Q_{91.9}$	$Q_{96.2}$

The River Manifold has an annual Q_{95} of 0.594 m^3s^{-1}; this flow equates to the September $Q_{79.4}$ and the October $Q_{90.1}$. From Table 6.12, the River Dove has an annual Q_{95} of 0.521 m^3s^{-1}, this flow is equivalent to the October $Q_{83.7}$ illustrating the potential inadequacy of the October Q_{95} as an *e-flow* at this location. Finally, Table 6.12 illustrates the degree of flow variability, particularly between July and October inclusive across the study sites with natural and semi-natural flow regimes.

Baxter (1961; 1963) style flow management approaches based on percentages of the long-term ADF were identified as unsuitable in three of the watercourses with natural and semi-natural flow regimes, due to the allocation of higher flows during the summer and were therefore discounted at this stage. The change in water allocation that would have resulted from the adoption of the scenarios summarised in Table 6.13 formed the final stage of the assessments of the adoption of alternative flow management scenarios in rivers with natural and semi-natural flow regimes. In all assessments the annual Q_{95} was used as a baseline.

Table 6.13: Flow management scenarios used in detailed assessments of the application of alternative hydrological approaches to setting environmental flows in rivers with natural and semi-natural flow regimes

Flow Management Scenario	**Spring**		**Summer**			**Autumn**	
	May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Annual Q_{95} (the current approach)	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}
Month Q_{95} (mimics natural flows)	May Q_{95}	Jun Q_{95}	Jul Q_{95}	Aug Q_{95}	Sep Q_{95}	Oct Q_{95}	Nov Q_{95}
Month Q_{90} and Month Q_{98}[1]/Q_{97}[2]	May Q_{90}	Jun Q_{90}	Jul Q_{98}/Q_{97}	Aug Q_{98}/Q_{97}	Sep Q_{98}/Q_{97}	Oct Q_{90}	Nov Q_{90}
Month Q_{84} and 5-year MAM10	May Q_{84}	Jun Q_{84}	5-year MAM10	5-year MAM10	5-year MAM10	Oct Q_{84}	Nov Q_{84}

[1] The month Q_{98} was used to allocate July to September flows with the Rivers Kym, Manifold and Dove
[2] The month Q_{97} was used to allocate July to September flows with the Rivers Tove and Sow

Flow assessments aimed to quantify the change in water allocation that adoption of the flow management scenarios in Table 6.13 would have resulted in. Assessments evaluated (a) flows to the river i.e. the proposed alternative *e-flow*: monthly daily mean flows can naturally fall below this value (all results are reported as m^3s^{-1}), and (b) the water available for supply i.e. the surplus in monthly daily mean flows above the *e-flow* (all results are reported as Ml). The flow assessment process followed three stages; (1) the application of the flow management scenarios outlined in Table 6.13 at a monthly scale, an example for the River Kym is provided in the next section, (2) the aggregation of the results of the monthly assessments into the spring, summer and autumn periods, and (3) calculation of the seasonal and overall percentage change in water allocation that would have resulted from the application of the alternative flow management scenarios.

Flow assessments were based on the May to November inclusive monthly daily mean flows recorded during the four driest years summarised in Table 6.10, detailed monthly and seasonal results tables for the five study sites are provided in Appendices 6.7a to 6.7e and Appendices 6.8a to 6.8e respectively. In this section, flows recorded within the River Kym during September 2009, the driest year in the 25-year study period are used to illustrate the approach used to calculate the initial set of results. The long-term annual Q_{95} was 0.023 m^3s^{-1}, the month Q_{95} 0.019 m^3s^{-1} and the September monthly daily mean flow 0.020 m^3s^{-1}. Flows during September 2009 were therefore 0.003 m^3s^{-1} lower than the long-term annual Q_{95}. This deficit illustrates that in September, use of the annual Q_{95} as an *e-flow* would have resulted in there being no water available for supply. Adopting the monthly Q_{95} as an *e-flow*, however, would have resulted in the allocation of lower flows to the River Kym during the summer period when the ecology is adapted to lower flows, and an increase in the volume of water available for supply.

Following the calculation of the change in water allocation that adoption of the alternative flow management scenarios (Table 6.13) would have resulted in at a monthly scale. For each scenario the spring (May and June), summer (July to September) and autumn (October and November) flows to the river were averaged. In addition, the aggregate spring, summer and autumn volumes to supply were calculated. Subsequently, using the annual Q_{95} as a baseline, the percentage change in the average spring, summer and autumn flows to the river, and the percentage change in the average volume of water available for supply during spring, summer and autumn that the adoption of each of the alternative flow management scenarios during the four driest years would have resulted in were calculated. The results of these assessments are provided in Appendices 6.7a to 6.7e.

The actual change and percentage change in water allocation that adoption of the alternative flow management scenarios would have resulted in are summarised in Tables 6.14 to 6.18. The baseline for all assessments is the annual Q_{95}. At all study sites HOF 1 is the month Q_{95} and HOF 3 is a combination of the month Q_{84} (May to June and October to November) and the 5-year MAM10 (July to September). However, although HOF2 comprises the gauged month Q_{90} in May, June, October and November at all study sites, the gauged monthly percentile that was selected to allocate July to September inclusive summer flows varied. At study sites where the gauged flows were marginally higher than the estimated naturalised flows (Rivers Dove, Manifold and Kym) the gauged monthly Q_{98} was used to allocate summer *e-flows* because there was a significant drop between the gauged Q_{98} and Q_{99} flows creating uncertainty. At study sites where gauged flows were significantly lower than the naturalised flow estimates (Rivers Tove and Sow) which indicates that there may be uncertainty in the record, the gauged monthly Q_{97} was used to allocate summer *e-flows*.

Each of the five study sites with natural and semi-natural flow regimes are considered individually and consideration is given as to whether the adoption of the more complex approaches outlined in Table 6.13 which are broadly based on Baxter's (1961) principles saved water, therefore, benefitting both riverine ecology and abstractors.

The results of the adoption of the alternative flow management approaches during the four driest years in the River Kym are illustrated in Table 6.14. Although it is possible to allocate higher flows to the River Kym during the spring and autumn critical ecological periods and lower flows during the summer, all three approaches would result in an overall reduction in the volume of water available for abstraction during the May to November inclusive regulation period.

Table 6.14: Change in water allocation – River Kym at Meagre Farm (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	**HOF2 flows to river (m^3s^{-1})**	**HOF3 flows to river (m^3s^{-1})**	**HOF1 abstraction (Ml)**	**HOF2 abstraction (Ml)**	**HOF3 abstraction (Ml)**
May – Jun (percentage change)	+0.006 (+26.1)	+0.010 (+41.3)	+0.014 (+60.9)	-31.96 (-18.1)	-50.46 (-28.6)	-74.31 (-42.1)
Jul – Sep (percentage change)	-0.004 (-19.4)	-0.007 (-31.3)	-0.005 (-23.9)	+34.54 (+9.2)	+55.71 (+14.8)	+42.40 (+11.3)
Oct – Nov (percentage change)	+0.006 (+24.6)	+0.009 (+38.8)	+0.012 (+54.1)	-29.09 (-1.1)	-105.00 (-3.9)	-64.37 (-2.4)
May – Nov (percentage change)	**+0.001 (+6.5)**	**+0.002 (+9.9)**	**+0.005 (+23.1)**	**-26.51 (-0.8)**	**-99.75 (-3.1)**	**-96.28 (-3.0)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.023 m^3s^{-1}/176.41 Ml; Jul-Sep (summer): 0.022 m^3s^{-1}/376.77 Ml; Oct-Nov (autumn): 0.023 m^3s^{-1}/2675.53 Ml

From Table 6.14 the adoption of HOF 1 would result in the optimum allocation of water during the May to November inclusive regulation period. The River Kym would benefit from a 26.1 and 24.6 per cent increase in flows to the river during the spring and autumn critical ecological periods respectively. The adoption of HOF 1 would result in summer flows to the River Kym being reduced by 19.4 per cent. In addition, there would be a small decrease in the overall volume of water available for abstraction of 0.8 per cent. The adoption of HOF 2 and HOF 3 would perhaps be difficult to justify from a water resources perspective due to the reduction in the overall volume of water available for abstraction of 3.1 and 3.0 per cent respectively.

Table 6.15 summarises the change in the allocation of water within the River Manifold, a watercourse with an essentially natural flow regime that would have resulted from the application of the alternative flow management approaches.

Table 6.15: Change in water allocation – River Manifold at Ilam (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	HOF2 flows to river (m^3s^{-1})	HOF3 flows to river (m^3s^{-1})	HOF1 abstraction (Ml)	HOF2 abstraction (Ml)	HOF3 abstraction (Ml)
May – Jun (percentage change)	+0.111 (+18.6)	+0.194 (+32.7)	+0.283 (+47.6)	-587.95 (-21.3)	-1030.15 (-37.2)	-1500.77 (-54.2)
Jul – Sep (percentage change)	-0.055 (-10.1)	-0.102 (-18.8)	-0.079 (-14.6)	+433.19 (+66.1)	+811.45 (+123.8)	+631.26 (+96.3)
Oct – Nov (percentage change)	+0.291 (+48.9)	+0.427 (+71.9)	+0.629 (+105.9)	-1499.56 (-17.3)	-2213.91 (-25.6)	-3274.00 (-37.8)
May – Nov (percentage change)	**+0.091 (+16.0)**	**+0.134 (+23.4)**	**+0.227 (+39.7)**	**-1654.32 (-13.7)**	**-2432.61 (-20.1)**	**-4143.51 (-34.3)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.594 m^3s^{-1}/2766.66 Ml; Jul-Sep (summer): 0.541 m^3s^{-1}/655.58 Ml; Oct-Nov (autumn): 0.594 m^3s^{-1}/8662.08 Ml

The results in Table 6.15 demonstrate that when the alternative flow management scenarios are employed as *e-flows* during the four driest years in the River Manifold it is possible to allocate lower summer flows to support higher spring and autumn flows to the river. Unfortunately, the adoption of all three approaches would result in a reduction of between 13.7 and 34.3 per cent in the overall volume of water available for abstraction during the regulation period. From a water supply perspective it is highly unlikely that such reductions in the availability of water for abstraction would be acceptable.

The results for the River Tove are provided in Table 6.16, and illustrate that all of the alternative flow management scenarios are capable of allocating increased flows to the river during the spring and autumn critical ecological periods in combination with lower summer flows to the river when the ecological demand for water is lower.

From Table 6.16 the adoption HOF 1, HOF 2 and HOF 3 as an alternative to the annual Q_{95} would, however, result in a corresponding 8.3, 16.8 and 31.0 per cent reduction respectively in the overall volume of water available for abstraction. This would not be acceptable from a water supply perspective. The assessment of the application of three alternative flow management scenarios has demonstrated that in watercourses with similar flow regimes to the River Tove it may not be possible to allocate increased flows to the watercourse during the spring and autumn critical ecological periods in combination with reduced summer flows without a substantial corresponding reduction in the volume of water available for abstraction.

Table 6.16: Change in water allocation – River Tove at Cappenham Bridge (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	**HOF2 flows to river (m^3s^{-1})**	**HOF3 flows to river (m^3s^{-1})**	**HOF1 abstraction (Ml)**	**HOF2 abstraction (Ml)**	**HOF3 abstraction (Ml)**
May – Jun (percentage change)	+0.060 (+32.2)	+0.084 (+45.6)	+0.104 (+56.0)	-310.70 (-41.5)	-447.09 (-59.7)	-548.37 (-73.3)
Jul – Sep (percentage change)	-0.017 (-9.7)	-0.026 (-14.4)	-0.010 (-5.8)	+136.58 (+53.5)	+203.10 (+79.6)	+81.30 (+31.9)
Oct – Nov (percentage change)	+0.001 (+0.7)	+0.023 (+12.8)	+0.039 (+21.6)	-5.06 (-0.4)	-120.92 (-10.4)	-204.90 (-17.6)
May – Nov (percentage change)	**+0.010** **(+5.4)**	**+0.020** **(+11.0)**	**+0.037** **(+20.2)**	**-179.18** **(-8.3)**	**-364.91** **(-16.8)**	**-671.96** **(-31.0)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.185 m^3s^{-1}/748.42 Ml; Jul-Sep (summer): 0.177 m^3s^{-1}/255.16 Ml; Oct-Nov (autumn): 0.182 m^3s^{-1}/1162.75 Ml

The results in Table 6.17 demonstrate that although the alternative flow management scenarios are capable of allocating additional water to the River Dove, a watercourse with an essentially natural, groundwater-dominated flow regime during the spring and autumn critical ecological periods and a reduction in flows to the river during the summer, all would result in a reduction in the volume of water available for abstraction. The adoption of HOFs 1, 2 and 3 would result in a 12.6, 24.8 and 41.3 per cent reduction respectively in the volume of water available for abstraction from the river during the May to November inclusive regulation period. It is unlikely that such large reductions in the volume of water that is available for abstraction would be acceptable from a water supply perspective.

The assessment of the application of three alternative flow management scenarios has demonstrated that in watercourses with groundwater-dominated flow regimes that are similar to the River Dove, it may not be possible to allocate increased flows to the river during the spring and autumn critical ecological periods in combination with lower summer flows without a reduction in the overall volume of water that is available for abstraction.

Table 6.17: Change in water allocation – River Dove at Izaak Walton (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	HOF2 flows to river (m^3s^{-1})	HOF3 flows to river (m^3s^{-1})	HOF1 abstraction (Ml)	HOF2 abstraction (Ml)	HOF3 abstraction (Ml)
May – Jun (percentage change)	+0.186 (+35.6)	+0.261 (+50.1)	+0.299 (+57.4)	-955.65 (-46.9)	-1382.90 (-67.8)	-1585.07 (-77.7)
Jul – Sep (percentage change)	-0.040 (-8.3)	-0.079 (-16.7)	-0.054 (-11.3)	+314.12 (+57.9)	+629.88 (+116.1)	+431.03 (+79.4)
Oct – Nov (percentage change)	-0.011 (-2.2)	+0.079 (+15.4)	+0.140 (+27.3)	+66.14 (+3.4)	-378.00 (-19.2)	-724.94 (-36.8)
May – Nov (percentage change)	**+0.031 (+6.2)**	**+0.063 (+12.6)**	**+0.102 (+20.5)**	**-575.38 (-12.6)**	**-1131.02 (-24.8)**	**-1878.98 (-41.3)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.521 m^3s^{-1}/2039.74 Ml; Jul-Sep (summer): 0.476 m^3s^{-1}/542.59 Ml; Oct-Nov (autumn): 0.513 m^3s^{-1}/1971.51 Ml

The results in Table 6.18 illustrate that all of the alternative flow management scenarios allocated higher flows to the River Sow during the spring and autumn critical ecological periods in combination with lower summer flows. The adoption of HOF 1 would have resulted in a small decrease in the overall allocation of flows to the river and a small corresponding increase in the volume of water available for abstraction.

Table 6.18: Change in water allocation – River Sow at Great Bridgford (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	HOF2 flows to river (m^3s^{-1})	HOF3 flows to river (m^3s^{-1})	HOF1 abstraction (Ml)	HOF2 abstraction (Ml)	HOF3 abstraction (Ml)
May – Jun (percentage change)	+0.379 (+16.8)	+0.092 (+28.3)	+0.120 (+36.8)	-273.65 (-34.9)	-485.94 (-62.0)	-633.20 (-80.7)
Jul – Sep (percentage change)	-0.045 (-15.6)	-0.071 (-24.6)	-0.039 (-13.5)	+357.74 (+137.0)	+565.01 (+216.4)	+310.31 (+118.9)
Oct – Nov (percentage change)	+0.012 (+3.8)	+0.050 (+16.5)	+0.070 (+23.1)	-58.49 (-7.5)	-258.12 (-32.9)	-362.51 (-46.2)
May – Nov (percentage change)	**-0.001 (-0.4)**	**+0.010 (+3.3)**	**+0.037 (+12.3)**	**+25.60 (+1.4)**	**-179.05 (-9.8)**	**-685.40 (-37.5)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.325 m^3s^{-1}/784.36 Ml; Jul-Sep (summer): 0.289 m^3s^{-1}/261.06 Ml; Oct-Nov (autumn): 0.302 m^3s^{-1}/784.66 Ml

The adoption of HOFs 2 and 3 would, however, result in a 9.8 and 37.5 per cent decrease respectively in the volume of water available for abstraction during the May to

November regulation period. From a water supply perspective it is extremely unlikely that such reductions in the volume of water available for abstraction would be acceptable. The assessment of the application of the three alternative flow management scenarios has demonstrated that in watercourses with similar flow regimes to the River Sow, allocating increased flows to the river during the spring and autumn critical ecological periods and lower summer flows without a corresponding reduction in the volume of water that is available for abstraction may be possible using HOF 1, the month Q_{95}.

The assessment of the change in water allocation that would have resulted from the application of three alternative flow management scenarios demonstrated that in five watercourses with natural and semi-natural flow regimes it was possible to allocate higher flows to the river to offer better environmental protection during the spring and autumn. However, in the majority of cases, the allocation of increased spring and autumn flows led to a reduction in the overall volume of water available for abstraction. The assessments have demonstrated that supporting flows during the critical spring and autumn ecological periods while sustaining current levels of abstractions would not be possible without risking degradation of the rivers during summer through the increase in frequency and duration of extreme low-flow conditions.

The next section explores the application of a range of flow management scenarios in five contrasting watercourses with flow regimes that have been modified by a range of artificial influences.

6.5.2 Assessment of the surplus/deficit in monthly daily mean flows resulting from the application of the current and alternative environmental flow approaches – modified watercourses

The classification of flow regimes based on the naturalised and gauged flow statistics summarised in Table 6.2 on page 187 identified five watercourses; the Rivers Bedford Ouse, Derwent, Trent, Hiz and Tame as having modified flow regimes. The final section considers a range of potential alternative flow management approaches to the annual Q_{95} for determining *e-flows* in watercourses with modified flow regimes. Previous assessments have demonstrated a wide variety of low-flow responses in terms of flow magnitude, timing and duration across both the River Trent and the River Great Ouse catchments, therefore, the study sites were considered on a case-by-case basis.

The methodology used to calculate the change in water allocation in watercourses with natural and semi-natural flow regimes was used to identify the impact that adoption of alternative flow management scenarios would have had on monthly daily mean flows during the four driest years (Table 6.10) in the 25-year study period. Detailed monthly and seasonal results for the final five study sites are provided in Appendices 6.9a to 6.9e and Appendices 6.10a to 6.10e respectively.

The four alternative flow management scenarios that were used to evaluate the watercourses with modified flow regimes are summarised in Table 6.19. The annual Q_{95} formed the baseline for all assessments of the change in water allocation, information on the allocation of flows to the river and water for abstraction is provided.

Table 6.19: Flow management scenarios used in the assessments of the application of alternative hydrological approaches to setting *e-flows* in rivers with modified flow regimes

Flow Management Scenario	**Spring**		**Summer**			**Autumn**	
	May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Gauged Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}	Annual Q_{95}
Gauged Month Q_{95}	May Q_{95}	Jun Q_{95}	Jul Q_{95}	Aug Q_{95}	Sep Q_{95}	Oct Q_{95}	Nov Q_{95}
Gauged Month Q_{90} and Gauged Month Q_{97}	May Q_{90}	Jun Q_{90}	Jul Q_{97}	Aug Q_{97}	Sep Q_{97}	Oct Q_{90}	Nov Q_{90}
Naturalised[1] Month QN_{95}	May QN_{95}	Jun QN_{95}	Jul QN_{95}	Aug QN_{95}	Sep QN_{95}	Oct QN_{95}	Nov QN_{95}
Naturalised[1] Month QN_{90} and Naturalised Month QN_{97}	May QN_{90}	Jun QN_{90}	Jul QN_{97}	Aug QN_{97}	Sep QN_{97}	Oct QN_{90}	Nov QN_{90}

[1] Naturalised (QN) flow estimates were obtained from Low Flows Enterprise. These estimates are described as ‘natural’ estimates by (Wallingford HydroSolutions, 2010) as they do not include the impact of artificial influences for example abstractions and discharges. Throughout this Chapter, however, flows obtained using Low Flows Enterprise are described as ‘naturalised’ flows as they are estimated values.

In Tables 6.20 to 6.24 HOF 1 is the gauged month Q_{95} and HOF 2 is a combination of the gauged month Q_{90} during the critical spring (May and June) and autumn (October and November) ecological periods and the gauged month Q_{97} during the summer (July to September) period. In order to quantify the degree of flow modification and in order to investigate the utility of flow management scenarios that use naturalised flow percentiles to protect flows in watercourses with modified flow regimes, two additional flow management scenarios were explored. In Tables 6.20 - 6.24 HOF 3 is the naturalised month Q_{95} and HOF 4 is the naturalised month Q_{90} during the critical spring and autumn ecological periods, and the naturalised month Q_{97} during the summer period. All naturalised flow percentiles were estimated using Low Flows Enterprise.

The results relating to watercourses that have flows that are augmented during low-flow and drought periods by river support schemes that support abstractions for public water supply (River Hiz) and by continuous effluent discharges (Rivers Trent and Tame) are considered first. The Environment Agency operates the River Hiz Support Scheme in conjunction with Veolia Water Central whereby groundwater may be pumped into the Rivers Hiz and Oughton during low flows to support abstraction for public water supply. In addition augmentation by effluent discharges is known to influence the diurnal flow pattern of the River Hiz (Marsh and Hannaford, 2008).

The results in Table 6.20 demonstrate that only HOF 2 is capable of allocating higher spring and autumn and lower summer flows to the River Hiz and also a greater overall volume of water for abstraction during the May to November regulation period.

Table 6.20: Change in water allocation – River Hiz at Arlesey (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	**HOF2 flows to river (m^3s^{-1})**	**HOF3 flows to river (m^3s^{-1})**	**HOF4 flows to river (m^3s^{-1})**	**HOF1 Abs (Ml)**	**HOF2 Abs (Ml)**	**HOF3 Abs (Ml)**	**HOF4 Abs (Ml)**
May – Jun (% age change)	+0.013 (+3.8)	+0.049 (+14.9)	-0.090 (-27.6)	-0.047 (-14.3)	-66.29 (-13.8)	-257.71 (-53.5)	+475.05 (+98.6)	+246.70 (+51.2)
Jul – Sep (% age change)	-0.023 (-7.3)	-0.044 (-14.1)	-0.099 (-31.4)	-0.120 (-38.0)	+181.41 (+87.6)	+352.81 (+170.4)	+788.57 (+380.8)	+955.41 (+461.4)
Oct – Nov (% age change)	-0.022 (-6.9)	+0.006 (+2.0)	-0.068 (-21.5)	-0.056 (-17.8)	+124.61 (+17.7)	-34.13 (-4.8)	+360.09 (+51.1)	+297.02 (+42.2)
May – Nov (% age change)	**-0.013 (-3.9)**	**-0.003 (-1.0)**	**-0.088 (-27.5)**	**-0.081 (-25.3)**	**+239.73 (+17.2)**	**+60.96 (+4.4)**	**+1623.71 (+116.6)**	**+1499.12 (+107.6)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.327 m^3s^{-1}/481.64 Ml; Jul-Sep (summer): 0.316 m^3s^{-1}/207.06 Ml; Oct-Nov (autumn): 0.317 m^3s^{-1}/704.08 Ml

The adoption of HOF 2 results in the optimal allocation of water within the River Hiz allocating 14.9 and 2.0 per cent higher flows to the river during the spring and autumn critical ecological periods respectively, and a 13.9 per cent reduction in flows during the summer period. HOF 2 would allocate 492.6 per cent more water for abstraction from the river during the summer period, and 4.4 per cent more water for abstraction overall during the May to November inclusive regulation period. Unfortunately, although the adoption of HOF 2 would result in the optimal allocation of flows to the River Hiz during the critical ecological periods, the 13.9 per cent reduction in summer flows is likely to be considered unacceptable in a river that already receives flow support during low-flow periods.

Finally the change in water allocation resulting from the adoption of the two alternative flow management scenarios that use naturalised flow percentiles to allocate potential *e-flows* are considered. The adoption of HOF 3 would result in a reduction of flows to the River Hiz ranging between 21.5 per cent during the autumn critical ecological period and 31.4 per cent during the summer, and a corresponding increase in the volume of water available for abstraction from the river of 51.1 and 380.8 per cent respectively. The adoption of HOF 4 would result in a reduction in flows to the River Hiz ranging between 14.3 per cent during the spring critical ecological period and 38.0 per cent during the summer, and a corresponding increase in the volume of water available for abstraction of 51.2 and 461.4 per cent.

The results in Table 6.20 have highlighted some of the issues surrounding the selection of appropriate *e-flows* in watercourses with modified flow regimes. In addition, the results relating to the application of HOF 3 and HOF 4 illustrate the degree that flows within the River Hiz have been modified, and highlight the futility of selecting hydrological *e-flow* approaches based on naturalised flows to protect low flows in watercourses with heavily modified flow regimes.

The issues surrounding the determination of *e-flows* in watercourses with heavily modified flow regimes are demonstrated further in Table 6.21 which summarises results for the River Trent at North Muskham, a watercourse with a discharge rich flow regime (Table 6.2).

Table 6.21: Change in water allocation – River Trent at North Muskham (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	**HOF2 flows to river (m^3s^{-1})**	**HOF3 flows to river (m^3s^{-1})**	**HOF4 flows to river (m^3s^{-1})**	**HOF1 Abs (Ml)**	**HOF2 Abs (Ml)**	**HOF3 Abs (Ml)**	**HOF4 Abs (Ml)**
May – Jun (% age change)	+2.966 (+10.8)	+4.712 (+17.2)	-10.629 (-38.9)	-8.529 (-31.2)	-15804.4 (-25.9)	-25012.0 (-40.9)	+55829.0 (+91.3)	+44737.0 (+73.2)
Jul – Sep (% age change)	-2.571 (-9.5)	-3.348 (-12.3)	-16.303 (-61.1)	-17.721 (-65.2)	+20461.6 (+72.9)	+26640.9 (+94.9)	+132034 (+470.3)	+140946 (+502.0)
Oct – Nov (% age change)	+1.376 (+5.0)	+4.491 (+16.4)	-8.414 (-30.8)	-5.409 (-19.8)	-6983.8 (-9.2)	-23313.2 (-30.6)	+44661.8 (+58.6)	+28924.0 (+37.9)
May – Nov (% age change)	**+0.139 (+0.5)**	**+1.195 (+4.4)**	**-12.556 (-46.0)**	**-11.577 (-42.4)**	**-2326.6 (-1.4)**	**-21684.3 (-13.1)**	**+232525 (+140.5)**	**+214607 (+129.7)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 27.339 m^3s^{-1}/61120.01 Ml; Jul-Sep (summer): 27.195 m^3s^{-1}/28077.28 Ml; Oct-Nov (autumn): 27.339 m^3s^{-1}/76272.22 Ml

The results in Table 6.21 illustrate that both HOF 1 and HOF 2 are capable of allocating higher flows to the River Trent during the spring and autumn critical ecological periods, and lower flows to the river during the summer. Unfortunately, both scenarios resulted in a reduction in the overall volume of water available for abstraction during the regulation period. The results in Table 6.2 illustrated that low flows within the River Trent during the study period were approximately double they would have been in the absence of artificial influences, therefore, from a management perspective, a reduction in the volume of water available for abstraction of between 1.9 and 15.0 per cent from the discharge-rich River Trent may be acceptable.

From Table 6.21 the adoption of HOF 2 would have resulted in the optimal allocation of water within the River Trent throughout the regulation period. HOF 2 allocated 17.2 per cent more flows to the River Trent during the spring, 16.4 per cent more flows to the river during the autumn, and 12.3 per cent lower flows to the river during the summer. In addition the adoption of HOF 2 would result in the allocation of 94.9 per cent more water for abstraction during the summer period, and would only result in a 13.1 per cent reduction in the volume of water available for abstraction.

Finally, the change in water allocation that the adoption of the flow management scenarios that use naturalised flows to allocate potential *e-flows* for the River Trent is considered. The adoption of HOF 3 would result in a reduction of flows to the River Trent ranging between 30.8 per cent during the critical autumn ecological period and 61.1 per cent during the summer period and a corresponding increase in the volume of water available for abstraction of 58.6 and 470.3 per cent respectively. The adoption of HOF 4 would result in a reduction of flows to the River Trent of between 19.8 per cent during the critical autumn ecological period and 65.2 per cent during the summer period and a corresponding increase in the volume of water available for abstraction of 37.9 and 502.0 per cent respectively.

Table 6.22 summarises the change in the allocation of water that the adoption of the alternative flow management scenarios would have resulted in within the River Tame at Lea Marston Lakes, a watercourse with discharge rich flow regime. During the summer, 80 per cent of the flow of the River Tame at this location may be made up of treated sewage effluent (Petts *et al*., 2002) and the flow statistics summarised in Table 6.2 indicate that recently low flows within the River Tame at this location are more than six times higher than they would have been in the absence of artificial influences. The long-term discharge of effluent from Minworth WTW into the River Tame has resulted in the substantial augmentation of low flows within the watercourse, the creation of anti-drought conditions, and the loss of flow seasonality.

Table 6.22: Change in water allocation – River Tame at Lea Marston Lakes (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^{3}s^{-1})	**HOF2 flows to river (m^{3}s^{-1})**	**HOF3 flows to river (m^{3}s^{-1})**	**HOF4 flows to river (m^{3}s^{-1})**	**HOF1 Abs (Ml)**	**HOF2 Abs (Ml)**	**HOF3 Abs (Ml)**	**HOF4 Abs (Ml)**
May – Jun (% age change)	+0.207 (+2.8)	+0.587 (+7.9)	-6.007 (-80.6)	-5.808 (-77.9)	-1088.4 (-6.4)	-3097.2 (-18.2)	+31637.7 (+186.3)	+30590.3 (+180.2)
Jul – Sep (% age change)	-0.360 (-4.8)	-0.510 (-6.8)	-6.588 (-88.4)	-6.679 (-89.6)	+2856.9 (+15.2)	+4045.8 (+21.5)	+52373.6 (+278.6)	+53093.0 (+282.4)
Oct – Nov (% age change)	+0.127 (+1.7)	+0.492 (+6.6)	-5.978 (-80.2)	-5.704 (-76.5)	-643.42 (-2.4)	-2562.4 (-9.5)	+31523.1 (+117.4)	+30091.0 (+112.1)
May – Nov (% age change)	**-0.059 (-0.8)**	**+0.090 (+1.2)**	**-6.248 (-83.8)**	**-6.152 (-82.5)**	**+1125.1 (+1.8)**	**-1613.8 (-2.6)**	**+115534 (+184.5)**	**+113774 (+181.7)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 7.453 m^{3}s^{-1}/16979.16 Ml; Jul-Sep (summer): 7.453 m^{3}s^{-1}/18802.05 Ml; Oct-Nov (autumn): 7.453 m^{3}s^{-1}/26849.34 Ml

The results in Table 6.22 illustrate that although two of the alternative flow management scenarios, HOF 1 and HOF 2 are capable of allocating higher spring and autumn and lower summer flows to the River Tame, only HOF 1 allocates more water for abstraction during the regulation period. Although the adoption of HOF 2 would result in a reduction of 2.6 per cent in the volume of water available for abstraction during the May to November inclusive regulation period, flows within the River Tame are more than six times higher than they would have been naturally. From a management perspective it is probable that a reduction in the volume of water available for abstraction from the River Tame of 2.6 per cent would be acceptable.

The setting of *e-flows* on such heavily modified rivers with a long history of flow augmentation by effluent discharge is required to guide future decisions on changing volumes of discharges. On the River Tame, the adoption of HOF 3 would result in a reduction of flows to the river ranging between 80.2 per cent in the autumn and 88.4 per cent in the summer and a corresponding increase in the volume of water available for abstraction of 117.4 and 278.6 per cent respectively. The adoption of HOF 4 would result in a reduction of flows to the River Tame of between 76.5 per cent in the autumn and 89.6 per cent in the summer, and a corresponding increase in the volume of water available for abstraction of 112.1 and 282.4 per cent respectively.

The results of the application of hydrologically based flow management scenarios that utilise naturalised flow percentiles to determine *e-flows* within watercourses with discharge rich flow regimes has highlighted two important questions: (1) should *e-flows* aim to protect naturalised or gauged flows within watercourses with discharge rich flow regimes?, and (2) is it possible to adapt the natural flow regime concept to restore flow variability to watercourses with discharge rich flow regimes? Further consideration will be given to these important questions in Chapter 7.

The results in Table 6.23 demonstrate that both HOF 1 and HOF 2 are capable of allocating higher flows during the spring and autumn critical ecological periods when the ecological demand for water is higher, and lower summer flows to the River Bedford Ouse when the ecological demand for water is lower. The application of HOFs1 and 2 would, however, result in a 7.2 and 15.5 per cent reduction respectively in the overall volume of water available for abstraction. Although the application of both HOF 1 and HOF 2 would have resulted in an increase in the volume of water available to abstract from the river during the summer, it is unlikely from a management perspective that the reduction in the overall volume of water available to abstract from the river would be acceptable.

Table 6.23: Change in water allocation – River Bedford Ouse at Bedford (average of the four driest years in the 25-year study period)

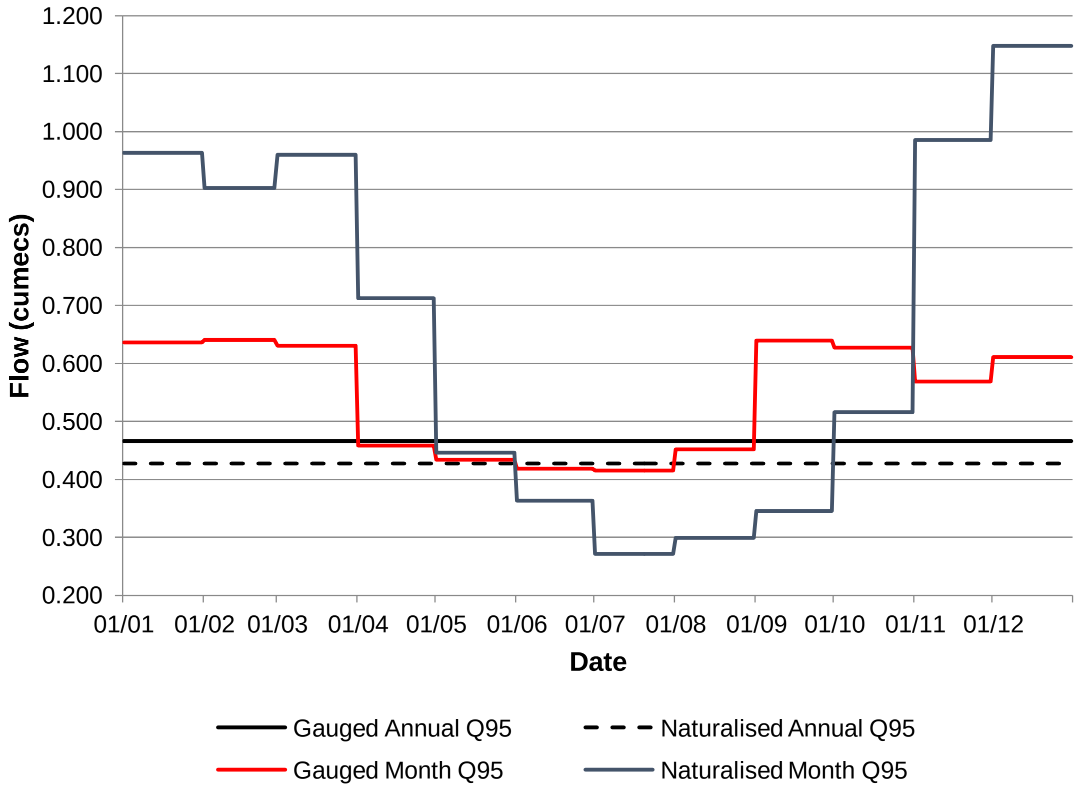
	HOF1 flows to river (m^3s^{-1})	**HOF2 flows to river (m^3s^{-1})**	**HOF3 flows to river (m^3s^{-1})**	**HOF4 flows to river (m^3s^{-1})**	**HOF1 Abs (Ml)**	**HOF2 Abs (Ml)**	**HOF3 Abs (Ml)**	**HOF4 Abs (Ml)**
May – Jun (% age change)	+0.643 (+28.4)	+0.913 (+40.4)	-0.815 (-36.0)	-0.570 (-25.2)	-3420.7 (-36.9)	-5414.8 (-58.4)	+4282.4 (+46.2)	+2986.9 (+32.2)
Jul – Sep (% age change)	-0.301 (-14.6)	-0.499 (-24.2)	-1.138 (-55.2)	-1.205 (-58.4)	+2385.5 (+50.1)	+3951.8 (+83.0)	+9039.6 (+189.8)	+9573.9 (+201.0)
Oct – Nov (% age change)	+0.163 (+7.2)	+0.495 (+21.9)	-1.132 (-50.0)	-0.978 (-43.2)	-839.64 (-7.0)	-2574.34 (-21.6)	+5976.02 (+50.1)	+5167.49 (+43.3)
May – Nov (% age change)	**+0.101 (+4.7)**	**+0.189 (+8.7)**	**-1.044 (-48.0)**	**-0.959 (-44.0)**	**-1874.8 (-7.2)**	**-4037.3 (-15.5)**	**+19298.0 (+74.3)**	**+17728.2 (+68.3)**

Allocation of water using the annual Q_{95}*: May-Jun (spring): 2.262* m^3s^{-1}*/9265.90 Ml; Jul-Sep (summer): 2.063* m^3s^{-1}*/ 4763.86 Ml; Oct-Nov (autumn): 2.262* m^3s^{-1}*/ 11935.97 Ml*

Gauged low flows within the River Bedford Ouse are today double they would have been naturally in the absence of artificial influences. The results in Table 6.23 that summarise the change in water allocation resulting from the application of HOFs 3 and 4 provide a further indication of the degree of flow modification at this location. The adoption of HOF 3 would result in a reduction of flows to the river ranging from 36.0 per cent during the critical spring ecological period and 55.2 per cent during the summer period. The corresponding increase in the volume of water available for abstraction during the spring and summer would be 46.2 and 189.8 per cent respectively. The adoption of HOF 4 would result in a reduction of flows to the river of between 25.2 per cent during the critical spring ecological period and 58.4 per cent during the summer and an increase in the volume of water available for abstraction from the river of 32.2 and 201.0 per cent respectively.

The final study site, the highly regulated River Derwent is located immediately downstream of a series of regulating reservoirs built for public water supply. The reservoirs maintain low flows and control high flows, Figure 6.10 provides an indication of the degree to which low flows within the River Derwent at Yorkshire Bridge have been regulated.

Figure 6.10 Schematic illustrating the variability in naturalised and gauged month Q_{95} flows – River Derwent at Yorkshire Bridge



The determination of *e-flows* in watercourses located immediately downstream of regulating reservoirs presents a different set of challenges. Although, the aim in watercourses with highly regulated flow regimes is to restore natural flow variability, regulating reservoirs make releases to support downstream abstraction and have to ensure that prescribed flows are maintained in the watercourse downstream of the reservoir.

The results summarised in Table 6.24 illustrate some of the issues surrounding the determination of *e-flows* and the restoration of natural flow variability in regulated watercourses. The flow management scenarios that employ monthly gauged flow percentiles (HOFs 1 and 2) as an alternative to the annual Q_{95} did not allocate higher flows to the River Derwent during the critical spring ecological period. In addition the adoption of HOF 1 and HOF 2 would result in a 9.9 and 13.0 per cent reduction respectively in the overall volume of water available for abstraction from the river during the regulation period.

Table 6.24: Change in water allocation – River Derwent at Yorkshire Bridge (average of the four driest years in the 25-year study period)

	HOF1 flows to river (m^3s^{-1})	**HOF2 flows to river (m^3s^{-1})**	**HOF3 flows to river (m^3s^{-1})**	**HOF4 flows to river (m^3s^{-1})**	**HOF1 Abs (Ml)**	**HOF2 Abs (Ml)**	**HOF3 Abs (Ml)**	**HOF4 Abs (Ml)**
May – Jun (% age change)	-0.031 (-6.7)	-0.002 (-0.4)	-0.054 (-11.8)	+0.036 (+7.9)	+161.35 (+18.3)	+9.89 (+1.1)	+281.75 (+31.9)	-195.66 (-22.1)
Jul – Sep (% age change)	+0.041 (+9.0)	+0.030 (+6.6)	-0.155 (-33.7)	-0.193 (-41.8)	-317.18 (-14.9)	-228.81 (-10.7)	+1236.25 (+58.0)	+1533.12 (+72.0)
Oct – Nov (% age change)	+0.126 (+26.9)	+0.163 (+34.9)	+0.189 (+40.5)	+0.360 (+77.0)	-664.41 (-12.6)	-861.93 (-16.3)	-985.30 (-18.7)	-1882.18 (-35.6)
May – Nov (% age change)	**+0.045 (+9.7)**	**+0.059 (+12.8)**	**-0.028 (-6.0)**	**+0.031 (+6.6)**	**-820.24 (-9.9)**	**-1080.85 (-13.0)**	**+532.69 (+6.4)**	**-544.71 (-6.6)**

Allocation of water using the annual Q_{95}: May-Jun (spring): 0.459 m^3s^{-1}/883.90 Ml; Jul-Sep (summer): 0.460 m^3s^{-1}/ 2130.80 Ml; Oct-Nov (autumn): 0.467 m^3s^{-1}/5281.55 Ml

HOF 4, a combination of the naturalised month Q_{90} during the spring and autumn critical ecological periods, and the naturalised month Q_{97} during the summer is capable of allocating higher spring and autumn and lower summer flows to the River Derwent. Unfortunately from a water resources management perspective the corresponding 35.6 per cent reduction in the volume of water available for abstraction during October and November would be unacceptable. The results in Table 6.24 demonstrate that the alternative flow management scenarios investigated in this Chapter are not capable of restoring natural flow variability to the highly regulated River Derwent.

6.6 DISCUSSION

This Chapter aimed to explore the utility of a range of hydrological *e-flow* approaches to managing low flows and ecological drought across two contrasting catchments; the heavily developed Trent catchment and the highly regulated lowland Great Ouse catchment. Initial assessments aimed to explore the transferability of Baxter's (1961) approach to watercourses located across the Trent and Great Ouse catchments. Baxter (1961) advocated the use of the long-term ADF as the basis of *e-flow* determination. Assessments explored the utility of hydrologic metrics calculated from proportions of the long-term ADF, identifying a range of low-flow responses across both the River Trent and the River Great Ouse catchments in terms of low-flow timing and duration. The unsuitability of hydrologic metrics calculated from proportions of the long-term ADF in discharge-rich watercourses and in watercourses with artificially augmented low flows has been clearly demonstrated. Indeed, the assessments in this Chapter appear to indicate that Baxter's approach may be restricted by the variety of flow regime types studied and may not be transferrable outside of surface-runoff dominated watercourses.

Fifteen years later Tennant (1976) also advocated the use of fixed percentages of the long-term ADF to determine *e-flows* in the United States; however, in England the preferred *e-flow* approach has been to employ the annual $Q_{95.}$ This is the first study to explore the utility of Baxter's (1961) approach to determining *e-flows* for watercourses in England. Several authors have, however, reviewed the transferability of the Tennant (1976) approach to England. For example Acreman *et al*. (2005) stated that although a Tennant type methodology could provide a model for the development of guidelines for use in England, the methodology is underpinned by extensive fieldwork in the regions it was developed for.

Baxter (1961) also advocated the use of seasonally variable *e-flows* taking into account the functional requirements of the different life stages of riverine ecology. This Chapter explored the premise that the adoption of a more complex approach based on Baxter's (1961) principles would save water benefitting both riverine ecology and abstractors in a future of increasing hydrological uncertainty. Using average daily flows recorded during selected low-flow years, assessments determined whether it is possible to allocate higher *e-flows* during the spring and autumn critical ecological periods and to still make more water available for abstraction by reducing the *e-flow* during the summer period.

Flow assessments demonstrated that the adoption of several seasonally variable *e-flow* approaches enabled the successful reallocation of flows to the majority of the watercourses studied, with higher flows allocated during the critical spring (May and June) and autumn (October and November) ecological periods, and lower flows during the summer (July to September) period when the majority of riverine biota are inactive. Assessments demonstrated that although the reallocation of flows to support the riverine ecology was generally successful, the reductions in summer *e-flows* were insufficient to counteract the increases in the allocation of flows required to allocate higher *e-flows* during the critical spring and autumn ecological periods. With a few exceptions, the adoption of the seasonally variable *e-flow* approaches explored here resulted in a reduction in the overall volume of water available for abstraction.

Previous, comparable studies have also identified that the adoption of more complex, seasonally variable *e-flow* approaches leads to a reduction in the overall volume of water available for abstraction. Kiernan *et al.* (2012) examined the responses of fishes to the establishment of a new flow regime designed to mimic the seasonal timing, and natural increases and decreases in river flow in a regulated watercourse located in the United States. The study concluded that the restoration of native fishes was achieved by manipulating river flows at biologically important times of the year, and only required a small increase in the total volume of water delivered downstream (i.e. not diverted) during most years (Kiernan *et al*., 2012).

Wilby *et al*. (2011) used the River Itchen in southern England as a case study to describe a framework for evaluating the sensitivity of low flows to different abstraction licensing configurations, under both historical climate variability and expected climate change. The paper also assessed the circumstances under which a “smarter” approach to abstraction licensing could better meet the needs of the environment and water users than current approaches (Wilby *et al*., 2011). A rainfall-runoff model was used to explore environmentally sensitive abstraction license limits and conditions, with the objective of providing protection to the environment where and when it most needed it, while minimising disruption to water supply (Wilby *et al*., 2011). The underpinning concept was that although permitted abstraction quantities may need to be limited to ensure that residual flows did not fall below seasonally varying *e-flow* targets, abstraction quantities could, however, increase as river flows increased (Wilby *et al*., 2011). Wilby *et al*. (2011) concluded that although smart licensing approaches clearly have the potential to deliver significant environmental gains at apparently little cost to long term average abstractable quantities, these gains may carry the cost of a reduction in abstractable quantities during dry and drought years.

This Chapter also aimed to determine whether the same flow metrics could be used to derive *e-flows* to manage low flows and ecological drought in watercourses with contrasting flow regimes. Assessments demonstrated that no single flow metric was capable of managing low flows and ecological drought throughout the May to November inclusive regulation period and across all of the contrasting watercourses. Indeed, results demonstrated that in the vast majority of cases, smarter solutions will require *e-flow* determination at the seasonal or monthly scale, and also at the local, sub-catchment scale.

Since the introduction of the ELOHA framework and partly in response to the limited availability of long-term hydrological and ecological datasets, the focus of recent international research appears to have shifted towards flow regime classification approaches to support the determination of regional *e-flows*. However, in the majority of catchments in England, river flow data is readily available, and following the introduction of the CAMS process, ecological monitoring and assessment has increased. The widespread availability of data should, therefore, enable the determination of *e-flows* at the local, sub-catchment scale rather than at the regional scale. Indeed, international experience has revealed that the complexity of water management at a national level lends itself to common principles but ultimately that local solutions are required at a catchment level to manage such challenges (Lumbroso *et al*. 2014).

6.7 CONCLUSIONS

This study has provided evidence of the potential limitations of more complex seasonally variable hydrological *e-flow* approaches in managing low flows and ecological drought at the local sub-catchment scale. Although the smarter *e-flow* approaches investigated in this Chapter were capable of allocating flows to support the seasonally varying requirements of the riverine ecology, the corresponding reduction in water availability suggests that it may not be possible to develop smarter hydrological *e-flow* approaches that do not reduce the overall volume of water available for abstraction.

Assessments highlighted issues surrounding the successful allocation of higher *e-flows* during the autumn ecological period. It was seemingly not possible to trade the allocation of lower summer *e-flows* for higher *e-flows* during October and November. November is a key recharge month for reservoirs following drought periods, therefore, provision may have to be made for watercourses with groundwater dominated flow regimes where extreme, rare low flows may be experienced during the autumn. To date the majority of research has focused on the summer period; the results of the assessments indicate that there is a clear need to move the focus of future research to the spring and autumn periods.

Although this study has highlighted some limitations in the utility of seasonally varying hydrological *e-flow* approaches based on Baxter's (1961) principles, based on current knowledge, hydrologically based methods are as good as any other *e-flow* approaches (Caissie *et al*., 2015). Until some of the research gaps identified by Shenton *et al*. (2012) are addressed, the case for the use of hydrological *e-flow* methodologies is compelling. Indeed, in England there is little to be gained from the use of more complex and data intensive *e-flow* methodologies.

CHAPTER 7: THE FUTURE FOR ENVIRONMENTAL FLOWS IN ENGLAND

7.1 INTRODUCTION

Research on *e-flows* has expanded considerably over the past three decades, often through case studies from many different geographical settings. The focus has been on approaches to determine an annual minimum flow to protect riverine ecosystems, or most often a single target species, with some studies advancing approaches that incorporate seasonal flows for specific environmental functions. This thesis has made two primary contributions to the *e-flows* debate: exploring the history of flow management in England and its impact on current practice, and elaborating the concept of ‘ecological drought’ as a basis for managing flows in the future. It has also highlighted the under-researched area of discharge-rich rivers within highly modified catchments, where low flows are dominated by (treated) effluent discharges.

7.2 THE CURRENT SITUATION

In England anthropogenic activities have modified the majority of watercourses, with some impacts dating back more than 1000 years (Gurnell and Petts, 1999). Today, the flow regimes of these rivers are modified by current and historic anthropogenic activities. There are approximately 21,500 abstraction licences in England and Wales of which only 17 per cent have restrictive conditions that prevent abstractions at low flows (Environment Agency, 2011). The current system for managing abstraction was introduced in the 1960s and was designed to manage competing human demands for water rather than to protect the environment (Department for Environment, Food and Rural Affairs, 2011). Concerns that many watercourses are being damaged by over abstraction, combined with uncertainties surrounding climate change and the increasing demand for water, have resulted in proposals to reform the abstraction regime.

This thesis has reviewed the development of flow protection policies in England (Chapter 3) from early rainfall based approaches up to the current CAMS process and its links to the WFD. Under the WFD, Member States are obliged to maintain or restore all surface waterbodies to GES by 2015. The exceptions to this are heavily modified waterbodies which must achieve GEP by 2015. The CAMS process is used to track, monitor, and licence water resource availability. Central to CAMS is the RAM framework which determines the water resource availability of catchments and WFD waterbodies (Klaar *et al*., 2014). Water availability is assessed using ‘naturalised’ flow as a reference condition, with natural flows derived from gauged flow time series data, or simulated using rainfall-runoff models.

The thesis has shown that the current approach to the determination and setting of *e-flows* in England is fundamentally inherited from the Water Resources Act 1963. Prior to the enactment of the 1963 Act there was limited control over abstraction from surface waters although compensation flows below dams were defined in the Acts that enabled each impoundment scheme. The 1963 Act required the River Authorities to set MAFs and since then all new abstraction licences have contained conditions to protect the environment where required (Petts, 1996; 2007). The 1963 Act also identified the need for routine hydrometric monitoring and the majority of gauging stations in England became operational in the mid to late 1960s. The 1963 Act was, however, not designed to protect the environment, and was constrained by the requirement to protect existing water users by the issuing of Licences of Right. Indeed, the emphasis on a single minimum flow for environmental protection and the issuing of Licences of Right with no regard to environmental need represent two major shortcomings of the 1963 Act.

In particular, this thesis identified and explored the impact of one person, George Baxter, an influential Scottish Water Engineer, who immediately before the introduction of the Water Resources Act 1963 proposed that from a fisheries standpoint, the practice of using a fixed rate minimum compensation flow had little to commend it. Baxter (1961; 1963) proposed the application of seasonally variable *e-flows* supplemented by freshets to support fish migration and for habitat management. He suggested that in many schemes the compensation flow could be varied not only to better suit the seasonal needs of the river and its ecology, but also to use less water than a single, fixed flow. Chapter 4 identified that Baxter's proposals had high immediate impact, but there was a failure to influence policy makers for a range of reasons, and some are still highly relevant today. The overwhelming pollution problems of the early 1960s, fear of agricultural drought, the legacy of the Licences of Right, and data limitations dominated the 1960s debates on *e-flows*.

The analysis of historical flow protection policies (Chapter 3) illustrated that an anthropocentric approach to water resources management led to policies that set minimum flows founded in fear of water shortage. Prior to the 1960s flows were not routinely monitored; limited flow data availability was a fundamental issue. In England, compensation flows have been set downstream of reservoirs by Acts of Parliament for over 100 years (Gustard *et al*., 1987). The first reservoir developments were in the Pennines and the quantity of compensation water was fixed as a proportion of the reliable yield during the three driest consecutive years (Sandeman, 1921). Such determinations were based on rainfall because early water engineers were constrained by the limited availability of river flow data. Debates in the 1920s and 1930s indicated that the engineers employed by water companies considered that rainfall-based approaches were not fit for purpose, and that it was preferable to base compensation water on the flow of the river to be impounded, even though such measures were often spot gaugings. The lack of river flow data and legislative constraints meant that rainfall-based approaches dominated until the 1960s. Following the 1963 Act further concerns grew about the accuracy of river gauging, particularly at low-flow rates on larger rivers (Rowntree, 1966). These concerns reinforced the reluctance to implement Baxter's proposals.

The 1963 Water Resources Act made general provision for controlling abstraction where necessary and introduced the MAF concept. Although in practice no formal MAFs were set (Petts *et al*., 1999), the less formal policy of using prescribed flows was adopted (Bradford, 1981). Consequently, the MAF concept has become embedded (Petts *et al*., 1999) in the control of abstraction licenses and in the management of water resources in England. However, the MAF lacked any formal ecological definition and practice has focussed on summer low flows, failing to recognise the critical importance of functional ecological flows, especially in spring and autumn.

7.3 THE ANATOMY OF ECOLOGICAL DROUGHT

The current status of rivers reflects their long term development within a catchment ecosystem. Rivers are systems with a history; their interpretation requires an understanding of time, as first highlighted by Schumm and Lichty (1965). Over geological timescales, the morphology of rivers contains evidence of their climatic history; over human timescales, short-term changes are seen as variations about an average state. From an ecological perspective, over evolutionary timescales biota adapt to their bio-climatic environment, manifest most clearly by the flow and temperature regimes, and to the physical habitats presented by different reaches along a river 'continuum'. Short term changes in communities and populations relate to the impact of disturbances caused by extreme events (floods and droughts) and the pathways of recovery from those disturbances. Often biological responses are complicated within individual river reaches by the pattern of short-term habitat changes that reflect morphological adjustments within the upstream drainage network and also within the reach immediately downstream. Such interactions were discussed for impounded rivers by Petts (1984). Ecological resilience, in part, reflects the variety of river segments that make up the drainage network within each river catchment and the passive downstream dispersal or active upstream dispersal of organisms following a disturbance. As demonstrated in this thesis for the Trent and Great Ouse catchments, it is exceptionally rare for all tributaries within a catchment to experience extreme events simultaneously. Furthermore, within affected reaches, refuge habitats may sustain populations to drive the recovery process.

This thesis introduced the concept of ‘ecological drought’ (Chapter 1), and postulated that as drought is an important driver of natural riverine ecosystems, a focus on system resilience, natural flow recession and regional scale variation in drought severity may offer benefits for both water resource management and ecological protection. The thesis also postulates that even in a heavily developed catchment like the Trent, unpredictable and prolonged droughts, extending into the autumn critical ecological period (October and November) or occurring during the spring critical ecological period (May and June) will have a greater impact on riverine ecology than a drought during the summer months (July to September inclusive), when the majority of riverine biota are adapted to extreme low-flow stress.

The examination of low-flow and drought characteristics across the heavily developed Trent catchment and the highly regulated, lowland Great Ouse catchment in Chapter 5 highlighted a wide variety of low-flow responses in terms of flow magnitude, timing and duration. Table 7.1 demonstrates the variability in the magnitude, duration and timing of four historical ecological drought events experienced by three watercourses with contrasting flow regimes.

Low flows in spring result from dry winters whereas low flows in autumn reflect a summer drought and delayed flow recovery and start of the hydrological year (e.g. River Manifold, 1989). In extreme cases, dry winters with limited groundwater recharge followed by a dry summer can produce severely low autumn flows, as in the case of the River Manifold’s 1996 event. In contrast, the 1997 River Bedford Ouse event was characterised by extreme low flows in the spring followed by a wet summer resulting in rapid flow recovery. Table 7.1 demonstrates the complexity in terms of flow magnitude, duration and timing, of the development of ecological drought. It also demonstrates the importance of not relying solely on the flow in April as a trigger flow for possible flow management scenarios, and suggests that where possible, flows must be continuously monitored.

Table 7.1: The development of historical ecological drought events within three watercourses with contrasting flow regimes

Year	Ratio April ADF: long-term April ADF	Flow in April	Drought Duration	Drought Type
River Dove - Izaak Walton (groundwater dominated)				
2011	0.47	Low	Average	Winter
1996	0.56	Low	Average	Winter
1991	0.85	Average	Long	Summer
1995	1.01	Average	Long	Summer
River Manifold - Ilam				
1996	0.45	Low	Average-Long	Winter/Summer
1989	1.80	High	Long	Summer
1991	0.73	Average	Long	Summer
1995	0.70	Average	Average	Summer
River Bedford Ouse - Bedford				
1990	0.43	Low	Average-Short	Winter
1997	0.24	Low	Average-Short	Winter
1995	0.58	Average	Average	Summer
1991	0.41	Low	Average-Long	Winter/Summer

In Chapter 5, the variability of low-flow responses between sub-catchment types was explored using a number of flow metrics; the annual Q_{95}, 20% ADF, and a range of MAM flows. Although the most severe indicator, the minimum MAM20 flow was found to be capable of determining the spatial impact of the most severe droughts experienced across the Trent and Great Ouse catchments, this particular flow metric is too severe/extreme, however, for informing the setting of *e-flows*. The minimum MAM50 flow metric was also discounted at this stage, as longer duration MAM flows are likely to include (perhaps an extended) period of flow recovery. Assessments in Chapter 5 demonstrated that the average MAM7 flow is effective at determining the variability in the timing of low flows and droughts across the contrasting sub-catchments located within the Trent and Great Ouse catchments.

The hydrological indicators of ecological drought demonstrated that across both the Trent and the Great Ouse catchments, extreme low flows are rarely observed throughout a drainage network during a single drought event, and that the natural resilience of riverine ecosystems may be related to regional scale variation in drought severity. The most severe hydrological indicator explored the minimum MAM20 flow, illustrated that severe drought rarely impacted on more than one third of the study sites in the Trent catchment in any one year, and even fewer study sites in the Great Ouse catchment. In addition, the timing of extreme low flows was found to vary between the sub-catchments, with the severest ecological droughts occurring in October and even early November on watercourses with groundwater-dominated flow regimes.

Although in some watercourses, natural low-flow periods have been eliminated, flow assessments and statistical analyses demonstrated that flows across the Trent and Great Ouse catchments during periods of below average annual rainfall are heterogeneous varying both spatially and temporally. Previous, comparable studies have also identified variability in flows during low-flow and drought periods. Caruso (2001, 2002) investigated temporal and spatial patterns of extreme low flows across 12 locations in Otago, New Zealand and identified considerable variation in low-flow regimes at a sub-catchment scale.

Following an analysis of the low-flow characteristics of South African rivers (Smakhtin *et al*., 1995) concluded that low-flow characteristics generally displayed a very high degree of spatial variability across South Africa. More importantly, Smakhtin *et al*. (1995) concluded that even within the same region, gauging stations with similar catchment areas and lengths of record may differ greatly, implying that low-flow characteristics are very dependent on local physiographic factors, and that the problems of low flows should, therefore, preferably be addressed at the catchment scale.

Studies have also explored the spatial coherence of low-flow and drought events (Rahiz and New, 2012) and in trends in runoff and low flows (Hannaford and Marsh, 2006) across the United Kingdom. Young *et al.* (2000) identified that within the Thames catchment upstream of Teddington Lock (catchment area 9948 km^2) that the Q_{95} flows measured at sub-catchment gauging stations do not all occur at the same point in time, with permeable chalk catchments experiencing low flows later in the year than the impermeable clay catchments. Comparable results were recorded within two watercourses with essentially natural flow regimes located within the Trent catchment, with the groundwater-dominated River Dove experiencing later low flows than the surface-runoff dominated Rothley Brook.

7.4 ENVIRONMENTAL FLOW ASSESSMENT

From a flow management perspective, assessments indicated that due to the wide variety of low-flow responses across both the Trent and the Great Ouse catchments, smarter solutions may require *e-flow* determination at the local, sub-catchment scale. Recently much research has focused on the development of regional *e-flow* approaches (e.g. Francisco *et al*., 2014; Mackay *et al*., 2014; Overton *et al*; 2014; Tavassoli *et al*., 2014); however, this finding suggests that the determination of *e-flows* at the regional scale may not provide adequate flow protection during the critical spring and autumn ecological periods and may also unnecessarily limit water abstractions in summer. Experience has demonstrated the importance of using local flow restrictions. Many newer licences have been tied to a downstream ‘control’ gauging station (e.g. the River Trent at North Muskham) and the timing of Q_{95} flows within the River Trent varied from the timing of low flows, for example within the Rivers Dove, Sow and Penk, and other watercourses located some distance upstream. Assessments also suggested that no single hydrological indicator of ecological drought would be suitable for all river types**.**

7.4.1 Metrics for environmental flow assessment

Most surface water licensing policies in England are based on the annual Q_{95} flow. Although exactly when the practice of using the Q_{95} flow as a prescribed/*e-flow* was initially introduced is uncertain, it is unlikely that the Q_{95} flow would have been expected to be so widely adopted. Across the Trent catchment, the majority of the Q_{95} prescribed flows in use today were set in the late 1970s and have not been updated. First-hand experience of determining when flow restrictions in the Upper Trent catchment should be enforced during low flows and droughts highlighted the importance of ensuring that Q_{95} flows and indeed all *e-flows* are updated on a regular cycle. For example, flows within the River Anker never fell below the Q_{95} flow; therefore, abstraction was never restricted. Investigations suggested that the volume of effluent being discharged into the River Anker had increased from the late 1970s; therefore, the Q_{95} flow had also increased and was now higher than the original Q_{95} prescribed flow.

7.4.2 The annual Q_{95} flow

Historically the annual Q_{95} flow was adequate to protect the majority of watercourses because only a small proportion of the available resource was actually abstracted and abstractions were allocated from the reliable baseflow component of the annual hydrograph (Gurnell and Petts, 1999). In watercourses with heavily modified flow regimes the Q_{95} flow may no longer be providing adequate flow protection during drought events, therefore, this thesis examined the practice of using the Q_{95} flow as the basis for setting *e-flows* in England.

This thesis also presents an empirical assessment of the effects of current and historic flow management practices on rivers with contrasting flow regimes. Daily mean flow data from gauging stations located across two contrasting catchments, the Trent and

Great Ouse, comprising tributaries that span the ‘natural – heavily modified’ continuum was assessed. Assessments aimed to illustrate the potential ecological significance of low-flow variability across both catchments. The review of historical and current low-flow management approaches identified that in the majority of cases; the use of the annual Q_{95} flow has arguably resulted in more water than necessary being allocated during the summer period, and inadequate flow protection during the critical spring and autumn periods. In addition, the use of the Q_{95} flow as an *e-flow* overlooks the importance for riverine biodiversity and resilience of ensuring that a degree of inter-annual flow variability is maintained.

The practice of using the annual Q_{95} as an 'environmental protection' flow is embedded in river management in England for both setting hands-off flows at abstractions and compensation flows below impoundments. As an *e-flow* metric the Q_{95} flow-duration statistic is hydrologically robust given an appropriate length of flow record of at least 20 years, and for the summer low-flow season is conservative. For the 10 watercourses used to examine the practice of using the annual Q_{95} flow as the basis for managing abstractions and compensation flows below impoundments (Chapter 6), the Q_{95} represents between 1.07 and 1.53 times the lowest summer month Q_{95} and between 1.29 and 2.09 times the minimum recorded flow. It is also between 3.9 and 52.8 per cent of the local ADF and these compare with Baxter's and Tennant's guidelines for summer flows of 20% ADF. Although the annual Q_{95} has no direct relationship with habitat for biota, it is a practical tool that implicitly incorporates magnitude, duration and frequency.

Following Baxter (1961; 1963), Chapter 6 explored the use of proportions of the long-term ADF as the basis of flow assessments. Initial assessments illustrated some of the issues surrounding the implementation of Baxter’s approach across the contrasting Trent and Great Ouse catchments. In watercourses with discharge-rich flow regimes and with artificially augmented low flows, flow metrics calculated from the ADF were found to be unsuitable measures of low-flow impact. A second tenet of Baxter’s approach was to use standardised flow metrics, at least at the regional scale. Four flow metrics; the annual Q_{95}, average MAM10, 20% ADF and 30% ADF were used to investigate the degree of hydrological dependency across the River Trent and Great Ouse study sites and also the similarity in hydrological behaviour year on year. The average MAM10 rather than the average MAM7 metric was selected because a 10 day period avoids issues surrounding the 7-day week and the varying temporal impact of artificial influences, and is less likely to be affected by weekly operational flow patterns.

Although results suggested that no flow metric effectively discriminated between dry and wet periods across all of the study sites, the average MAM10 appeared to be the most effective metric at discriminating between wet and dry years, and as potentially the most useful metric in describing ecological droughts across the contrasting sub-catchments.

7.5 NEW AND FUTURE PRESSURES

It is now well accepted that the climate is changing (Rahiz and New, 2012). From a hydrologic and water management perspective, the assumption of a stationary climate has been undermined by the realisation of rapid climate change (Poff and Matthews, 2013). Within the United Kingdom, the best understanding of the potential impact of climate change on water resources is based on the UKCP09 climate projections released in 2009 (Murphy *et al*., 2009). The UKCP09 climate projections are described by Charlton and Arnell (2014) as representing a “step change” in the climate scenario information available for the United Kingdom as they follow a probabilistic approach, and are based on many thousands of scenarios. Although considerable uncertainty exists, most UKCP09 projections suggest the United Kingdom will experience wetter winters and hotter, drier summers in future (Hannaford and Buys, 2012).

Any new *e-flow* approach to flow management during ecological drought must consider the potential impacts of climate change on river flows and on the magnitude, duration, frequency and timing of droughts. Charlton and Arnell (2014) used the UKCP09 climate projections to assess the implications of climate change on the flow regimes in six representative English catchments, and concluded that changes in indicators of low-flow (Q_{95}) are determined by changes in both summer precipitation and temperature, with the greatest reductions with higher temperature changes and the largest reduction in summer precipitation. Changes in rainfall in other seasons were identified by Charlton and Arnell (2014) as having a much smaller effect on low flows. Rahiz and New (2013) analysed drought characteristics of ensemble projections made using the Met Office Hadley Centre’s regional climate model (HadRM3) which was developed for UKCP09, and identified profound increases in drought intensity, duration and extent for the 2050s and 2080s, with more winter (wet season) droughts in the already water stressed South (Mitchell and McDonald, 2015). Rahiz and New (2013) also determined that future droughts are more coherent, with higher probabilities of the same drought events occurring across locations and over a larger area. This is likely to limit the extent to which water can be shared to defend against drought (Mitchell and McDonald, 2015).

Demographic changes and economic growth are also increasing demand, exacerbating water stress (Mitchell and McDonald, 2015) and increasing pressure on water supplies and infrastructure (Department for Environment, Food and Rural Affairs, 2011). The Office for National Statistics forecast that the population of England will grow by just under 10 million by 2035 (Office for National Statistics, 2011a) with much of this increase likely to be concentrated in some of the most water stressed areas of the country (Department for Environment, Food and Rural Affairs, 2011). The population of the wider South East and East Midlands will grow by 23.2 per cent from 2010 to 2035, with London growth projected at nearly 30 per cent over this period (Office for National Statistics, 2012; Mitchell and McDonald, 2015). Longer-term projections suggest major growth beyond 2035, with England's population reaching almost 85 million in 2110, an increase of more than 60 per cent over the 2010 base (Office for National Statistics, 2011b; Mitchell and McDonald, 2015).

Climate change, demographic changes and economic growth will increase water demand placing increased pressure on water resources in both of the study catchments. It is, however, likely that the increased demand for hydroelectric power (HEP) development to meet increasing future energy demand, and spray irrigation to support increasing food demand, will create additional pressure on water resources within the Trent and Great Ouse catchments respectively. The United Kingdom generates approximately 1.5 per cent of its electricity from HEP schemes, and although further large-scale development potential is limited, there is scope for exploiting the remaining small-scale HEP resources in a sustainable way (Department of Energy and Climate Change, 2013). The Environment Agency published *Mapping Hydropower Opportunities and Sensitivities in England and Wales* (Environment Agency, 2010b) and estimated that potential HEP sites located in the Midlands Region had a power potential of approximately 130,800 kW.

Increasing concerns surrounding the abstraction of water for spray irrigation across East Anglia during the late 1950s and following the 1959 drought were identified in Chapter 4 as a key reason for the reluctance to adopt the hydrological *e-flow* approach proposed by Baxter. Today, similar concerns relating to future irrigation demands in an uncertain changing climate exist. One of the impacts of climate change will be increased summer temperatures and corresponding longer growing seasons. Climate change will therefore provide the opportunity to increase food productivity, and spray irrigation will increase, but only if the water is available to abstract.

7.6 A PROGRESSIVE ENVIRONMENTAL FLOW FRAMEWORK FOR AN AGE OF HYDRO-CLIMATIC UNCERTAINTY

Although the focus of research over the past 30 years has been on water abstraction and the need to maintain *e-flows* during the summer, this thesis also addresses the reality of discharge-rich watercourses, most of which have had low flows sustained by river regulating dams or by effluent returns for three decades or more. The final aim of this thesis was to produce a set of management recommendations for the setting of *e-flows* for river protection in an age of climatic uncertainty. From a practical perspective the proposed *e-flow* approach had to make use of existing/available data; therefore, the application of selected hydrological *e-flow* approaches was explored.

Chapter 4 identified that a hydrological *e-flow* approach based on the natural flow regime paradigm, taking into account the key principles of Baxter's (1961; 1963) approach could be used to determine *e-flows* for regulated rivers in the 21st century. This thesis hypothesised that such an approach may represent an improvement on the current method of basing *e-flows* on a single low-flow duration statistic with little or no regard to seasonally variable ecological need. By employing the current annual Q_{95} as a baseline, assessments aimed to determine whether more complex hydrological *e-flow* approaches were not only capable of offering better environmental protection but were also capable of allocating more water for abstraction. An *e-flow* approach that results in the reduced allocation of water for abstraction would be considered unacceptable from a water resource management perspective, even if that approach offered better environmental protection.

Given the case of hotter, drier summers, an assessment of alternative flow management approaches aimed to determine (a) how much water above the annual Q_{95} (the current hydrological *e-flow* approach) would be available for abstraction for irrigation in the summer growing season, and (b) whether it was possible to allocate a higher *e-flow* during the critical spring and autumn months, and still make more water available for abstraction across the regulation period by reducing the *e-flow* during the summer period. Assessments also explored whether the application of the selected hydrological *e-flow* approaches at more complex temporal resolutions saved water and protected the environment.

During initial flow assessments, Baxter (1961; 1963) style flow management approaches based on percentages of the long-term ADF were identified as unsuitable due to the allocation of higher flows during the summer and were therefore discounted. Indeed, assessments in thesis appear to indicate that Baxter's approach may be restricted by the variety of flow regime types studied, and may not be transferrable outside of surface-runoff dominated watercourses. The application of four alternative flow management scenarios was subsequently evaluated in more detail at monthly, seasonal and annual scales using the May to November inclusive monthly daily mean flows recorded during four dry years. Results illustrated that in the majority of cases, it was not possible to reduce summer *e-flows* enough to support the allocation of higher spring and autumn *e-flows* without reducing the overall volume of water available for abstraction. Arguably none of the approaches explored adequately protected flows during the critical spring ecological period, and few protected flows throughout the critical autumn ecological period.

To date the vast majority of research has centred on droughts and low flows occurring during the summer abstraction period and the on the protection of summer flows, arguably the results in Chapter 6 suggest that we need to shift the focus of research from the summer to the critical ecological periods of spring and autumn.

Much recent research for example Sanderson *et al*. (2012) and McManamay *et al*. (2013) has centred on the development of regional approaches to setting *e-flows*. Throughout this thesis, assessments of flows recorded during periods of below average rainfall across two contrasting catchments, demonstrated that due to the wide variety of low-flow responses it is important that *e-flows* are determined at the local or sub-catchment scale. One justification for the use of a regional *e-flow* approach is the limited availability of long-term hydrological and ecological datasets. The majority of main rivers in England have been gauged since the mid to late 1960s; flow data is therefore readily available. Although the accuracy of the measurement of low flows can be problematical, future *e-flow* approaches should utilise hydrological data, in addition, any future *e-flows* should be determined at the local sub-catchment scale and not at the regional scale. During drought events some abstraction from watercourses will cease but effluent will continue to be discharged into watercourses creating 'anti-drought' conditions. This suggests that low flows and drought will be more of an issue in headwater streams/rivers not supported by effluents or river support schemes. This also means that the majority of extreme low-flow drought events are not monitored as these smaller watercourses are generally not gauged.

7.6.1 An ecological approach to future environmental flows

The current approach to managing abstractions and compensations flows employs a single minimum hands-off flow or maintained flow, the annual Q_{95}, appears to have sustained habitats for lotic biota. This may relate to the relatively high proportion of ADF allocated, licence holders not using their total allocations, and Drought Orders further constraining abstractions during periods of severe drought. Furthermore, as demonstrated by this thesis, larger basins have a natural hydrological resilience across their drainage networks, as it is exceptionally rare for all sub-catchments, with different geology, landuse, topography, morphometry, etc, to experience extreme drought during the same year. Recognising the spatial and temporal character of ecological drought, and in the context of a future balanced approach to resource management and environmental protection, this thesis proposes the following guidelines for catchments in central England:

- Use seasonally-based *e-flows* targeting the key ecological periods: (May-June; July-September; October-November)
- Base the *e-flow* on the MAM10 flow for each ecological period and a minimum of 20-year daily-flow record.
- Determine *e-flows* at the sub-catchment level, ideally focussing on catchments of 100 < 300km^2. The implications for maintaining and developing hydrometric networks are significant.

7.6.2 Should the position on artificially higher flows be reviewed?

Initial characterisation for the WFD suggested that as many or more river stretches are discharge-rich as are over abstracted, leading Waddingham *et al.* (2008) to question whether the position on artificially higher flows should be reviewed. Chapter 5 introduced the concept of anti-droughts, and identified that there is currently a poor understanding of the ecological ramifications of the loss of low flows and droughts in watercourses with discharge-rich flow regimes. During the summer, 80 per cent of the flow of the River Tame may be made up of treated sewage effluent, and downstream of the River Tame confluence, discharges have more than doubled the dry weather flow of the main River Trent (Petts *et al*., 2002). Due to the augmentation of flows it is highly unlikely that the majority of main rivers will experience prolonged low-flow and drought events. It is also probable that only watercourses with natural flow regimes and headwater streams will experience prolonged drought events. Perhaps the focus of future research should be on the protection of natural/headwater streams?

Assessments of the change in flows in the Rivers Tame and Trent resulting from the application of a range of alternative hydrological *e-flow* approaches in Chapter 6 raised two important questions: (1) should *e-flows* aim to protect naturalised or gauged flows within watercourses with discharge-rich flow regimes?; and (2) is it possible to adapt the natural flow regime concept to restore flow variability to watercourses with discharge-rich flow regimes?

Low flows within the River Tame were identified as more than six times higher than they would have been naturally. The discharge of effluent into the River Tame has resulted in the substantial augmentation of low flows, the creation of anti-drought conditions, and the loss of flow seasonality. The riverine ecology will have adapted over time to the discharge-rich flow regime of the River Tame, therefore, the setting of *e-flows* that aim to protect natural flows would probably be detrimental.

An awareness that flow management approaches were failing to recognise that the integrity of flowing water systems depends largely on their natural dynamic character, led Poff *et al*. (1997) to propose the natural flow regime paradigm. The paradigm proposes that the structure and function of riverine ecosystems, and the adaptations of their constituent aquatic and riparian species are dictated by patterns of both intra- and inter-annual variation in river flows (Kennard *et al*., 2010a), with a number of ecologically important flow characteristics including the seasonal patterning of flows; timing of extreme flows; the frequency, predictability, and duration of floods, droughts, and intermittent flows; daily, seasonal, and annual flow variability; and rates of change, constituting the natural flow regime.

Many watercourses in England have a long history of modification; therefore, a focus on the restoration of natural flow regimes may no longer be appropriate. The climate is changing, therefore, the flow regimes of rivers will change, and in future years will bear little resemblance to the rivers of today. In natural watercourses the current natural system will change and the riverine ecosystem will adapt. Recognition that in an altered climate and under intense river management, hydrological and ecological change is inevitable led Acreman *et al.* (2014a) to propose the “designer” paradigm approach for the setting of *e-flows* in managed and modified rivers like the River Tame, where a return to natural conditions is no longer feasible. In any case, flow management approaches must also be updated as the flow regime evolves; flows recorded in today’s climate must not be used to manage the rivers of the future.

7.6.3 Implications for other regions/countries

Although the research in this thesis was centred on the development of *e-flows* for English watercourses with modified flow regimes, some of the key findings may have implications for the setting of *e-flows* in other countries. Assessments illustrated that Baxter style *e-flow* approaches that use proportions of the long-term ADF as the basis of flow assessments were not suited to the protection of low flows in the majority of the watercourses explored. Interestingly one of the most widely applied *e-flow* approaches; the Tennant (Montana) method also uses percentages of mean flow as the basis of flow assessments. The assessments in this thesis have perhaps demonstrated that *e-flows* determined using the Tennant method should be revisited.

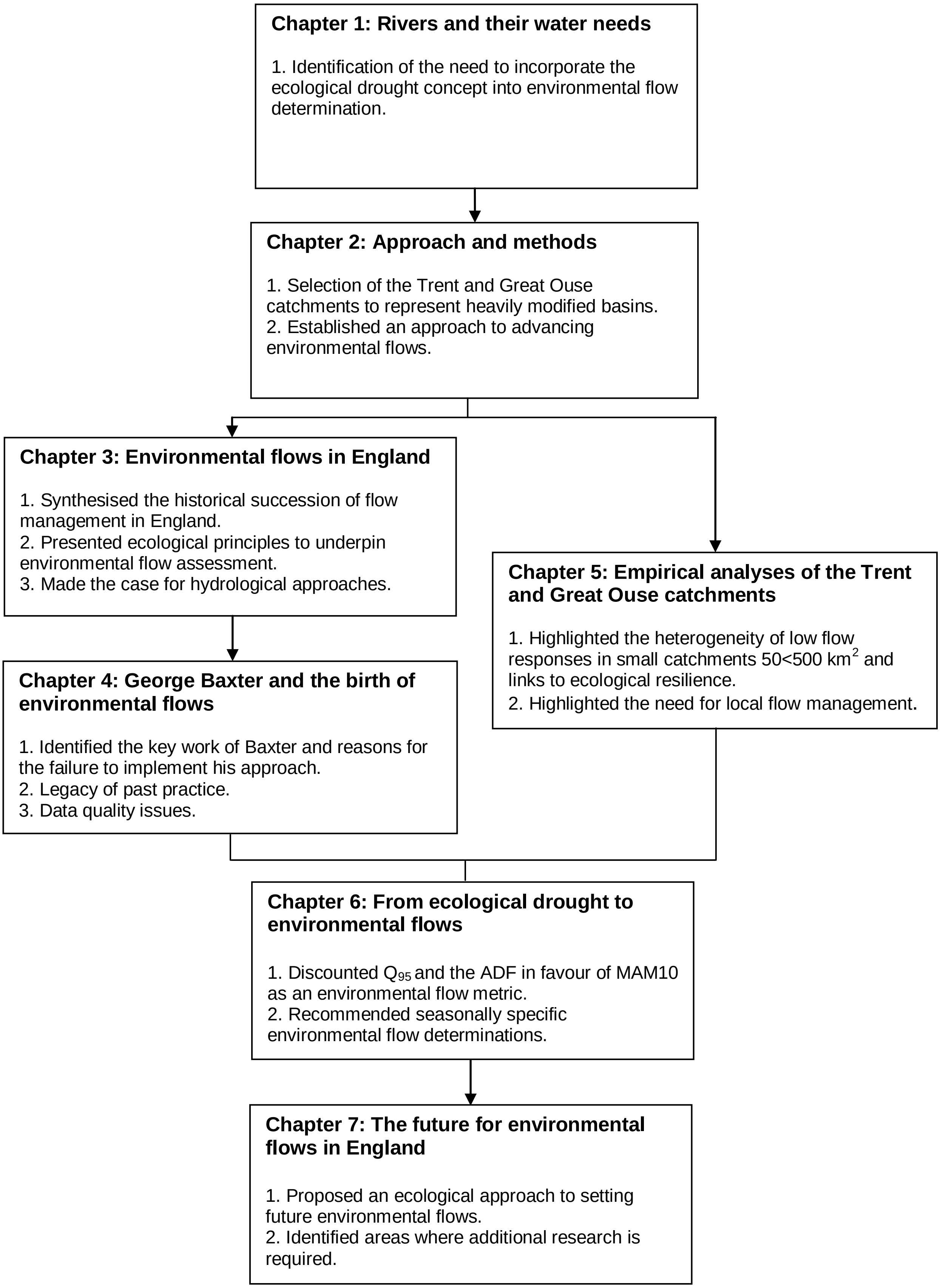
Finally, consideration is given to the setting of *e-flows* in countries with limited or no river flow data. Recent research identified a number of limitations to the science of *e-flows*, with many relating to the persistent gaps in the understanding of flow-ecology relationships. Shenton *et al*. (2012) highlighted a number of assumptions that undermine the capacity of *e-flow* approaches; these included the use of historical time series to forecast future conditions, the inability of some *e-flow* approaches to handle the extreme flow events associated with climate variability, and the assumption of process stationarity. Until some of these research gaps are addressed, the case for the use of hydrological *e-flow* approaches is compelling and there is little to be gained from the use of more complex and data intensive *e-flow* approaches. In countries with limited or no river flow data regional approaches such as ELOHA may be used to estimate *e-flows* and the recommendation is that the Q_{95} flow should be used to provide an initial/conservative *e-flow* where needed. Once more flow data has been collected then *e-flows* should be updated on a regular cycle.

7.7 SUMMARY AND RECOMMENDATIONS

7.7.1 Summary of key findings

Figure 7.1 on the next page summarises the key findings from each Chapter of this thesis.

Figure 7.1: Summary of key findings



Chapter 1: Rivers and their water needs

1. Identification of the need to incorporate the ecological drought concept into environmental flow determination.

Chapter 2: Approach and methods

1. Selection of the Trent and Great Ouse catchments to represent heavily modified basins.
2. Established an approach to advancing environmental flows.

Chapter 3: Environmental flows in England

1. Synthesised the historical succession of flow management in England.
2. Presented ecological principles to underpin environmental flow assessment.
3. Made the case for hydrological approaches.

Chapter 4: George Baxter and the birth of environmental flows

1. Identified the key work of Baxter and reasons for the failure to implement his approach.
2. Legacy of past practice.
3. Data quality issues.

Chapter 5: Empirical analyses of the Trent and Great Ouse catchments

1. Highlighted the heterogeneity of low flow responses in small catchments 50<500 km^2 and links to ecological resilience.
2. Highlighted the need for local flow management.

Chapter 6: From ecological drought to environmental flows

1. Discounted Q_{95} and the ADF in favour of MAM10 as an environmental flow metric.
2. Recommended seasonally specific environmental flow determinations.

Chapter 7: The future for environmental flows in England

1. Proposed an ecological approach to setting future environmental flows.
2. Identified areas where additional research is required.

7.7.2 Recommendations for further research

7.7.2.1 Extend the flow assessments to more study sites/catchments

Only 10 watercourses located in two catchments were explored in detail, expanding the assessments to additional catchments and watercourses may be beneficial. It would also be interesting to determine whether given the increased availability of flow data, Baxter's (1961; 1963) approach is capable of setting *e-flows* in the watercourses he originally investigated. A particular problem is the lack of gauging stations on second order streams that are impacted by diversions and groundwater abstractions.

7.7.2.2 Focus on the spring and autumn

Most research has centred on flow protection during the summer period; the assessments in this thesis have demonstrated that future *e-flow* research should focus more on environmental protection during the spring and autumn ecological periods, building on metrics that combine magnitude, frequency and duration of ecological droughts.

7.7.2.3 Future flows

As datasets improve to test future flow scenarios - datasets are available for nine sites in the Trent catchment and 10 sites in the Great Ouse catchment - it would be beneficial to model the implications of flow-control rules under climate change scenarios.

7.7.2.4 Anti-droughts in discharge-rich catchments

There is a lack of information surrounding the potential ecological ramifications of discharge-rich watercourses. Given the large number of watercourses with discharge-rich flow regimes this represents an area where further research is required.

7.7.2.5 Quantification of artificial influences

Given the dominant influence of flow augmentation in a number of the study sites, time series discharge data should be used to determine the spatial dependency of reaches on flow augmentation, updating the work of Pirt (1983), with particular reference to the key ecological periods.

References

Ackroyd, D.S. 1966. The fishery implications of the Water Resources Act. In *Proceedings of the 2nd British Coarse Fish Conference*, held at the Department of Zoology. University of Liverpool, pp 7-11.

Acreman, M.C. 2005. Linking science and decision-making: features and experience from environmental river flow setting. *Environmental Modelling and Software*, **20**(2): 99-109.

Acreman, M.C. 2007. *Guidance on Environmental Flow Releases from Impoundments to Implement the Water Framework Directive: Final Report*. Project WFD 82, Scotland and Northern Ireland Forum for Environmental Research, 32 pp.

Acreman, M.C., and Dunbar, M.J. 2004. Defining environmental flow requirements – a review. *Hydrology and Earth System Sciences*, **8**: 861-876.

Acreman, M.C. and Ferguson, A.J.D. 2010. Environmental flows and the European Water Framework Directive. *Freshwater Ecology*, **55**(1): 32-48.

Acreman, M.C., Dunbar, M.J., Hannaford, J., Black, A.R., Rowan, J.S., and Bragg, O.M. 2005. *Development of Environmental Standards (Water Resources) Stage 1: Environmental Standards.* Report Project WFD 48, Scotland and Northern Ireland Forum for Environmental Research, 91 pp.

Acreman, M.C., Dunbar, M.J., Hannaford, J., Bragg, O.M., Black, A.R., Rowan, J.S. and King, J. 2006. *Development of Environmental Standards (Water Resources) Stage 3: Environmental Standards*. Report Project WFD 48, Scotland and Northern Ireland Forum for Environmental Research, 146 pp.

Acreman, M., Dunbar, M., Hannaford, J., Mountford, O., Wood, P., Holmes, N., Cowx, I., Noble, R., Extence, C., Aldrick, J., King, J., Black, A., and Crookall, D. 2008a. Developing environmental standards for abstractions from UK rivers to implement the EU Water Framework Directive. *Hydrological Sciences Journal*, **53**(6): 1105-1120.

Acreman, M.C., Booker, D.J., Goodwin, T.H., Dunbar, M.J., Maddock, I., Hardy, T., Rivas-Casado, M., Young, A., and Gowing, I.M. 2008b. *Rapid Assessment of Physical Habitat Sensitivity to Abstraction (RAPHSA)*. Report to the Environment Agency and the Centre for Ecology and Hydrology, Environment Agency, Bristol, 26 pp.

Acreman, M.C., Aldrick, J., Binnie, C., Black, A., Cowx, I., Dawson, H., Dunbar, M., Extence, C., Hannaford, J., Harby, A., Holmes, N., Jarrett, N., Old, G., Peirson, G., Webb, J., and Wood, P. 2009. Environmental flow from dams: the Water Framework Directive. *Engineering Sustainability*, **162**(1): 13-22.

Acreman, M.C., Arthington, A.H., Colloff, M.J., Couch, C., Crossman, N., Dyer, F., Overton, I., Pollino, C.A., Stewardson, M.J., and Young, W. 2014a. Environmental flows for natural, hybrid and novel riverine ecosystems in a changing world. *Frontiers in Ecology and Environment*, **12**(8): 466-473.

Acreman, M.C., Overton, I.C., King, J., Wood, P.J., Cowx, I.G., Dunbar, M.J., Kendy, E., and Young, W.J. 2014b. The changing role of ecohydrological science in guiding environmental flows. *Hydrological Sciences Journal*, **59**(3-4): 433-450.

Ainger, W.D., and Barclay, J.S. undated. *Fresh water fisheries in rivers and the impact of the Water Resources Act 1963.* Palantype Organisation, London, 63 pp.

Aitken, P.L. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 893-896.

Aitken, P.L., Dickerson, L.H., and Menzies, W.J.M. 1966. Fish passes and screens at water power works. *Proceedings of the Institution of Civil Engineers*, **35**(1): 29-57.

Alexander, J.N.L. 1963. Discussion on Preservation of fish life, amenities and facilities for recreation. In *Conservation of Water Resources in the United Kingdom*, Institution of Civil Engineers, London, 77-78.

Annear, T., Chisholm, I., Beecher, H., Locke, A., Aarrestad, P., Coomer, C., Estes, C., Hunt, J., Jacobsen, T., Jobsis, G., Kauffman, J., Marshall, J., Mayes, K., Smith, G., Wentworth, R., and Stainaker, C. 2004. *Instream Flows for Riverine Resource Stewardship*. Revised Edition, Instream Flow Council, Cheyenne, Wyoming, 267 pp.

Anon. 1952. New Water Supply for Edinburgh Opened – Daily Potential up by 6,000,000 gallons. *The Glasgow Herald*, December 6th 1952.

Anon. 1953. Fruid-Menzion Scheme of the City of Edinburgh Water Department. *Water and Water Engineering*, **57**: 49-55.

Anon. 1975. Obituary Mr George Baxter. *Journal of the Institution of Water Engineers and Scientists*, **29**(3): 102.

Arthington, A.H. 2012. *Environmental Flows: Saving Rivers in the Third Millennium*, University of California Press, Berkeley, 424 pp.

Arthington, A.H., Brizga, S.O., Pusey, B.J., McCosker, R.O., Bunn, S.E., Loneragan, N., Growns, I.O., and Yeates, M. 1998. *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods,* Arthington, A.H., and Zalucki, J.M. eds., Land and Water Resources Research and Development Centre Occasional Paper 27/98, Canberra, 141 pp.

Arthington, A.H., Bunn, S.E., Poff, N.L., and Naiman, R.J. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, **16**(4): 1311-1318.

Arthington, A.H., Naiman, R.J., McClain, M.E., and Nilsson, C. 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology*, **55**(1): 1-16.

Arthington, A.H., Mackay, S.J., James, C.S., Rolls, R.J., Sternberg, D., Barnes, A., and Capon, S.J. 2012. *Ecological limits of hydrological alteration: a test of the ELOHA framework in south-east Queensland*. Waterlines Report Series No. 75. Canberra, Australia, 176 pp.

Atlantic Salmon Trust and Scottish Office Agriculture and Fisheries Department. 1995. *Effects of River Flow and Water Abstraction on Salmon: Analyses of Fish Counter Data and Catches by Rod and Line in the River Dee*, Scottish Office Environment Department Edinburgh, 79 pp http://www.scotland.gov.uk/Uploads/Documents/Coll1594.pdf

Baker, R.F. 1934. Presidential address. *Water and Water Engineering*, **36**: 338-344.

Banks, J.W. 1969. A review of the literature on the upstream migration of Adult Salmonids. *Journal of Fish Biology*, **1**: 85-136.

Barker, I.C., and Kirmond, A. 1998. Managing surface water abstraction. In *Hydrology in a Changing Environment*, Volume 1, Wheater, H., and Kirby, C eds., British Hydrological Society, London, pp 249-258.

Baxter, G. 1961. River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 225-244.

Baxter, G. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **21:** 892-911.

Baxter, G. 1963. Preservation of fish life, amenities and facilities for recreation. In *Conservation of Water Resources in the United Kingdom*, Proceedings of the Symposium organised by and held at the Institution of Civil Engineers, Institution of Civil Engineers, London, pp 59-65.

Belmar, O., Velasco, J., and Martinez-Capel, F. 2011. Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean Rivers, Segura River Basin (Spain). *Environmental Management*, **47**(5): 992-1004.

Berg, C.L. 1963. Discussion on Preservation of fish life, amenities and facilities for recreation. In *Conservation of Water Resources in the United Kingdom*, Proceedings of the Symposium organised by and held at the Institution of Civil Engineers, Institution of Civil Engineers, London, pp 76.

Beveridge, D., Curry, R.A., and St-Hilaire, A. 2012. Selecting hydrologic indices for the Prairie Provinces. *River Research and Applications*, **28**(10): 1595-1608.

Biggs, B.J.F., Nikora, V.L., and Snelder, T.H. 2005. Linking scales of flow variability to lotic ecosystem structure and function. *River Research and Applications*, **21**(2-3): 283-298.

Bino, G., Steinfeld, C., and Kingsford, R.T. 2014. Maximizing colonial waterbirds' breeding events using identified ecological thresholds and environmental flow management. *Ecological Applications*, **24**(1): 142-157.

Binnie, W.J.E. 1922. Presidential address. *Transactions of the Institution of Water Engineers*, **27**: 10-14.

Blackburn, A.B.E. 1936. The assessment of compensation water. *Municipal Engineering, Sanitary Record and Municipal Motor*, 675-676.

Bleasdale, A., Boulton, A.G., Ineson, J., and Law, F. 1963. Study and assessment of water resources. In *Conservation of Water Resources in the United Kingdom*, Proceedings of the Symposium organised by and held at the Institution of Civil Engineers, Institution of Civil Engineers, London, pp 121-136.

Board of Trade 1921. *Final Report of the Water Power Resources Committee*. Her Majesty's Stationery Office, London, 178 pp.

Bobbi, C.J., Warfe, D.M., and Hardie, S.A. 2014. Implementing environmental flows in semi-regulated and unregulated rivers using a flexible framework: case studies from Tasmania, Australia. *River Research and Applications*, **30**(5): 578-592.

Bond, N.R., Lake, P.S., and Arthington, A.H. 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, **600**(1): 3-16.

Booker, D.J., Goodwin, T.G., Acreman, M.C., Dunbar, M.J., Rivas-Casado, M., Maddock, I., and Hardy, T.B. 2006a. *Rapid Assessment of Physical Habitat Sensitivity to Abstraction: Interim Technical Report 5 April 05 – October 05*. Report to the Environment Agency and the Centre for Ecology and Hydrology, CEH Wallingford, 82 pp.

Booker, D.J., Goodwin, T.G., Acreman, M.C., Dunbar, M.J., Rivas-Casado, M., Maddock, I., Hill, G., Hardy, T.B., and Gowing, I.M. 2006b. *Rapid Assessment of the Physical Habitat Sensitivity to Abstraction: Interim Technical Report 6 November 05 – April 06*. Report to the Environment Agency and the Centre for Ecology and Hydrology, CEH Wallingford, 86 pp.

Boulton, A.G. 1965. Minimum Acceptable Flow. *Journal of the Institution of Water Engineers*, **19**: 15-58

Boulton, A.J. 2003. Parallels and contrasts in the effect of drought on stream macroinvertebrate assemblages. *Freshwater Biology*, **48**(7): 1173-1185.

Bovee, K.D. 1982. *A guide to stream habitat analysis using the instream flow incremental methodology*. United States Fish and Wildlife Service, Report FWS/OBS-82/26, Instream Flow Information Paper 12, Washington, D.C., 248 pp.

Bovee, K.D. 1986. *Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology*. United States Fish and Wildlife Service, Report FWS/OBS-86/7, Instream Flow Information Paper 21. Washington, D.C., 235 pp.

Bradford, W.T. 1981. ”Minimum Acceptable Flows” Reconsidered. Water Science and Technology, **13**(6): 73-79.

Brayshaw, J.D. 1967. The effects of river discharges on inland rivers. In *River Management*, Isaac, P.C.G. ed. Proceedings of a Symposium organised by the Department of Civil Engineering, University of Newcastle upon Tyne, 20 and 21 September 1966, Maclaren and Sons Limited, London, pp 102-118.

Brisbane Declaration 2007. The Brisbane Declaration. Environmental Flows are Essential for Freshwater Ecosystem Health and Human Well-Being. Declaration of the 10th International River Symposium and International Environmental Flows Conference, Brisbane, Australia, 3–6 September 2007.

Bryant, S.J., Arnell, N.W., and Law, F.M. 1994. The 1988-92 drought in its historical perspective. *Water and Environment Journal*, **8**(1): 39-51.

Bunn, S.E., and Arthington, A.H. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, **30**(4): 492-507.

Bunn, S.E., Thoms, M.C., Hamilton, S.K., and Capon, S.J. 2006. Flow variability in dryland rivers: boom, bust and the bits in between. *River Research and Applications*, **22**(2): 179-186.

Bureau of Land Management 1979. *Instream flow guidelines*. Bureau of Land Management, Lakewood, Colorado, 57 pp.

Caissie, J., Caissie, D., and El-Jabi, N. 2015. Hydrologically based environmental flow methods applied to rivers in the maritime provinces (Canada). *River Research and Applications*, **31**(6), 651-662.

Caruso, B.S. 2001. Regional river flow, water quality, aquatic ecological impacts and recovery from drought. *Hydrological Sciences Journal*, **46**(5): 677-699.

Caruso, B.S. 2002. Temporal and spatial patterns of extreme low flows and effects on stream ecosystems in Otago, New Zealand. *Journal of Hydrology*, **257**(1-4): 115-133.

Central Advisory Water Committee 1959. *First Report of the Sub-Committee on the Growing Demand for Water*. Her Majesty’s Stationery Office, London, 27 pp.

Central Advisory Water Committee 1962. *Final Report of the Sub-Committee on the Growing Demand for Water*. Her Majesty’s Stationery Office, London, 43 pp.

Charlton, M.B., and Arnell, N.W. 2014. Assessing the impact of climate change on river flows in England using the UKCP09 climate change projections. *Journal of Hydrology*, **519**: 1723-1738.

Chester, E.T., Matthews, Ty.G., Howson, T.J., Johnston, K., Mackie, J.K., Strachan, S.R., and Robson, B.J. 2014. Constraints upon the response of fish and crayfish to environmental flow releases in a regulated headwater stream network. *PLOS ONE*, **9**(3): article number e91925.

Clausen, B., and Biggs, B.J.F. 2000. Flow variables for ecological studies in temperate streams: groupings based on covariance. *Journal of Hydrology*, **237**(3-4): 184-197.

Cowx, I.G., Young, W.O., and Hellawell, J.M. 1984. The influence of drought on the fish and invertebrate population of an upland stream in Wales. *Freshwater Biology*, **14**(2): 165-177.

Davies, A.W. 1978. Pollution problems arising from the 1975-76 Drought. *Proceedings of the Royal Society of London Series A: Mathematical and Physical Sciences*, **363**(1712): 97-107.

Davies, PM., Naiman, R.J., Warfe, D.M., Pettit, N.E., Arthington, A.H., and Bunn, S.E. 2014. Flow-ecology relationships: closing the loop on effective environmental flows. *Marine and Freshwater Research*, **65**(2): 133-141.

Deitch, M.J., and Kondolf, G.M. 2012. Consequences of variations in magnitude and duration of an instream environmental flow threshold across a longitudinal gradient. *Journal of Hydrology*, **420-421**: 17-24.

Department for Environment, Food and Rural Affairs 2011. *Water for Life* (Government White Paper). CM 8230, The Stationery Office, London, 100 pp. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/228861/8230.pdf

Department of Energy and Climate Change 2013. Environmental Management – Guidance. *Harnessing hydroelectric power* https://www.gov.uk/harnessing-hydroelectric-power

Department of Scientific and Industrial Research 1961. *Water Pollution Abstracts*, **34**(10), 1940, Her Majesty's Stationery Office, London, 358.

Dixon, E.W. 1925. *Compensation water and its effect on river flow* read before the Yorkshire Association of the Institution of Civil Engineers on Thursday November 26th 1925, 15 pp.

Dixon, H. 2010. Managing national hydrometric data: from data to information. In *Global Change: Facing Risks and Threats to Water Resources*. Proceedings of the Sixth World FRIEND Conference, Fez, Morocco, October 2010, IAHS Publication 340, pp 451-458.

Downing, R.A. 2004. Groundwater in a national water strategy, 1964-1979. In *200 Years of British Hydrogeology*, Mather, J.D. ed. Geological Society, London, Special Publications, **225**, 323-338.

Downing, R.A., Land, D.H., Allender, R., Lovelock, P.E.R., and Bridge, L.R. 1970. *The hydrogeology of the Trent River Basin*. Water Supply Papers of the Institute of Geological Sciences: Hydrogeological Report No. 5, Institute of Geological Science, Natural Environment Research Council, London, 104 pp.

Dracup, J.A., Lee, K.S., and Paulson, E.G. 1980a. On the statistical characteristics of drought events. *Water Resources Research*, **162**: 289-296.

Dracup, J.A., Lee, K.S., and Paulson, E.G. 1980b. On the definition of droughts. *Water Resources Research*, **162**: 297-302.

Drake, P.J., and Sherriff, J.D.F. 1987. A method for managing river abstractions and protecting the environment. *Journal of the Institution of Water and Environmental Management*, **1**(1): 27-38.

Dunbar, M.J., Gustard, A., Acreman, M.C., and Elliot, C.R.N. 1998. *Overseas Approaches to Setting River Flow Objectives*. R&D Technical Report W145, Report by the Institute of Hydrology for the Environment Agency, Bristol, 78 pp.

Dunbar, M., Ibbotson, A., Gowing, I., McDonnel, N., Acreman, M., and Pinder, A. 2002. *Further Validation of PHABSIM for the Habitat Requirements of Salmonid Fish*, R&D Technical Report W6-036/TR, Environment Agency, Bristol, 140 pp. http://www.freshwaterlife.org/projects/media/projects/images/4/42596_ca_object_representations_media_422_original.pdf

Dunbar, M.J., Acreman., M., and Kirk, S. 2004. Environmental flow setting in England and Wales: strategies for managing abstraction in catchments. *Water and Environment Journal*, **18**(1): 5-10.

Dunbar, M.J., Alfredson, K., and Harby, A. 2012. Hydraulic-habitat modelling for setting environmental river flow needs for salmonids. *Fisheries Management and Ecology*, **19**(6): 500-517.

Edwards, A.M.C., Freestone, R.J., and Crockett, C.P. 1997. River management in the Humber catchment. *The Science of the Total Environment*, **194-195**: 235-246.

Edwards, FK., Baker, R., Dunbar, M., and Laize, C. 2012. *A review of the processes and effects of droughts and summer floods in rivers and threats due to climate change on current adaptive strategies.* Centre for Ecology and Hydrology, Wallingford, 75 pp.

Entec 2008. *Water Resource Assessments for the Water Framework Directive, CAMS & Abstraction Licensing: Methods Summary*, paper produced for the Environment Agency, 65 pp.

Environment Agency 2002a. *Managing Water Abstraction: the Catchment Abstraction Management Strategy process*. Environment Agency, Bristol, 48 pp.

Environment Agency 2002b. *Resource Assessment and Management Framework Report and User Manual* (*Version 3*). R&D Technical Manual W6-066M, Environment Agency, Bristol, 538 pp.

Environment Agency 2003. *The Trent Corridor Catchment Abstraction Management Strategy*. Environment Agency, Solihull, 29 pp.

Environment Agency 2008a. *Managing Water Abstraction: Interim Update*. Environment Agency, Bristol, 22 pp.

Environment Agency 2008b. *Water resources in England and Wales – current state and future pressures*. Environment Agency, Bristol, 22 pp.
http://cdn.environment-agency.gov.uk/geho1208bpas-e-e.pdf

Environment Agency 2010a. Section 2: Catchment Overview, *Great Ouse Catchment Flood Management Plan – Draft Plan, March 2010*. Environment Agency, Bristol, 90 pp. http://cdn.environment-agency.gov.uk/gean0310bsea-e-e.pdf

Environment Agency 2010b. *Mapping Hydropower Opportunities and Sensitivities in England and Wales: Technical Report*. Final Report February 2010, Environment Agency, Bristol, 67 pp. http://cdn.environment-agency.gov.uk/geho0310brzh-e-e.pdf

Environment Agency 2011. *The case for change – current and future water availability*. Report GEH01111BVEP-E-E, Environment Agency, Bristol, 41 pp. http://publications.environment-agency.gov.uk/PDF/GEHO1111BVEP-E-E.pdf

Environment Agency 2012. *Anglian Drought Plan*. February 2012, Environment Agency, Bristol, 171 pp.
http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/gean0112bvyl-e-e.pdf

Environment Agency 2013. *Environmental Flow Indicator: What it is and what it does*, 4 pp. http://cdn.environment-agency.gov.uk/LIT_7935_811630.pdf

Estes, C.C., and Orsborn, J.F. 1986. Review and analysis of methods for quantifying instream flow requirements. *Water Resources Bulletin*, **22**(3): 389-398.

Everard, M. 1996. The importance of periodic droughts for maintaining diversity in the freshwater environment. *Freshwater Forum*, **7**: 33-50.

Extence, C.A. 1981. The effect of drought on benthic macroinvertebrate communities in a lowland river. *Hydrobiologia*, **83**(2): 217-224.

Fitzhugh, T.W. 2014. EFCAM: A method for assessing alteration of environmental flow components. *River Research and Applications*, **30**(7): 825-844.

Francisco, F.J., Juanes, J.A., Álvarez-Cabria, M., Álvarez, C., García, A., Puente, A., and Barquín, J. 2014. Integration of hydrological and habitat simulation methods to define minimum environmental flows at the basin scale. *Water and Environment Journal*, **28**(2): 252-260.

Fraser, J.C. 1972. Regulated discharge and the stream environment. In Oglesby, R.T., Carlson, C.A., and McCann, J.A. eds., *River Ecology and Man*, Academic Press, New York, pp 263-286.

Fulton, A.A. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 892-893.

Gordon. N.D., McMahon, T.A. and Finlayson, B.L. 1992. *Stream Hydrology: An Introduction for Ecologists*. John Wiley and Sons Limited, Chichester, 526 pp.

Greenwood, M.T., Wood, P.J., and Monk, W.A. 2006. The use of fossil caddisfly assemblages in the reconstruction of flow environmental from floodplain paleochannels of the River Trent, England. *Journal of Paleolimnology*, **35**(4): 747-761.

Gurnell, A.M., and Petts, G.E. 1999. Causes of catchment scale hydrological changes. In *The Hydrology of the UK: A study of change*, Acreman, M.C. ed. Routledge, London, pp 82-98.

Gurnell, A.M., and Petts, G.E. 2011. Hydrology and Ecology of River Systems. In *Treatise in Water Science Volume 2*, Wilderer, P. ed. Academic Press, Oxford, pp 237-269.

Gustard, A., and Elliott, C.R.N. 1997. The role of hydro-ecological models in the development of sustainable water resources. In *Sustainability of water resources under increasing uncertainty*. Proceedings of the Rabat Symposium S1, April. IAHS Publication No. 240, pp 407-417.

Gustard, A., Cole, G., Marshall, D., and Bayliss, A. 1987. *Report No. 99: A study of compensation flows in the UK*, Institute of Hydrology, Wallingford, Oxford, 86 pp.

Hakala, J.P., and Hartman, K.J. 2004. Drought effect on stream morphology and brook trout (*Salvelinus fontinalis*) populations in forested headwater streams. *Hydrobiologia*, **515**(1-3): 203-213.

Halliday, S.J., Skeffington, R.A., Bowes, M.J., Gozzard, E., Newman, J.R., Loewenthal, M., Palmer-Felgate, E.J., Jarvie, H.P., and Wade, A.J. 2014. The Water Quality of the River Enborne, UK: Observations from High-Frequency Monitoring in a Rural, Lowland River System. *Water*, **6**(1): 150-180.

Hannaford, J., and Buys, G. 2012. Trends in seasonal river flow regimes in the UK. *Journal of Hydrology*, **475**: 158-174.

Hannaford, J., and Marsh, T. 2006. An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. *International Journal of Climatology*, **26**(9): 1237-1253.

Harkness, N. 1982. The River Tame – a short history of water pollution and control within an industrial river basin. *Water Science and Technology*, **14**(1-2): 153-165.

Harper, D. 1996. *Building Blocks for Rivers Conservation: Summary Guidance Manual*. National Rivers Authority R&D Note 18, Foundation for Water Research, Marlow, 39 pp.

Hassan, J. 1998. *A history of water in modern England and Wales*. Manchester University Press, Manchester, 214 pp.

Helsel, D.R. and Hirsch, R.M. 2002. *Statistical Methods in Water Resources*. Techniques of Water Resources Investigations, Book 4, Chapter A3. U.S. Geological Survey. 522 pp.

Herschy, R.W. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 906-907.

Hindley, D.R. 1973. The definition of dry-weather flow in river flow measurement. *Journal of the Institution of Water Engineers and Scientists*, **27**: 438-440.

Hisdal, H., and Tallaksen, L. eds. 2000. *Drought Event Definition*, Technical Report to the ARIDE Project Number 6, University of Oslo, Oslo, Norway, 41 pp. http://www.hydrology.uni-freiburg.de/forsch/aride/navigation/publications/pdfs/aride-techrep6.pdf

Holmes, M.G.R., Young, A.R., Gustard, A., and Grew, R. 2002. A region of influence approach to predicting flow duration curves within ungauged catchments. *Hydrology and Earth System Sciences*, **6**(4): 721-731.

Holmes, M.G.R., Young, A.R., Goodwin, T.H., and Grew, R. 2005. A catchment-based water resource decision-support tool for the United Kingdom. *Environmental Modelling and Software*, **20**(2): 197-202.

Humphries, P., and Baldwin, D.S. 2003. Drought and aquatic ecosystems: an introduction. *Freshwater Biology*, **48**(7): 1141-1146.

Humphries, P., Brown, P., Douglas, J., Pickworth, A., Strongman, R., Hall, K., and Serafini, L. 2008. Flow-related patterns in abundance and composition of the fish fauna of a degraded Australian lowland river. *Freshwater Biology*, **53**(4): 789-813.

James, A.W., and Suren, A.M. 2009. The response of invertebrates to a gradient of flow reduction – an instream channel study in a New Zealand lowland river. *Freshwater Biology*, **54**(11): 2225-2242.

Jarvie, H.P., Neal, C., Tappin, A.D., Burton, J.D., Harrow, M., Hill, L., and Neal, M. 2000. The water quality of the River Trent: from the lower non-tidal reaches to the freshwater tidal zone. *The Science of the Total Environment*, **251-252**: 335-367.

Jones, P.D., and Lister, D.H. 1998. Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrologic drought since 1865. *International Journal of Climatology*, **18**(9): 999-1013.

Jones, P., Conway, D., and Briffa, K. 1997. Precipitation variability and drought. In *Climates of the British Isles: Present, Past and Future*, Hulme, M., and Barrow, E. eds. Routledge, London, pp 197-219.

Jowett, I.G. 1997. Instream flow methods: a comparison of approaches. *Regulated Rivers: Research and Management*, **13**(2): 115-127.

Kendon, M., Marsh, T., and Parry, S. 2013. The 2010-2012 drought in England and Wales. *Weather*, **68**(4): 88-95.

Kennard, M.J., Mackay, S.J., Pusey, B.J., Olden, J.D., and Marsh, M. 2010a. Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. *River Research and Applications*, **26**(2): 137-156.

Kennard, M.J., Pusey, B.J., Olden, J.D., Mackay, S.J., Stein, J.L., and Marsh, N. 2010b. Classification of natural flow regimes in Australia to support environmental flow management. *Freshwater Biology*, **55**(1): 171-193.

Kiernan, J.D., Moyle, P.B., and Crain, P.K. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. *Ecological Applications*, **22**(5): 1472-1482.

Klaar, M.J., Dunbar, M.J., Warren, M., and Soley, R. 2014. Developing hydroecological models to inform environmental flow standards: a case study from England. *WIRES Water*, **1**(2): 207-217.

Kondolf, G.M., Larsen, E.W., and Williams, J.G. 2000. Measuring the modelling the hydraulic environment for assessing instream flows. *North American Journal of Fisheries Management*, **20**(4): 1016-1028.

Lacey, G. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 898-900.

Lake, P.S. 2000. Disturbance, patchiness, and diversity in streams. *Journal of the North American Benthological Society*. **19**(4): 573-592.

Lake, P.S. 2003. Ecological effects of perturbation by drought in flowing waters, *Freshwater Biology*. **48**(7): 1161-1172.

Lake, P.S. 2007. Flow-generated Disturbances and Ecological Responses: Floods and Droughts. In *Hydroecology and Ecohydrology: Past, Present and Future*, Wood, P.J., Hannah, D.M., and Sadler, J.P. eds., John Wiley and Sons Limited, Chichester, pp 75-92.

Lane, B.A., Sandoval-Solis, S., and Porse, E.C. 2015. Environmental flows in a human-dominated system: integrated water management strategies for the Rio Grande/Bravo basin. *River Research and Applications*. **31**(9): 1053-1065.

Lapworth, H. 1930. Meteorology and water supply. *Quarterly Journal of the Royal Meteorological Society*, **56**: 271-286.

Large, A.R.G., and Petts, G.E. 1996. Historical channel-floodplain dynamics along the River Trent: Implications for river rehabilitation. *Applied Geography*, **163**(3): 191-209.

Law, F. 1966. Engineering and Economic Problems of Large-Scale Water Supply. In *Man-Made Lakes*, Proceedings of a Symposium held at the Royal Geographical Society London, Lowe-McConnell, R.H. ed., Institute of Biology, Academic Press, London, pp 161-172.

Law, M., Wass, P., and Grimshaw, D. 1997. The hydrology of the Humber catchment. *The Science of the Total Environment*, **194-195**: 119-128.

Le Cren, E.D. 1961. How Many Fish Survive? *Association of River Authorities Yearbook 1961*, 57-64.

Ledger, M.E., and Hildrew, A.G. 2001. Recolonisation by the benthos of an acid stream following drought. *Archiv für Hydrobiologie*, **152**(1): 1-17.

Lees, M.L. 1987. Inland Water Surveying in the United Kingdom – A short history. In Institute of Hydrology and British Geological Survey, *Hydrological data United Kingdom 1985 Yearbook: an account of rainfall, river flows and groundwater levels January to December 1985*, Natural Environment Research Council Institute of Hydrology, Wallingford, Oxford, pp 35-47.

Legendre, P., and Legendre, L. 1998. *Numerical Ecology*. Developments in Environmental Modelling 20, Elsevier, Amsterdam, 853 pp.

Leopold, L.B. and Maddock, T. Jr. 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. *United States Geological Survey Professional Paper 252,* Washington, 56 pp.

Li, R., Chen, Q., Tonina, D., and Cai, D. 2015. Effects of upstream reservoir regulation on the hydrological regime and fish habitats of the Lijiang River, China. *Ecological Engineering*, **76**, 75-83.

Linnansaari, T., Monk, W.A., Baird, D.J., and Curry, R.A. 2013. *Review of approaches and methods to assess Environmental Flows across Canada and internationally*. Fisheries and Oceans Canada, Canadian Science Advisory Secretarial Research Document 2012/039, vii+75 pp. http://www.dfo-mpo.gc.ca/library/348885.pdf

Lloyd, D. 1935a. Rainfall Loss: Climatic Causations. *Water and Water Engineering*, **37**: 337-338.

Lloyd, D. 1935b. Rainfall Loss: The Effect of Temperature. *Water and Water Engineering*, **37**: 462-463.

Lloyd, D. 1935c. Rainfall Loss: Associated Periodicities and Causal Variations. *Water and Water Engineering*, **37**: 486-487.

Lloyd, D. 1935d. Rainfall Loss: Relation in Five Year Periods. *Water and Water Engineering*, **37**: 575-576.

Lloyd, D. 1936. Compensation Water: Stream Characteristic. *Water and Water Engineering*, **38**: 231-232.

Logan, P. 2001. Ecological quality assessment of rivers and integrated catchment management in England and Wales. In Scientific and legal aspects of biological monitoring in freshwater, Ravera, O. ed., *Journal of Limnology*, **60** Supplement 1, 25-32.

Lumbroso, D.M., Twigger-Ross, C., Raffensperger, J., Harou, J.J., Silcock, M., and Thompson, A.J.K. 2014. Stakeholders' Responses to the Use of Innovative Water Trading Systems in East Anglia, England. *Water Resources Management*, **28**(9): 2677-2694.

Lytle, D.A., and Poff, N.L. 2004. Adaptation to natural flow regimes. *Trends in Ecology and Evolution*, **19**(2): 94-100.

Mackay, S.J., Arthington, A.H., and James, C.S. 2014. Classification and comparison of natural and altered flow regimes to support an Australian trial of the Ecological Limits of Hydrologic Alteration framework. *Ecohydrology*, **7**(6): 1485-1507.

Mackie, J.K., Chester, E.T., Matthews, Ty.G., Robson, B.J. 2013. Macroinvertebrate response to environmental flows in headwater streams in western Victoria, Australia. *Ecological Engineering*, **53**: 100-105.

Mann, R.H.K. 1997. Temporal and spatial variations in the growth of 0 group roach (*Rutilus rutilus*) in the River Great Ouse, in relation to water temperature and food availability. *Regulated Rivers: Research and Management*, **13**(3): 277-285.

Marsh, T.J. 2002. Capitalising on river flow data to meet changing national needs – a UK perspective. *Flow Measurement and Instrumentation*, **13**(5-6): 291-298.

Marsh, T. and Hannaford, J. eds. 2008 *UK Hydrometric Register*. Hydrological data UK series, Centre for Ecology and Hydrology, Wallingford, 210 pp.

Marsh, T., Cole, G., and Wilby, R. 2007. Major droughts in England and Wales, 1800-2006. *Weather*, **62**(4): 87-93.

Martin, J.R. 1994. Water quality improvements in the Trent catchment, UK: a view of their relationship to management and legislative changes. *Water Science and Technology*, **30**(5): 167-176.

Mathews, R.C., and Bao, Y. 1991. The Texas method of preliminary instream flow assessment. *Rivers*, **2**(4): 295-310.

Mathews, R., and Richter, B.D. 2007. Application of the Indicators of Hydrologic Alteration Software in Environmental Flow Setting. *Journal of the American Water Resources Association*, **43**(6): 1400-1413.

Mathur, D., Bason, W.H., Purdy, E.J., and Silver, C.A. 1985. A critique of the instream flow incremental methodology. *Canadian Journal of Fisheries and Aquatic Sciences*, **42**(4): 825-831.

Mawson, J.H. 1936. *The Assessment of Compensation Water: A review of the present position and a suggested new method of assessment and control*. Unpublished Original Communication No 5114, Institution of Civil Engineers, 41 pp.

McLeod, G. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 904-906.

McMahon, T.A., and Finlayson, B.L. 2003. Droughts and anti-droughts: the low-flow hydrology of Australian rivers. *Freshwater Biology*, **48**(7): 1147-1160.

McManamay, R.A., Orth, D.J., Dolloff, C.A., and Mathews, D.C. 2013. Application of the ELOHA framework to regulated rivers in the Upper Tennessee River Basin: a case study. *Environmental Management*, **51**(6): 1210-1235.

Menzies, W.J.M. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 896-898.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J. 2008. Stationarity is Dead: Whither Water Management? *Science*, **319**(5863): 573-574.

Ministry of Agriculture and Fisheries 1954a. *The Calculation of Irrigation Need*. Technical Bulletin Number 4, Her Majesty's Stationery Office, London, 37 pp.

Ministry of Agriculture and Fisheries 1954b. *Irrigation*. Bulletin Number 138, Her Majesty's Stationery Office, London, 42 pp.

Ministry of Health 1930. *Report of the Technical Sub-Committee on the Assessment of Compensation Water*. London, Her Majesty's Stationery Office, 44 pp.

Ministry of Housing and Local Government 1960a. *River Severn Basin: Hydrological Survey*, Hydrometric Area 54, Her Majesty's Stationery Office, London, 134 pp.

Ministry of Housing and Local Government 1960b. *River Great Ouse Basin Hydrological Survey*. Hydrometric Area Number 33, Her Majesty's Stationery Office, London, 99 pp.

Ministry of Housing and Local Government 1961. *Wear and Tees Rivers: Hydrological Survey*, Hydrometric Areas 24 and 25, Her Majesty's Stationery Office, London, 103 pp.

Mishra, A.K., and Singh, V.P. 2010. A review of drought concepts. *Journal of Hydrology*, **391**(1-2): 202-216.

Mitchell, B. 1970. The institutional framework for water management in England and Wales. *Natural Resources Journal*, **10**: 566-589.

Mitchell, G., and McDonald, A. 2015. Developing resilience to England's future droughts: Time for cap and trade. *Journal of Environmental Management*, **149**, 97-107.

Montagu, 1870. Watershed Boards or Conservancy Boards for River Basins. Published in the *Second Report of the Royal Sanitary Commission*, Volume II: Arrangement of Sanitary Statutes, Analysis of Evidence, Précis of Oral Evidence, Paper on Watershed Boards, and Memorandum on Medical Duties of Medical Officers of Public Health. Her Majesty's Stationery Office, London, pp 339-350.

Morrison, R.R., and Stone, M.C. 2015. Investigating environmental flows for riparian vegetation recruitment using system dynamics modelling. *River Research and Applications*, **31**(4), 485-496.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A. 2009. *UK Climate Projections Science Report: Climate Change Projections.* Meteorological Office Hadley Centre, Exeter, UK 192 pp.
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87851&filetype=pdf

Naiman, R.J., Bunn, S.E., Nilsson, C., Petts, G.E., Pinay, G., and Thompson, L.C. 2002. Legitimizing fluvial ecosystems as users of water: an overview. *Environmental Management*, **30**(4): 455-467.

Naiman, R.J., Latterell, J.J., Pettit, N.E., and Olden, J.D. 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience*, **340**(9-10): 629-643.

Nehring, R.B., and Anderson, R.M. 1993. Determination of population-limiting critical Salmonid habitats in Colorado streams using the Physical Habitat Simulation System. *Rivers*, **4**(1): 1-19.

Nixon, M. 1964. The Successive re-use of river water: its effects and its limitations. Symposium of Papers of Water Sources, *Journal of the Institution of Water Engineers*, **18**: 225-231.

Office for National Statistics 2011a. Table A1-4, Principal Projection - Components of change, 2010-based, published 26th October 2011 (online). Office for National Statistics.
http://www.ons.gov.uk/ons/rel/npp/national-population-projections/2010-based-projections/rft-table-a1-4-principal-projection---england-summary.xls

Office for National Statistics 2011b. Table A2-4, Principal Projection – England Population in Age Groups, 2010-based, published 26th October 2011 (online). Office for National Statistics. http://www.ons.gov.uk/ons/rel/npp/national-population-projections/2010-based-projections/rft-table-a2-4-principal-projection---england-population-in-age-groups.xls

Office for National Statistics 2012. 2010-based Sub-national Population Projections for England. Table 1: Projections by Sex and Quinary Age, published 21st March 2012 (online). Office for National Statistics. http://www.ons.gov.uk/ons/rel/snpp/sub-national-population-projections/2010-based-projections/rft-table-1-regions-quinary.xls

Office of the Minister for Science 1962. *Irrigation in Great Britain*. a report by the Natural Resources Technical Committee, Her Majesty's Stationery Office, London, 82 pp.

Office of Water Services and Environment Agency 2011. *The case for change – reforming water abstraction management in England*, Environment Agency, Bristol, 33 pp.

Okun, D.A., Weiss, C.M., Alspaugh, T.A., Berg, E.J., Berger, B.B., Clark, H.F., Connell, C.H., DeMartini, F.E., Dobbins, W.E., Edwards, G.P., Engelbrecht, R.S., Ettinger, M.B., Foulke, D.G., Furman, T. deS., Gaffeny, P.E., Gellman, I., Gloyna, E.F., Harding, H.G., Helwig, J.D., Hoak, R.D., Ingols, R.S., Ingram, W.M., Kabler, P.W., Katz, M., Kittrell, F.W., Lardieri, N.J., Luley, H.G., Lynn, W.R., McGauhey, P.H., Olds, J., Porges, R., Shuval, H., Steffen, A.J., Straub, C., Surber, E., Tarzwell, C.M., Teletzke, G.H., Towne, W.W., Trebler, H.A., Tsivoglou, E.C., Weisberg, E., and Woodward, R.L. 1962. A review of the literature of 1961 on wastewater and water pollution control. *Journal Water Pollution Control Federation*, **34**: 629-703.

Olden, J.D., and Poff, N.L. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, **19**(2): 101-121.

Orth, D.J. 1987. Ecological considerations in the development and application of instream flow habitat models. *Regulated Rivers: Research and Management*, **1**(2): 171-181.

Orth, D.J., and Maughan, O.E. 1981. Evaluation of the “Montana Method” for recommending instream flows in Oklahoma streams. *Proceedings of the Oklahoma Academy of Science*, **61**: 62-66.

Orth, D.J., and Maughan, O.E. 1982. Evaluation of the incremental methodology for recommending instream flows for fishes. *Transactions of the American Fisheries Society*, **111**(4): 413-445.

O’Riordan, T. 1970. Spray irrigation and the Water Resources Act, 1963. *Transactions of the Institute of British Geographers*, **49**: 33-47

Overton, I.C., Smith, D.M., Dalton J., Barchiesi S., Acreman M.C., Stromberg, J.C., and Kirby, J.M., 2014. Implementing environmental flows in integrated water resources management and the ecosystem approach. *Hydrological Sciences Journal*, **59**(3–4), 860–877.

Paul, M.J., and Meyer, J.L. 2001. Streams in the urban landscape. *Annual Review of Ecology and Systematics*, **32**: 333-365.

Parry, S., Marsh, T., and Kendon, M. 2013. 2012: from drought to floods in England and Wales. *Weather*, **68**(10): 268-274.

Pentelow, F.T.K. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 898.

Petts, G.E. 1984. *Impounded Rivers: Perspectives for Ecological Management*, John Wiley and Sons Limited, Chichester, 326 pp.

Petts, G.E. 1987. Time-scales for ecological change in regulated rivers. In *Regulated streams: advances in ecology*, Craig, J.F. and Kemper, J.B, eds., Plenum, London, pp. 257-266.

Petts, G.E. 1988. Regulated rivers in the United Kingdom. *Regulated Rivers: Research and Management*, **2**(3): 201-220.

Petts, G.E. 1996. Water allocation to protect river ecosystems. *Regulated Rivers: Research and Management*, **12**(4-5): 353-365.

Petts, G.E. 2007. Hydroecology: the Scientific Basis for Water Resources Management and River Regulation. In *Hydroecology and Ecohydrology: Past, Present and Future*, Wood, P.J., Hannah, D.M., and Sadler, J.P. eds. John Wiley and Sons Limited, Chichester, pp 225-252.

Petts, G.E. 2009. Instream flow science for sustainable river management. *Journal of the American Water Resources Association*, **45**(5): 1071-1086.

Petts, G.E., and Bickerton, M.A. 1994. River Wissey Investigations: linking hydrology and ecology. *National Rivers Authority Anglian Region Operational Investigation 526, Project Report OI/526/2/A.*

Petts, G.E., and Gurnell, A.M. 2013. Hydrogeomorphic Effects of Reservoirs, Dams, and Diversions. In *Treatise on Geomorphology*, Volume 13, Geomorphology of Human Disturbances, Climate Change and Natural Hazards Shroder, J.F. Editor-in-Chief and James, L.A., Harden, C.P., and Clague, J.J. Volume Editors., Academic Press, San Diego, pp 96-114.

Petts, G.E., and Maddock, I. 1996. Flow allocation for in-river needs. In *River Restoration: selected extracts from the Rivers Handbook*, Petts, G.E., and Calow, P. eds., Blackwell Scientific Publications, Oxford, pp 60-79.

Petts, G.E., Maddock, I., Bickerton, M., and Ferguson, A.J.D. 1995. Linking hydrology and ecology: the scientific basis for river management. In *The Ecological Basis for River Management*. Harper, D.M., and Ferguson, A.J.D. eds. John Wiley and Sons Limited, Chichester, pp 1-16.

Petts, G.E., Crawford, C., and Clarke, R. 1996. *Determination of Minimum Flows*. Research & Development Note 449, National Rivers Authority, Bristol.

Petts, G.E., Bickerton, M.A., Crawford, C., Lerner, D.N., and Evans, D. 1999. Flow management to sustain groundwater-dominated stream ecosystems. *Hydrological Processes*, **13**(3): 497-513.

Petts, G.E., Sparks, R., and Campbell, I. 2000. River restoration in developed economies. In *Global Perspectives on River Conservation: Science, Policy and Practice*, Boon, P.J., Davies, B.R., and Petts, G.E. eds. John Wiley and Sons Limited, Chichester, pp 493-508.

Petts, G.E., Heathcote, J., and Martin, D. eds. 2002. *Urban Rivers: Our Inheritance and Future*, IWA Publishing and Environment Agency, London, 117 pp.

Petts, G.E., Nestler, J., Kennedy, R. 2006. Advancing science for water resources management. *Hydrobiologia*, **565**: 277-288.

Pinder, L.C.V., Marker, A.D.H., Mann, R.H.K., Bass, J.A.B., and Copp, G.H. 1997. The River Great Ouse, a highly eutrophic, slow-flowing, regulated, lowland river in Eastern England. *Regulated Rivers: Research and Management*, **13**(3): 203-219.

Pirt, J. 1983. *The estimation of riverflows in ungauged catchments*. Unpublished PhD Thesis, Loughborough University of Technology, Two Volumes.

Pirt, J., and Douglas, J.R. 1982. A study of low flows using data from the Severn and Trent catchments. *Journal of the Institution of Water Engineers and Scientists*, **36**: 299-308.

Poff, N.L., and Matthews, J.H. 2013. Environmental flows in the Anthropocence: past progress and future prospects. *Current Opinion in Environmental Sustainability*, **5**(6): 667-675.

Poff, N.L., and Zimmerman, J.K.H. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, **55**(1): 194-205.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. 1997. The Natural Flow Regime: A paradigm for river conservation and management. *BioScience*, **47**(11): 769-784.

Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Rogers, K.H., Meyer, J.L., and Stanford, J.A. 2003. River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment*, **1**: 298-306.

Poff, N.L., Olden, J.D., Pepin, D.M., and Bledsoe, B.P. 2006. Placing global stream flow variability in geographic and geomorphic contexts. *River Research and Applications*, **22**(2): 149-166.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keeffe, J.H., Olden, J.D., Rogers, K., Tharme, R.W., and Warner, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, **55**(1): 147-170.

Porter, E. 1978. *Water Management in England and Wales*. Cambridge University Press, Cambridge, 178 pp.

Postel, S., and Richter, B.D. 2003. *Rivers for Life: Managing Water for People and Nature*, Island Press, Washington, 253 pp.

Power, M.E., Sun, A., Parker, G., Dietrich, W.E., and Wotton, J.T. 1995. Hydraulic food-chain models. *BioScience*, **45**(3): 159-167.

Prescot Hill, E. 1906. The yield of catchment areas. *Proceedings of the Institution of Civil Engineers*, **167**: 181-185.

Prescot Hill, H. 1931. Presidential address. *Transactions of the Institution of Water Engineers*, **36**: 21-33.

Prickett, C.N. 1966. Water supply and conservation for agriculture. In Thorn, R.B. ed., *River Engineering and Conservation Works*, Butterworths, London, pp 441-478.

Rahiz, M., and New, M. 2012. Spatial coherence of meteorological droughts in the UK since 1914. *Area*, **44**(4): 400-410.

Rahiz, M., and New, M. 2013. 21st Century Drought Scenarios for the UK. *Water Resources Management*, **27**, 1039-1061.

Reiser, D.W., Wesche, T.A., and Estes, C. 1989. Status of instream flow legislation and practices in North America. *Fisheries*, **14**(2): 22-29.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, **10**(4): 1163-1174.

Richer, B.D., Baumgartner, J.V., Wigington, R., and Braun, D.P. 1997. How much water does a river need? *Freshwater Biology*, **37**(1): 231-249.

Richter, B.D., Baumgartner, J.V., Braun, D.P., and Powell, J. 1998. A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research and Management*, **14**(4): 329-340.

Richter, B.D., Warner, A.T., Meyer, J.L., and Lutz, K. 2006. A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications*, **22**(3): 297-318.

Richter, B.D., Davis, M.M., Apse, C., and Konrad, C. 2012. A presumptive standard for environmental flow protection. *River Research and Applications*, **28**(8): 1312-1321.

Risbridger, C.A. 1963. Compensation water, re-use of water and waste prevention. In *Conservation of Water Resources in the United Kingdom*, Proceedings of the Symposium organised by and held at the Institution of Civil Engineers, Institution of Civil Engineers, London, pp 97-118

Rivett, M.O., Ellis, P.A., and Mackay, R. 2011. Urban groundwater baseflow influence upon inorganic river-water quality: The River Tame headwaters catchment in the City of Birmingham, UK. *Journal of Hydrology*, **400**(1-2): 206-222.

Rolls, R.J., and Arthington, A.H. 2014. How do low magnitudes of hydrologic alteration impact riverine fish populations and assemblage characteristics? *Ecological Indicators*, **39**: 179-188.

Rolls, R.J., Leigh, C., and Sheldon, F. 2012a. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshwater Science*, **31**(4): 1163-1186.

Rolls, R., Marsh, N., and Sheldon, F. 2012b. *Review of literature quantifying ecological responses to low flows*. National Water Commission, Canberra, 55 pp.

Rowntree, N.A.F. 1966. The extent to which the Water Resources Act, 1963, has been implemented: the work of the Water Resources Board. *Association of River Authorities Yearbook 1966*, pp 162-178.

Rydz, B. 1965. in discussion of Minimum Acceptable Flow. *Journal of the Institution of Water Engineers*, **19**: 50-51.

Salmon and Freshwater Fisheries Committee 1961. Report of the Committee on Salmon and Freshwater Fisheries. Cmnd 1350, Her Majesty's Stationery Office, London, 104 pp.

Sandeman, E. 1921. Compensation Water, a paper presented at the 1921 Engineering Conference held at the Institution of Civil Engineers, London, pp 42-49.

Sanderson, J.S., Rowan, N., Wilding, T., Bledsoe, B.P., Miller, W.J., and Poff, N.L. 2012. Getting to scale with environmental flow assessment: the Watershed Flow Evaluation Tool. *River Research and Applications*, **28**(9): 1369-1377.

Schumm, S.A., and Lichty, R.W. 1965. Time, space and causality in geomorphology. *American Journal of Science*, **263**, 110-119.

Sedgwick, S.D. 1963. Discussion on Preservation of fish life, amenities and facilities for recreation. In *Conservation of Water Resources in the United Kingdom*, Proceedings of the Symposium organised by and held at the Institution of Civil Engineers, Institution of Civil Engineers, London, pp 72.

Sheail, J. 1984. Constraints on water-resource development in England and Wales: the concept and management of compensation flows. *Journal of Environmental Management*, **19**: 351-361.

Sheail, J. 1985. Edinburgh, the Upper Tweed, and the question of compensation water. *Scottish Geographical Magazine*, **101**: 66-76.

Sheail, J. 1987. Appendix 1: Historical development of setting compensation flows. In Gustard, A., Cole, G., Marshall, D., and Bayliss, A. *A study of compensation flows in the UK*, Report No. 99, Institute of Hydrology, Wallingford, pp 1-28.

Shenton, W., Bond, N.R., Yen, J.D.L., and Mac Nally, R. 2012. Putting the "Ecology" into environmental flows: Ecological dynamics and demographic modelling. *Environmental Management*, **50**(1): 1-10.

Shiau, J.-T., and Wu, F.-C. 2013. Optimizing environmental flows for multiple reaches affected by a multipurpose reservoir system in Taiwan: Restoring natural flow regimes at multiple temporal scales. *Water Resources Research*, **49**(1): 565-584.

Smakhtin, V.Y. 2001. Low-flow hydrology: a review. *Journal of Hydrology*, **240**(3-4): 147-186.

Smakhtin, V.Y., Watkins, D.A., and Hughes, D.A. 1995. Preliminary analysis of low-flow characteristics of South African rivers. *Water SA*, **21**(3): 201-210.

Snelder, T., Booker, D., and Lamouroux, N. 2011. A method to assess and define environmental flow rules for large jurisdictional regions. *Journal of the American Water Resources Association*, **47**(4): 828-840.

Spence, R., and Hickley, P. 2000. The use of PHABSIM in the management of water resources and fisheries in England and Wales. *Ecological Engineering*, **16**(1): 153-158.

Stalnaker, C.B. 1994. Evolution of instream flow habitat modelling. In Calow, P., and Petts, G.E. eds. *The Rivers Handbook Volume 2*, Blackwell Scientific Publications, Oxford, pp 276-288.

Stewart, L. 1967. In Contributed discussion on River Management in Relation to River Flow. In *River Management*, Isaac, P.C.G. ed. Proceedings of a Symposium organised by the Department of Civil Engineering, University of Newcastle upon Tyne, 20 and 21 September 1966, Maclaren and Sons Limited, London, pp 135-136.

Stewart, L. 1968a. *The Water Requirements of Salmon in the River Lune*. Lancaster River Authorities Fisheries Department, Report of Fisheries Officer, Lancaster, 10 pp (cited in Banks, 1969). http://aquaticcommons.org/7779/1/2_Stewart_report_1.pdf

Stewart, L. 1968b. *The Water Requirements of Salmon in the River Leven*. Lancaster River Authorities Fisheries Department, Report of Fisheries Officer, Lancaster (cited in Banks, 1969).

Stewart, L. 1969. Criteria for safeguarding fisheries, fish migration, and angling in rivers. *Yearbook of the Association of River Authorities*, 134-149.

Stubbington, R., Wood, P.J., and Boulton, A.J. 2009. Low-flow controls on benthic and hyporheic macroinvertebrate assemblages during supra-seasonal drought. *Hydrological Processes*, **23**(15): 2252-2263.

Tait, W.A.P. 1907. The Talla water supply of the Edinburgh and District Waterworks. *Proceedings of the Institution of Civil Engineers*, **167**: 102-152.

Tavassoli, H.R., Tahershamsi, A., and Acreman, M.A., 2014. Classification of natural flow regimes in Iran to support environmental flow management. *Hydrological Sciences Journal*, **59**(3–4): 517–529.

Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries*, **1**(4): 6-10.

Tessmann, S.A. 1980. *Reconnaissance Elements of the Western Dakotas Region of South Dakota study*. Environmental Assessment - Appendix E. Water Resources Research Institute, South Dakota State University, Brookings, South Dakota, 57 pp.

Tharme, R.E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications,* **19**(5-6): 397-441.

The Nature Conservancy 2009. *Indicators of Hydrologic Alteration Version 7.1 Users Manual*. The Nature Conservancy, 76 pp.

Tonkin, J.D., Jähnig, S.C., and Haase, P. 2014. The Rise of Flow-ecology and Environmental Flow Research. *Environmental Processes*, **1**(3): 323-330.

Turing, H.D. 1947a. *First of a Series of Reports on Pollution Affecting Rivers in England and Wales*. British Field Sports Society, London, 48 pp.

Turing, H.D. 1947b. *Second of a Series of Reports on Pollution Affecting Rivers in England and Wales*. British Field Sports Society, London, 40 pp.

Turing, H.D. 1949a. *Third of a Series of Reports on Pollution Affecting Rivers in England and Wales*. British Field Sports Society, London, 48 pp.

Turing, H.D. 1949b. *Fourth of a Series of Reports on Pollution Affecting Rivers in Scotland*. British Field Sports Society, London, 59 pp.

Van Oosterom, H. 1967. Control of Abstractions. In *River Management,* Isaac, P.C.G. ed., Proceedings of a Symposium organised by the Department of Civil Engineering, University of Newcastle upon Tyne, 20th and 21st September 1966, Maclaren and Sons Limited, London, pp 75-85.

Waddingham, J., Cadman, D., Murray-Bligh, J., and Tanner, K. 2008. Towards appropriate emphasis on regulation of the hydrological regime in integrated river basin management. *BHS 10th National Symposium, Exeter, 2008*, pp 481-486

Waddington, J.I. 1962. Discussion on River utilization and the preservation of migratory fish life. *Proceedings of the Institution of Civil Engineering*, **18**: 904.

Wallingford HydroSolutions 2010. *LowFlows 2™ User Guide December 2010*, Wallingford HydroSolutions, Wallingford, 59 pp.

Warfe, D.M., Hardie, S.A., Uytendaal, A.R., Bobbi, C.J., and Barmuta, L.A. 2014. The ecology of rivers with contrasting flow regimes: identifying indicators for setting environmental flows. *Freshwater Biology*, **59**(10): 2064-2080.

Wood, P.J., and Armitage, P.D. 2004. The response of the macroinvertebrate community to low-flow variability and supra-seasonal drought within a groundwater dominated stream. *Archiv für Hydrobiologie*, **161**(1): 1-20.

Wood, P.J., Agnew, M.D., and Petts, G.E. 2000. Flow variations and macroinvertebrate community responses in a small groundwater-dominated stream in south-east England. *Hydrological Processes*, **14(16-17)**: 3133-3147.

Wilby, R. L., Fenn, C.R., Wood, P.J., Timlett, R., and LeQuesne, T. 2011. Smart licensing and environmental flows: Modeling framework and sensitivity testing. *Water Resources Research,* **47***: W12524* DOI: 10.1029/2011WR011194

Withers, W.B.J. 1973. The evolution and evaluation of irrigation in Britain. *The Agricultural Engineer*, Winter 1973, 136-139.

Yang, W., and Yang, Z. 2014. Effects of long-term environmental flow releases on the restoration and preservation of Baiyangdian Lake, a regulated Chinese freshwater lake. *Hydrobiologia*, **730**(1): 79-81.

Young, A.R., Round, C.E., Gustard, A. 2000. Spatial and temporal variations in the occurrence of low-flow events in the UK. *Hydrology and Earth System Sciences*, **4**(1): 35-45.

Young, A.R., Gustard, A., Bullock, A., Sekulin, A.E. and Croker, K.M. 2000. A river network based hydrological model for predicting natural and influenced flow statistics at ungauged sites: Micro LOW FLOWS. *Science of the Total Environment*, **251-252**: 293-304.

Young, A.R., Grew, R., and Holmes, M.G.R. 2003. Low flows 2000: a national water resources assessment and decision support tool. *Water Science and Technology*, **48**(10): 119-126.

Yount, D.D. and Niemi, G.D. 1990. Recovery of lotic communities and ecosystems from disturbance - a narrative review of case studies. *Environmental Management*, **14**(5): 547-569.

Appendices

Appendix 1.1: Summary of selected recent International environmental flow research

Author(s)	**Research Aims**	**Location**	**Findings**
REVIEW PAPERS			
Acreman *et al*. 2014b	Provision of an overview of recent developments and applications of *e-flows* to explore the changing role of ecohydrological science.	N/A	A major issue is dealing with uncertainty, *e-flow* science is uncertain; there is a need to demonstrate the utility of research outputs. Areas for future research include ecosystem function and species interactions, groundwater-surface water interactions, paradigms and approaches and dealing with uncertainty.
Davies *et al*. 2014	The review aimed to highlight the lack of connection between current trends in *e-flow* literature and theory with assessments of the efficacy and practical application of *e-flow* methods. Steps that will improve the applicability, implementation and success of *e-flows* will be determined.	N/A	*E-flows* should have adaptive capacity and variability built into them. Long-term research and the formal establishment of long-term ecological monitoring sites is required.
Dunbar *et al*. 2012	Review of developments over the past 15 years in hydraulic-habitat modelling and the use of four examples illustrating the use of model output.	N/A	Data requirements for hydraulic-habitat model approaches are still high, and hydraulic-habitat modelling is still dependent on the development of habitat suitability models. Although meso-scale physical habitat models show promise in that their ecological scale closely matches that of riverine communities, they are currently limited in their ability to make predictions for unobserved conditions.
Poff and Matthews 2013	Provision of an outline of the scientific foundations and progressive development of the current *e-flow* framework over the past 25 years. Discussion of the challenges facing the framework during the current period of rapid global change.	N/A	Since its emergence as a holistic perspective, the *e-flow* concept has shown a remarkable record of consolidation, expansion, globalisation and now transition. Managing rivers, their floodplains and entire catchments for balanced human and ecological goals is a principle that has become embraced globally. The Anthropocene poses monumental and growing management challenges.
Shenton *et al*. 2012	Discussion of assumptions undermining the capacity of *e-flow* methods (1) the use of habitat suitability as a proxy for population status; (2) the use of historical time series to forecast future conditions and flow sequences; (3) an inability to handle extreme flow events associated with climate variability, and (4) the assumption of process stationarity for flow sequences.	N/A	Scientists should broaden methods used in *e-flow*s to include tools that implicitly model flow-ecology dynamics. Future methods are needed to capture the dynamics of freshwater ecosystems in ways that can translate alternative flow regimes into estimates of population response, which, in turn, can guide water allocation trade-offs.

Tonkin *et al*. 2014	Examination of trends in riverine flow-ecology research from 1995-2012 with the aim of identifying trends in *e-flow* research.	N/A	Although the USA dominated flow-ecology research output, Australia dominated *e-flow* research. *E-flow* research has exponentially expanded since the mid 1990s with research mostly performed in developed countries.

Author(s)	**Research Aims**	**Location**	**Findings**
FLOW-ECOLOGY LINKAGES			
Bino *et al*. 2014	Exploration of alternative water management strategies and the identification of maximal strategies for the successful long-term management of colonial waterbirds and the ecosystem as a whole. Assessments aimed to link waterbird ecological response, as breeding abundances, to water availability using Bayesian logistic regression models.	Macquarie Marshes, Australia	Clear relationships existed between flows and breeding both in frequencies and total abundances. Thresholds emerged for triggering breeding events in all species studied, but these varied among species. Management to different targets of *e-flows* affected overall and specific breeding probabilities.
Chester *et al*. 2014	Sampling of fish and crayfish in four regulated headwater streams before and after the release of summer-autumn *e-flows* and in four unregulated streams to determine whether fish abundances increased in response to flow releases.	Victoria, Australia	Although fish were recorded in the regulated streams before 1996, they were not recorded in the present study upstream or downstream of weirs despite flow releases. Crayfish remained in the regulated streams throughout but did not become more abundant in response to flow releases. Flow release volumes may have been too small or have operated for an insufficient time to allow fish to recolonise regulated streams.
Kiernan *et al*. 2012	Examination of the response of fishes to the establishment of a new flow regime that was designed to mimic the seasonal timings of natural increases and decreases in streamflow.	California, USA	The restoration of native fishes was achieved by manipulating streamflows at biologically important times of the year. This only required a small increase in the total volume of water delivered downstream during most years. Results validate that natural flow regimes can be used to effectively manipulate and manage fish assemblages in regulated rivers.
Li *et al*. 2015	The development of an integrated hydro-environmental-habitat model using a target species of cyprinid fish, and the analysis of the effects of flow regime changes due to upstream reservoir operation on juvenile fish.	Lijiang River, China	The model allowed the development of an ecologically based flow regime and development of reservoir operating rules meet several conservation levels for the target fish habitats.
Mackie *et al*. 2013	An examination of the post-drying recovery of macroinvertebrate assemblages in regulated headwater streams following small *e-flow* releases.	Victoria, Australia	The streams that received *e-flows* showed progressive increases in taxa richness downstream of the release point over time. Relatively small *e-flow* allocations can have positive impacts on macroinvertebrate assemblages in small regulated streams over short time periods.

Rolls and Arthington 2014	The quantification of patterns of fish response to flow regime alteration by the testing of four flow regulation effects on 17 (univariate and multivariate) response variables.	South East Queensland, Australia	Only three of 17 response variables representing fish population abundance and assemblage attributes showed significant differences between regulated and unregulated reaches. Effects associated with flow regulation were most evident where historically intermittent flow regimes had become more perennial due to managed dam releases.
Warfe *et al*. 2014	Description of the ecological characteristics of rivers with different flow regimes and the identification of ecological indicators that could be used to evaluate the success of implemented *e-flows*.	Tasmania, Australia	Rivers with different flow regimes can support a distinctive ecology, and conventional metrics of ecological characteristics may not be the most sensitive to flow regime. Multivariate rather than univariate metrics of biotic assemblages were more effective at distinguishing perennial and intermittent flow regimes. Fish assemblages were not strong indicators of flow regime.
Yang and Yang 2014	The use of existing data to determine whether intermittent flow releases over a 16-year period had successfully restored China's Baiyangdian Lake ecosystem.	China	Critical components of the water level regime including the annual mean, the 7-day low and the 30-day low and high water levels differed significantly before and after releases. Releases significantly improved water quality, however, changes in the reed yield and fish species were not significant. *E-flow* releases had tended to stabilise water levels at levels below those pre-release with lower intra- and inter-annual fluctuations. This excessive stability had not benefited the ecosystem's health and biodiversity.

Author(s)	**Research Aims**	**Location**	**Findings**
APPLICATION OF EXISTING *E-FLOW* METHODOLOGIES / PRACTICAL EXAMINATION OF *E-FLOWS*			
Caissie *et al*. 2014	Evaluation of six hydrology based *e-flow* methodologies using flow data from 52 gauging stations located across the Maritime Provinces.	Maritime Provinces, Canada	Based on current knowledge, hydrology based methods are as good as any other *e-flow* approach. Some methods tested provided adequate *e-flow* protection; however, other methods did not provide adequate flow protection. The study demonstrated the importance of the hydrologic flow regime, particularly as it pertains to the baseflow component, as a significant determinant in the level of instream flow protection.
Deitch and Kondolf 2012	Examination of an *e-flow* that has been proposed as the threshold for the operation of small instream diversions in northern coastal California along a longitudinal channel gradient.	California, USA	The magnitude and frequency of threshold exceedence varied among streams draining smaller catchments, whereas threshold flows occurred continuously throughout most of the rainy season in larger streams. Differences in threshold duration have important management consequences, water users diverting from headwater streams may acquire water over much shorter periods than those diverting from streams further downstream.

Lane *et al*. 2015	Addressing the need for integrated water management by the development of an alternative reservoir operation policy to provide *e-flows* while reducing water management trade-offs. The development of spatially distributed *e-flows* and an alternative reservoir rule curve.	Rio Grande and Bravo Basins, USA and Mexico	A single optimal policy was identified that maximised *e-flow*s while maintaining specified human objectives. By changing the timing but not the volume of releases, the proposed policy has the potential to sustain key ecological and geomorphic functions without significantly impacting current water management objectives.
McManamay *et al*. 2013	A test of the utility of ELOHA in informing flow restoration applications for fish and riparian communities in regulated rivers.	Upper Tennessee River Basin, USA	Results of the study did not suggest that univariate relationships between flow and ecology can produce results sufficient to guide flow restoration in regulated rivers.
Morrison and Stone 2015	The development and demonstration of a stochastic system dynamics modelling framework to evaluate *e-flow* alternatives.	New Mexico, USA	Results demonstrated how flow alternatives can be evaluated using comparative metrics which allow water resource managers to more easily evaluate alternatives before incorporating *e-flow*s into existing operations.
Sanderson *et al*. 2012	Application of the ELOHA framework to develop the Watershed Flow Evaluation Tool. WFET aims to estimate flow-related ecological risk at a regional scale.	Colorado, USA	Although the WFET was successfully implemented to assess ecological risk across one study catchment, active channel change and limited data precluded the successful application of the WFET in a second catchment.
Shiau and Wu 2013	Proposal of an *e-flow* proportion strategy and three-period release approach, and multireach operation scenarios that simultaneously optimise reservoir performances and *e-flow* objectives at a range of timescales.	Taiwan	Results implied that taking into account *e-flow* objectives did not necessarily degrade the overall reservoir performance. This was due to the positive effect on flood control which compensated for the adverse effects on hydropower generation and domestic water supply.
Snelder *et al*. 2011	Development of a method for assessing hydrological rules of thumb. The method links regionalised flow duration curves, at-station hydraulic geometry, and generalised physical habitat models to make regional assessments.	New Zealand	The methodology was applied to assess a set of rules that are proposed as default minimum flows and allocation limits for New Zealand rivers, illustrating that the minimum flow rules had variable consequences. The approach could be used to quantify the trade-off between environmental protection and water resources availability and reliability.

Author(s)	**Research Aims**	**Location**	**Findings**
NEW *E-FLOW* APPROACHES/FRAMEWORKS			
Acreman *et al*. 2014a	Definition of a new framework for considering the range of *e-flow* methodologies focussing on the role of the designer flow regime paradigm designing to support socially-defined novel ecosystems.	N/A	The natural flow regime approach is more applicable to natural and semi-natural rivers where the aim is ecological conservation with little change to the natural flow regime. The designer approach suits regulated and managed rivers. In the future the designer approach may become the only feasible paradigm.

Belmar *et al*. 2011	Development of a classification for 390 stream sections of the Segura Basin based on 73 hydrologic metrics that characterise their natural flow regime.	Segura Basin, Spain	A PCA indicated high redundancy among most hydrologic metrics as well as flow magnitude for main rivers and temporal variability for tributary streams. A classification successfully produced groups of rivers with different seasonal discharge patterns displaying a high degree of spatial cohesion.
Bobbi *et al*. 2014	Description of a framework with the flexibility to support applications across different catchments while catering for catchment-specific issues to guide the assessment and recommendation of *e-flow* regimes in Tasmania.	Tasmania, Australia	Experiments demonstrated the imperative that scientists are not only involved in water planning but also in the implementation, monitoring and evaluation of plans so that the benefits of adaptive management can be realised.
Fitzhugh 2014	Demonstration of a new method EFCAM (environmental flow component assessment method) that analyses and summarises the alteration of environmental *e-flow* components.	USA (66 rivers)	Results demonstrated that EFCAM is an effective method for efficiently summarising flow alteration of ecologically relevant components of flows. The EFCAM was considered a useful potential addition to the Indicators of Hydrologic Alteration.

Appendix 2.1: Information on gauging stations used in flow assessments (Trent catchment 31 study sites)

Watercourse	Station Name	FAR[1]	Sensitivity[2] (%)	Long-term[3]		1990 – 2009[4]		
				Mean Flow (m^3s^{-1})	Q_{95} (m^3s^{-1})	Mean Flow (m^3s^{-1})	Q_{95} (m^3s^{-1})	Q_{95} (% Mean Flow)
River Amber	Wingfield Park	SRPG	22	1.370	0.348	1.400	0.387	27.6
River Anker	Polesworth	GE	15.1	3.098	0.708	3.406	0.865	25.4
River Churnet	Basford Bridge	SP	35.2	1.927	0.433	1.937	0.407	21.0
River Cole	Coleshill	EI	26.7	0.946	0.188	0.958	0.182	19.0
River Derwent	Chatsworth	SRP	12.9	6.301	1.460	6.419	1.487	23.2
River Derwent	Church Wilne	SPEI	5.4	18.582	5.072	18.558	5.051	27.2
River Derwent	St Marys Bridge	SRPGEI	n/a	17.293	4.542	16.618	4.220	25.4
River Derwent	Yorkshire Bridge	SRP	8.8	2.089	0.516	2.070	0.475	22.9
River Dove	Izaak Walton	N	9.4	1.913	0.540	1.926	0.544	28.2
River Dove	Marston on Dove	SRPG	5.8	13.909	3.573	13.933	3.478	25.0
River Dove	Rocester Weir	N	14.7	7.448	1.740	7.587	1.812	23.9
Dover Beck	Lowdham	G	8	0.155	0.049	0.155	0.048	31.0
River Ecclesbourne	Duffield	PE	15.8	0.628	0.097	0.627	0.099	15.8
River Greet	Southwell	GI	n/a	0.298	0.098	0.297	0.095	32.0
River Idle	Mattersey	SRGE	n/a	2.351	0.825	2.149	0.788	36.7
River Manifold	Ilam	N	18.1	3.560	0.629	3.463	0.605	17.5
Meece Brook	Shallowford	EI	n/a	0.656	0.139	0.680	0.130	19.1
River Penk	Penkridge	EI	10.6	2.270	0.582	2.355	0.605	25.7
River Rea	Calthorpe Park	E	11.5	0.776	0.213	0.751	0.202	26.9
Rothley Brook	Rothley	SE	17.7	0.735	0.123	0.732	0.115	15.7
River Ryton	Blyth	EI	n/a	1.544	0.538	1.534	0.516	33.6
River Ryton	Worksop	GE	n/a	0.488	0.088	0.413	0.086	20.8
River Sence	South Wigston	EI	n/a	0.946	0.141	0.915	0.146	16.0
River Soar	Littlethorpe	E	n/a	1.355	0.261	1.307	0.244	18.7
River Sow	Great Bridgford	GE	11.6	1.148	0.332	1.196	0.352	29.4
River Tame	Lea Marston Lakes	EI	n/a	13.801	7.280	14.289	7.576	53.0
River Torne	Auckley	GE	12.5	0.888	0.330	0.851	0.317	37.3
River Trent	Colwick	SRPGEI	2.56	83.799	27.590	83.538	26.910	32.2
River Trent	North Muskham	SRPGEI	7.9	88.426	28.160	88.286	28.230	32.0

River Trent	Stoke on Trent	SGE	18.3	0.629	0.119	0.609	0.110	18.1
River Wreake	Syston Mill	GE	15.7	2.834	0.319	2.963	0.369	12.5

Notes:

[1] Factors affecting runoff were obtained from the National River Flow Archive and provide an indication of the various types of artificial influences operating within the catchment which alter the natural runoff

S – reservoir(s) in catchment affect runoff
R – regulation from surface water and/or groundwater
P – runoff reduced by public water supply abstraction
G – runoff influenced by groundwater abstraction and/or recharge
E – runoff increased by effluent returns
I – runoff reduced by industrial and/or agricultural abstraction
N – flows are natural to within 10 per cent of the Q_{95} flow

[2] Sensitivity: The sensitivity index used here is the percentage change in flow associated with a 10mm increase in stage at the Q_{95} flow; the higher the percentage change, the greater the uncertainty in computed flows associated with a given systematic error in stage measurement. A high percentage change is therefore indicative of an insensitive gauging station. The sensitivity index provides a guide to the susceptibility of low flows at individual stations to errors arising from imprecise stage measurement; commonly these produce an overestimation of flows. At any gauging station, sensitivity varies throughout the flow range.

[3] Long-term mean flow and Q_{95} flow information was obtained from the National River Flow Archive in April 2012.

[4] Mean flows and Q_{95} flows were calculated from daily mean flows recorded between 01/01/1990 and 31/12/2009 (i.e. 20 complete years of flows).

Appendix 2.2: Information on gauging stations used in flow assessments (Great Ouse catchment: 17 study sites)

Watercourse	Station Name	FAR[1]	Sensitivity[2] (%)	Long-term[3]		1981 – 2010[4]		
				Mean Flow (m^3s^{-1})	Q_{95} (m^3s^{-1})	Mean Flow (m^3s^{-1})	Q_{95} (m^3s^{-1})	Q_{95} (% Mean Flow)
Bedford Ouse	Bedford	SPGEI	n/a	10.596	1.127	12.144	2.252	18.5
River Babingley	Castle Rising	GEI	67	0.506	0.175	0.501	0.168	33.5
River Cam	Dernford	GEI	14.6	0.917	0.266	0.883	0.244	27.6
River Flit	Shefford	GEI	10.5	0.88	0.356	0.965	0.466	48.3
River Granta	Linton	GEI	25	0.186	0.007	0.189	0.007	3.7
River Heacham	Heacham	GI	33.5	0.209	0.053	0.212	0.05	23.6
River Hiz	Arlesey	GEI	19	0.67	0.325	0.681	0.344	50.5
River Ivel	Blunham	GEI	8.6	2.941	1.04	2.93	1.052	35.9
River Kym	Meagre Farm	EI	66	0.607	0.02	0.61	0.023	3.8
River Lark	Temple	GEI	6.8	1.281	0.453	1.319	0.404	30.6
River Little Ouse	Knettishall	GEI	19	0.474	0.117	0.483	0.122	25.2
River Nar	Marham	PGEI	12	1.137	0.384	1.111	0.341	30.7
River Rhee	Burnt Mill	GEI	19.4	1.168	0.252	1.142	0.258	22.6
River Stringside	Whitebridge	GI	21.1	0.504	0.053	0.486	0.041	8.4
River Thet	Melford Bridge	GEI	14.2	1.902	0.467	2.014	0.513	25.5
River Tove	Cappenham Bridge	EI	12	1.052	0.188	1.082	0.2	18.5
River Wittle	Quidenham	GI	32.4	0.138	0.016	0.142	0.016	11.3

Notes:

[1] Factors affecting runoff were obtained from the National River Flow Archive and provide an indication of the various types of artificial influences operating within the catchment which alter the natural runoff

S – reservoir(s) in catchment affect runoff
P – runoff reduced by public water supply abstraction
G – runoff influenced by groundwater abstraction and/or recharge
E – runoff increased by effluent returns
I – runoff reduced by industrial and/or agricultural abstraction

[2] Sensitivity: The sensitivity index used here is the percentage change in flow associated with a 10mm increase in stage at the Q_{95} flow; the higher the percentage change, the greater the uncertainty in computed flows associated with a given systematic error in stage measurement. A high percentage change is therefore indicative of an insensitive gauging station. The sensitivity index provides a guide to the susceptibility of low flows at individual stations to errors arising from imprecise stage measurement; commonly these produce an overestimation of flows. At any gauging station, sensitivity varies throughout the flow range.

[3] Long-term mean flow and Q_{95} flow information was obtained from the National River Flow Archive.

[4] Mean flows and Q_{95} flows were calculated from daily mean flows recorded between 01/01/1981 and 31/12/2010 (i.e. 30 years of flows).

Appendix 2.3: Additional Information on the Descriptors of Ecological Drought: Trent catchment

Ecological Drought Descriptor	**Definition of Ecological Drought Descriptor**	**Calculation of Ecological Drought Descriptor**
Annual Q_{95} exceedence probability (Q_{95})	The Q_{95} exceedence probability; the flow that is equalled or exceeded for 95% of the time.	The annual Q_{95} was calculated within Excel using the 20-year daily mean flow record for each study site.
20% long-term average daily flow (20%ADF)	20% of the long-term average daily flow for each study site.	The value of 20% ADF was calculated using the 20-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 20% ADF. Although 20% ADF is not a descriptor of drought, it is included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
30% long-term average daily flow (30%ADF)	30% of the long-term average daily flow for each study site.	The value of 30% ADF was calculated using the 20-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 30% ADF. Although 30% ADF is not a descriptor of drought, it is included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
Annual 7-day minimum flow (minimum for study period) Minimum MAM(7)	The minimum value taken from the series of annual values of the mean annual 7-day minimum flow (n=20) at each study site. The MAM(7) is defined as the mean annual 7-day minimum flow and describes the lowest consecutive 7-day flow period each year.	At each study site the MAM(7) for each year in the 20-year study period was calculated within Excel. The minimum value from the series of MAM(7) values (n=20) was then identified and used as the minimum mean annual 7-day minimum flow descriptor for each study site (n=31).
Annual 7-day minimum flow (average for study period) Average MAM(7)	The average value taken from the series of annual values of the mean annual 7-day minimum flow (n=20) at each study site. The MAM(7) is defined as the mean annual 7-day minimum flow and describes the lowest consecutive 7-day flow period each year.	At each study site the MAM(7) for each year in the 20-year study period was calculated within Excel. The average value of the series of MAM(7) values (n=20) was then identified and used as the average mean annual 7-day minimum flow descriptor for each study site (n=31).
Annual 20-day minimum flow (minimum for study period) Minimum MAM(20)	The minimum value taken from the series of annual values of the mean annual 20-day minimum flow (n=20) at each study site. The MAM(20) is defined as the mean annual 20-day minimum flow and describes the lowest consecutive 20-day flow period each year.	At each study site the MAM(20) for each year in the 20-year study period was calculated within Excel. The minimum value from the series of MAM(20) values (n=20) was then identified and used as the minimum mean annual 20-day minimum flow descriptor for each study site (n=31).
Annual 20-day minimum flow (average for study period) Average MAM(20)	The average value taken from the series of annual values of the mean annual 20-day	At each study site the MAM(20) for each year in the 20-year study period was calculated

	minimum flow (n=20) at each study site. The MAM(20) is defined as the mean annual 20-day minimum flow and describes the lowest consecutive 20-day flow period each year.	within Excel. The average value of the series of MAM(20) values (n=20) was then identified and used as the average mean annual 20-day minimum flow descriptor for each study site (n=31).
Annual 30-day minimum flow (minimum for study period) Minimum MAM(30)	The minimum value taken from the series of annual values of the mean annual 30-day minimum flow (n=20) at each study site. The MAM(30) is defined as the mean annual 30-day minimum flow and describes the lowest consecutive 30-day flow period each year.	At each study site the MAM(30) for each year in the 20-year study period was calculated within Excel. The minimum value from the series of MAM(30) values (n=20) was then identified and used as the minimum mean annual 30-day minimum flow descriptor for each study site (n=31).
Annual 30-day minimum flow (average for study period) Average MAM(30)	The average value taken from the series of annual values of the mean annual 30-day minimum flow (n=20) at each study site. The MAM(30) is defined as the mean annual 30-day minimum flow and describes the lowest consecutive 20-day flow period each year.	At each study site the MAM(30) for each year in the 20-year study period was calculated within Excel. The average value of the series of MAM(30) values (n=20) was then identified and used as the average mean annual 30-day minimum flow descriptor for each study site (n=31).
Annual 50-day minimum flow (minimum for study period) Minimum MAM(50)	The minimum value taken from the series of annual values of the mean annual 50-day minimum flow (n=20) at each study site. The MAM(50) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 50-day flow period each year.	At each study site the MAM(50) for each year in the 20-year study period was calculated within Excel. The minimum value from the series of MAM(50) values (n=20) was then identified and used as the minimum mean annual 50-day minimum flow descriptor for each study site (n=31).
Annual 50-day minimum flow (average for study period) Average MAM(50)	The average value taken from the series of annual values of the mean annual 50-day minimum flow (n=20) at each study site. The MAM(50) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 50-day flow period each year.	At each study site the MAM(50) for each year in the 20-year study period was calculated within Excel. The average value of the series of MAM(50) values (n=20) was then identified and used as the average mean annual 50-day minimum flow descriptor for each study site (n=31).
Annual 100-day minimum flow (minimum for study period) Minimum MAM(100)	The minimum value taken from the series of annual values of the mean annual 100-day minimum flow (n=20) at each study site. The MAM(100) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 100-day flow period each year.	At each study site the MAM(100) for each year in the 20-year study period was calculated within Excel. The minimum value from the series of MAM(100) values (n=20) was then identified and used as the minimum mean annual 100-day minimum flow descriptor for each study site (n=31).
Annual 100-day minimum flow (average for study period) Average MAM(100)	The average value taken from the series of annual values of the mean annual 100-day minimum flow (n=20) at each study site. The MAM(100) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 100-day flow period each year.	At each study site the MAM(50) for each year in the 20-year study period was calculated within Excel. The average value of the series of MAM(50) values (n=20) was then identified and used as the average mean annual 100-day minimum flow descriptor for each study site (n=31).

Julian Date of the ecological drought descriptor	The Julian Date of the occurrence of each ecological drought descriptor listed above was identified (n=20) for each study site. Julian dates represent calendar dates with integer values, which start with 1 on January 1st and end with 366 on December 31st .	In this Chapter the Julian Date is calculated as the last day of the low-flow series (e.g. average MAM(7)) for each ecological drought descriptor.
Total Number of days below each ecological drought descriptor	The total number of days average daily flows at each study site in the 1990-2009 study period were lower than each ecological drought descriptor.	The total number of days average daily flows fell below each ecological drought descriptor was determined using daily mean flow data within Excel.
Consecutive Number of days below each ecological drought descriptor	The greatest consecutive number of days average daily flows at each study site in the 1990-2009 study period were lower than each ecological drought descriptor.	The greatest number of consecutive days average daily flows fell below each ecological drought descriptor was determined using daily mean flow data within Excel.

Appendix 2.4: Additional Information on the Descriptors of Ecological Drought: Great Ouse catchment

Ecological Drought Descriptor	Definition of Ecological Drought Descriptor	Calculation of Ecological Drought Descriptor
Annual Q_{95} exceedence probability (Q_{95})	The Q_{95} exceedence probability; the flow that is equalled or exceeded for 95% of the time i.e. a measure of low flow.	The annual Q_{95} was calculated within Excel using the 30-year daily mean flow record for each study site.
Annual Q_{84} exceedence probability (Q_{84})	The Q_{84} exceedence probability; the flow that is equalled or exceeded for 84% of the time i.e. a measure of low flow.	The annual Q_{84} was calculated within Excel using the 30-year daily mean flow record for each study site.
10% long-term average daily flow (10%ADF)	10% of the long-term average daily flow for each study site.	The value of 10% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 10% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
15% long-term average daily flow (15%ADF)	15% of the long-term average daily flow for each study site.	The value of 15% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 15% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
20% long-term average daily flow (20%ADF)	20% of the long-term average daily flow for each study site.	The value of 20% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 20% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
25% long-term average daily flow (25%ADF)	25% of the long-term average daily flow for each study site.	The value of 25% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 25% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
30% long-term average daily flow (30%ADF)	30% of the long-term average daily flow for each study site.	The value of 30% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 30% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).

35% long-term average daily flow (35%ADF)	35% of the long-term average daily flow for each study site.	The value of 35% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 35% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
40% long-term average daily flow (35%ADF)	40% of the long-term average daily flow for each study site.	The value of 40% ADF was calculated using the 30-year daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 40% ADF. Included here as it was proposed as an *e-flow* metric by Baxter (1961) and Tennant (1976).
Annual 1-day minimum flow Annual Minimum Flow	The annual minimum daily mean flow for each study site.	At each study site for each year in the 30-year study period the annual minimum flow was identified within Excel (n=30).
Annual 7-day minimum flow (average for study period) Average MAM(7)	The average value taken from the series of annual values of the mean annual 7-day minimum flow (n=30) at each study site. The MAM(7) is defined as the mean annual 7-day minimum flow and describes the lowest consecutive 7-day flow period each year.	At each study site the MAM(7) for each year in the 30-year study period was calculated within Excel. The average value of the series of MAM(7) values (n=30) was then identified and used as the average mean annual 7-day minimum flow descriptor for each study site (n=17).
Annual 7-day minimum flow (minimum for study period) Minimum MAM(7)	The minimum value taken from the series of annual values of the mean annual 7-day minimum flow (n=30) at each study site. The MAM(7) is defined as the mean annual 7-day minimum flow and describes the lowest consecutive 7-day flow period each year.	At each study site the MAM(7) for each year in the 30-year study period was calculated within Excel. The minimum value from the series of MAM(7) values (n=30) was then identified and used as the minimum mean annual 7-day minimum flow descriptor for each study site (n=17).
Annual 10-day minimum flow (average for study period) Average MAM(10)	The average value taken from the series of annual values of the mean annual 10-day minimum flow (n=30) at each study site. The MAM(10) is defined as the mean annual 10-day minimum flow and describes the lowest consecutive 10-day flow period (month) each year.	At each study site the MAM(30) for each year in the 30-year study period was calculated within Excel. The average value of the series of MAM(10) values (n=30) was then identified and used as the average mean annual 10-day minimum flow descriptor for each study site (n=17).
Annual 10-day minimum flow (minimum for study period) Minimum MAM(10)	The minimum value taken from the series of annual values of the mean annual 10-day minimum flow (n=30) at each study site. The MAM(10) is defined as the mean annual 10-day minimum flow and describes the lowest consecutive 10-day flow period each year.	At each study site the MAM(10) for each year in the 30-year study period was calculated within Excel. The minimum value from the series of MAM(10) values (n=30) was then identified and used as the minimum mean annual 10-day minimum flow descriptor for each study site (n=17).
Annual 20-day minimum flow (average for study period) Average MAM(20)	The average value taken from the series of annual values of the mean annual 20-day minimum flow (n=30) at each	At each study site the MAM(20) for each year in the 30-year study period was calculated within Excel. The average value

	study site. The MAM(20) is defined as the mean annual 20-day minimum flow and describes the lowest consecutive 20-day flow period (month) each year.	of the series of MAM(20) values (n=30) was then identified and used as the average mean annual 20-day minimum flow descriptor for each study site (n=17).
Annual 20-day minimum flow (minimum for study period) Minimum MAM(20)	The minimum value taken from the series of annual values of the mean annual 20-day minimum flow (n=30) at each study site. The MAM(20) is defined as the mean annual 20-day minimum flow and describes the lowest consecutive 20-day flow period each year.	At each study site the MAM(20) for each year in the 30-year study period was calculated within Excel. The minimum value from the series of MAM(20) values (n=30) was then identified and used as the minimum mean annual 20-day minimum flow descriptor for each study site (n=17).
Annual 30-day minimum flow (average for study period) Average MAM(30)	The average value taken from the series of annual values of the mean annual 30-day minimum flow (n=30) at each study site. The MAM(30) is defined as the mean annual 30-day minimum flow and describes the lowest consecutive 30-day flow period (month) each year.	At each study site the MAM(30) for each year in the 30-year study period was calculated within Excel. The average value of the series of MAM(30) values (n=30) was then identified and used as the average mean annual 30-day minimum flow descriptor for each study site (n=17).
Annual 30-day minimum flow (minimum for study period) Minimum MAM(30)	The minimum value taken from the series of annual values of the mean annual 30-day minimum flow (n=30) at each study site. The MAM(30) is defined as the mean annual 30-day minimum flow and describes the lowest consecutive 30-day flow period each year.	At each study site the MAM(30) for each year in the 30-year study period was calculated within Excel. The minimum value from the series of MAM(30) values (n=30) was then identified and used as the minimum mean annual 30-day minimum flow descriptor for each study site (n=17).
Annual 50-day minimum flow (average for study period) Average MAM(50)	The average value taken from the series of annual values of the mean annual 50-day minimum flow (n=30) at each study site. The MAM(50) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 50-day flow period (month) each year.	At each study site the MAM(50) for each year in the 30-year study period was calculated within Excel. The average value of the series of MAM(50) values (n=30) was then identified and used as the average mean annual 50-day minimum flow descriptor for each study site (n=17).
Annual 50-day minimum flow (minimum for study period) Minimum MAM(50)	The minimum value taken from the series of annual values of the mean annual 50-day minimum flow (n=30) at each study site. The MAM(50) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 50-day flow period each year.	At each study site the MAM(50) for each year in the 30-year study period was calculated within Excel. The minimum value from the series of MAM(50) values (n=30) was then identified and used as the minimum mean annual 50-day minimum flow descriptor for each study site (n=17).
Julian Date of the ecological drought descriptor	The Julian Date of the occurrence of each ecological drought descriptor listed above was identified (n=30) for each study site. Julian dates represent calendar dates with integer values, which start with 1 on January 1st and end with 366 on December 31st .	In this Chapter the Julian Date is calculated as the last day of the low flow series (e.g. average MAM(7)) for each ecological drought descriptor.
Total Number of days below each ecological drought descriptor	The total number of days average daily flows at each study site in the 1990-2009	The total number of days average daily flows fell below each ecological drought

	study period were lower than each ecological drought descriptor.	descriptor was determined using daily mean flow data within Excel.
Consecutive Number of days below each ecological drought descriptor	Low flow persistence defined as the occurrence of daily mean flows below an ecological drought descriptor for more than 5 consecutive days.	The number of consecutive days average daily flows fell below each ecological drought descriptor was determined using daily mean flow data within Excel.

Appendix 3.1: Legislative framework

Please note that European Legislation is not included in this framework.

Year	Legislation/ Committee	Key Outcomes	Key Limitations
1867-1869	Royal Commission on Water Supply	Recommended that cities should not be allowed to appropriate a source of supply which naturally and geographically belonged to a town/district nearer the source.	
1876	Rivers Pollution Prevention Act	A pioneering measure in placing an absolute prohibition on polluting discharges. Described as the cornerstone of national rivers pollution law until the 1950s.	Numerous 'safeguards' protected polluters. View is the 1876 Act failed as a pollution prevention measure.
1888	Local Government Act	Creation of County Councils and viewed as significantly improving the prospects for pollution control. Council's responsibilities included application of the 1876 Act.	
1912	Royal Commission on Sewage Disposal	Set what became known as the 30:20 standard for effluent disposal.	
1930	Land Drainage Act	Consolidated and amended drainage law and reorganised its administration by establishing river basin based river conservancy (catchment) boards.	Integrated management was not achieved. Powers to control river pollution or influence source developments not allocated to the new boards.
1934	Water Supplies (Exceptional Shortages Orders) Act	Made it possible during droughts to apply for a reduction in compensation.	
1937	Public Health (Drainage of Trade Premises) Act	Required local authority sewers to receive trade effluent and represented an important step forward in curtailing the industrial pollution of the water environment.	System was arguably both inflexible and complex and did not inaugurate sustained change.
1945	Water Act	Marked the beginning of a national water policy. Although not fully defined in this act, it also marked the start of abstraction licensing, with powers to control new requests to abstract groundwater from aquifers in designated conservation areas.	In many respects was a disappointing reform and made no progress in promoting integrated management and no control of abstraction from surface waters.
1948	Rivers Board Act	Led to the formation of 32 River Boards. An unprecedented integration of functions. Closely followed the recommendations of the Central Advisory Committee on Water.	The Act fell well short of achieving comprehensive river management.
1951	Rivers (Prevention of Pollution) Act	Each new discharge required the consent of the River Board and individual consents required qualitative and quantitative standards for the discharge.	
1958	Water Act	Section 1 of the Act made it possible during droughts to apply for a Drought Order reducing (for a maximum of 6 months) the amount of compensation water to be discharged.	Used extensively during the drought of 1959. No provision for water undertakings to remove excessively onerous compensation requirements.
1960	Clean Rivers (Estuaries and Tidal Water) Act	Introduced the power to control new discharges to tidal waters or estuaries.	Described as a cumbersome procedure that was rarely used.

1961	Rivers (Prevention of Pollution) Act	Extended the application of the 1951 Act to all discharges to inland waters, including those made before 1951.	
1963	Water Resources Act	Described as a significant piece of legislation. Established 29 River Authorities and created a national Water Resources Board. Removed riparian rights to water resources and introduced a system of licensing and charges for all surface and groundwater abstractions. Following the 1963 Act it became illegal to discharge any sewage or trade effluent without an appropriate consent.	The issuing of Licences of Right with no time limits and no environmental controls. The powers of the River Authorities were quite restricted.
1973	Water Act	Described as the culmination of attempts to establish the integrated management of water resources in England and Wales. Responsibility for the entire water cycle was allocated to 10 Regional Water Authorities.	The 1973 reform did not deliver integrated management in its entirety. The RWAs failed to meet the expectations of government and society.
1974	Control of Pollution Act (Part II)	Part II of the Act applied to the water environment and superseded the 1951 and 1961 Rivers Pollution Acts. Introduced periodic review and alteration of consent conditions.	
1976	Drought Act	Enabled Water Authorities and undertakers to temporarily change or be relieved of their statutory obligations during times of drought.	Took at least 7 weeks between a Drought Order application first being considered and finally made.
1989	Water Act	Transformed the existing Water Authorities into the new Water and Sewerage companies and also provided for the National Rivers Authority to manage pollution and environmental control. Introduced statutory water quality classifications and objectives for the first time.	
1991	Water Resources Act	An Act to consolidate enactments relating to the National Rivers Authority and the matters in relation to which it exercises functions.	
1995	Environment Act	Act provided for the establishment of a body corporate to be known as the Environment Agency.	Arguably the loss of the National Rivers Authority.
2003	Water Act	Created transfer licence and temporary licences. Replaced exemptions based on water use. Ended the current exemption for irrigation (other than spray irrigation) and dewatering. Required all new licences to be time-limited. Empowered the EA to revoke/vary a licence without compensation if not used for four years. Removed the entitlement to compensation if the Secretary of State (or the Assembly) directs that a licence without a time limit should be curtailed, on or after 15 July 2012, on the grounds of serious environmental damage.	Failure to provide a mechanism for varying Licences of Right.
2006	The Water Resources (Abstraction and Impounding) Regulations	Specified new procedural requirements in respect of the licensing of abstraction and impounding of water in England and Wales.	

Information on pre-1989 legislation was obtained from Sheail (1987) and Hassan (1998).

Appendix 3.2: Issues that should be considered before setting a Minimum Acceptable Flow (MAF)

Issues that should be considered before setting a Minimum Acceptable Flow (MAF)	**Reference (Organisation)**
Rowntree felt that it was evident that the consideration of MAF was linked with the other urgent new duties of the river authorities. The object of the new functions under the 1963 Act was to meet demands for water. These demands were diverse in time and space, included water for fishing and amenity and affected the location and amount of the MAF, not directly but indirectly.	Rowntree (Director Water Resources Board)
Southgate discussed water quality issues observing that increasing the minimum flow of a river might well play an important part in maintaining its quality.	Southgate
Bannerman dealt with time and cost in relation to MAF, and felt that there should not be a fixed quantity for any river and that the MAF should vary in time according to need. Bannerman cited the Thames at Teddington as an example of how the MAF would historically have varied according to need. Bannerman also highlighted the financial implications of MAFs and was of the opinion that it was necessary to determine if there were alternatives.	Bannerman
Nixon stated that it would be easier to fix a MAF than to defend it. Nixon stated that although he had already fixed MAFs, he expected everybody to object to the answer that he had found. When calculating MAFs, Nixon had started from a basic flow figure of ¼ cusec per 1000 acres (0.002 $m^3 s^{-1} km^2$) (the minimum flow a river required to remain a river). Consideration should then be given to the requirements of fisheries, pollution and other water demands. Nixon hoped that no MAF would be fixed at less than ¼ cusec per 1000 acres (0.002 $m^3 s^{-1} km^2$).	Nixon (Engineer Trent River Board)
Machon proposed that conditions in a river controlled by a MAF might be represented by plotting the various pollutants, flows and temperatures along the stream that would describe the condition of the river along with the worst acceptable levels of the significant ones in each reach. Machon questioned if MAF itself could become a fixed rule that resulted in rivers serving society at their lowest capacity all the time.	Machon
Cole reinforced the idea of MAF as a user concept and stated that it was not possible to write an explicit equation for MAF. Cole concluded that it would be necessary to provide for seasonal variation of the MAF.	Cole
Law suggested that rivers fell into two categories; (1) lowland rivers where pollution was the main factor to consider when setting MAFs, and (2) upland rivers where fisheries and amenity were of greater importance than pollution. Law stated that the two classes of rivers should be considered “quite separately with regard to MAF” With lowland rivers it was essential to increase the flow to the MAF, with upland rivers it would be better to leave the river in its natural state. Law referred to Baxter (1961; 1963) and to the recommendation of variable flows according to ecological need. Law agreed that MAFs should not be rigidly fixed throughout the year.	Law

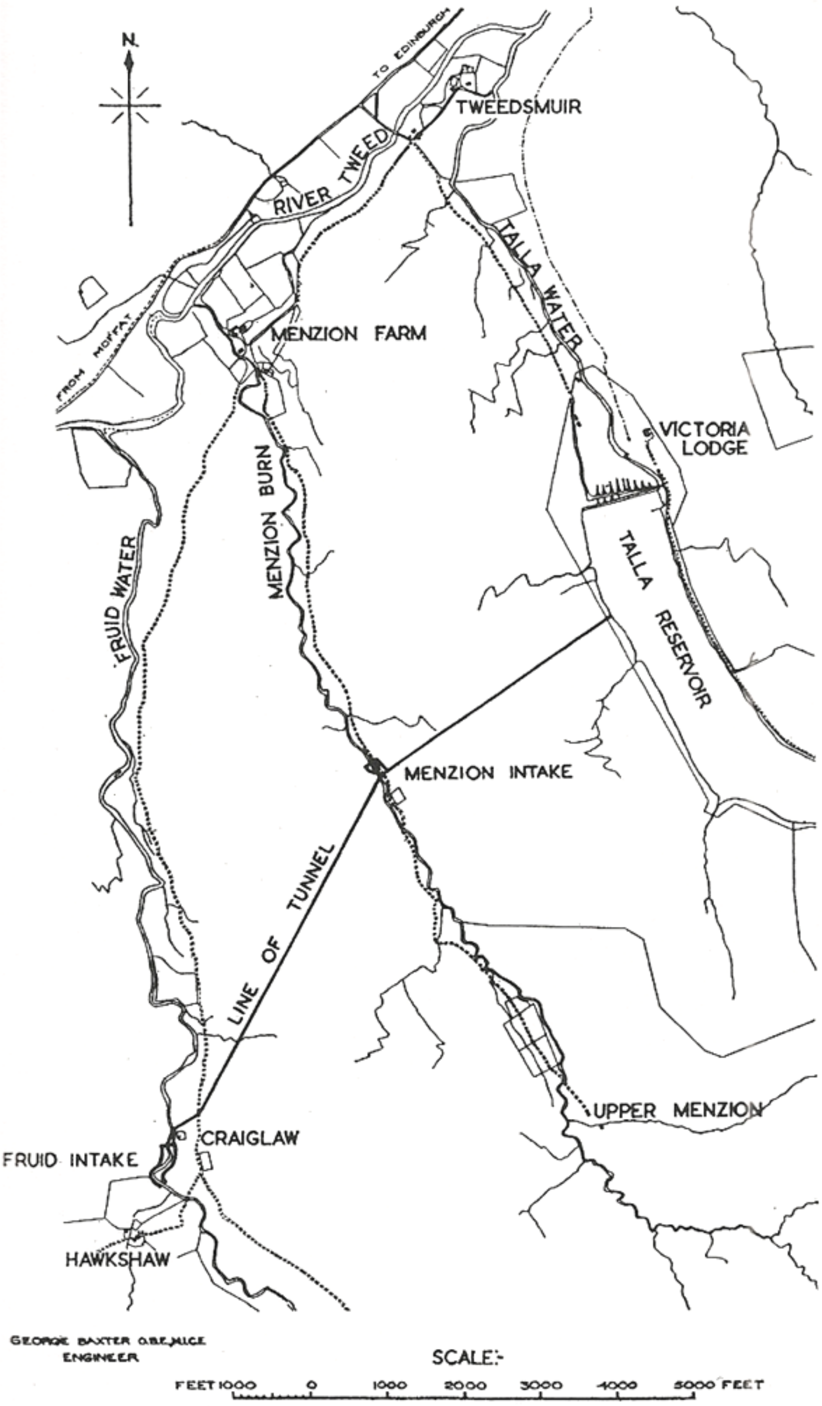
Cartwright was concerned with the implications of a MAF being set too high. Cartwright felt that water authorities needed to take a greater interest in river gaugings to prevent this happening. Cartwright stated that “although the whole business of river management hinged on the MAF, the Act could be read by some to treat it rather lightly”. Cartwright felt that some of the duties of the river authorities with regards to MAF were potentially “somewhat conflicting”.	Cartwright
Snell considered the question of irrigation demand and its effect on rivers citing rivers in Essex as an example. In one catchment, the effect of a new MAF of 240 mgd would be to reduce the irrigation abstraction time from 30% to 5% in an average year. Snell stated that there could be “formidable opposition by the farming community in defence of their irrigation proposals”.	Snell
When referring to the question of the variability of MAF, Rydz observed how MAF had been presented in the WRA virtually as a fixed quantity, although subject to periodic review. Rydz felt that the long-term variation of MAF was a matter of great importance. Rydz observed that over time the regulation of rivers would improve and sewage effluent quantities would increase. Rydz asked “What sort of conditions should be applied to the review of MAF as flows became better-sustained in dry weather? Should it be left fixed? ...” Rydz was of the opinion that there were many ways in which the re-allocation of MAF could be done, but if the MAF was left constant so that the abstracting authority could abstract greater amounts during low-flow as due to the added effluent, it might mean the total flow bypassing the abstraction point would be reduced as the river became more regulated.	Rydz
Burston wrote that what was first required was some rational basis for the fixing of MAF. A rational procedure would be to relate the MAF to the flow characteristics of the river under consideration. Burston stated that such characteristics were best described by the flow duration curve and suggested that as a first step; the MAF should be the flow that was exceeded for 90% of the time (or some other percentage depending on the characteristics of the river) in a dry year. Burston recommended that the MAF should increase as abstraction increased.	Burston
Downing was of the opinion that insufficient stress was generally given to the role of groundwater when considering MAF. Downing stated that MAF should be based not only on the minimum contribution from groundwater sources but should also take into account the quantity of groundwater that might be developed in the future.	Downing
Green referred to conditions experienced during the 1959 drought, identifying that in the late summer, “no doubt most rivers fell below the MAF which would be likely to be prescribed for them”. Green concluded by stating that “it would be interesting to know whether hitherto this conception of MAF had been used for purposes of water-resource administration in any other parts of the world”.	Green
Smith referred to a recently completed study on hydrology and water use in the Nidd Valley. Smith had employed the MAF concept in an attempt to determine how much additional water could be abstracted from the Valley rather than to place limitations on existing users or to recreate or preserve an acceptable condition in the stream.	Smith

Taken from the discussion of Boulton (1965).

Appendix 4.1: Baxter’s Experience with the Fruid-Menzion Scheme

The Fruid-Menzion scheme on tributaries to the River Tweed (Figure A1) was recommended by Baxter to meet the ever-increasing demand for water in Edinburgh.

Figure A1: Plan of the Fruid-Menzion Scheme



Anon (1953); page 50.

The Edinburgh and Midlothian Order of 1949 increased the area of supply in the county from about 130 to 930 km^2 and the population to be supplied by almost 100,000 (Anon, 1952). On investigating the flows of the Fruid and Menzion streams it was identified that by abstracting between 0.132 and 1.441 m^3 s^{-1} in the case of Fruid, and between 0.033 and 0.822 m^3 s^{-1} in the case of the Menzion, and equalising the flows of the two streams in Talla Reservoir, approximately 0.316 m^3 s^{-1} could be obtained during dry years (Anon, 1953). At that time traditionally the reliable yield was defined as the average daily flow of the three driest consecutive years. The average daily flow was the average daily flow over the long-term period.

The Order limited the abstraction of water from the two streams to between the maximum and minimum flow limits defined by Baxter. These limits represented in the case of the Fruid double the minimum dry weather flow of the stream, the minimum flow of Fruid being 0.059 m^3 s^{-1}, and in the case of the Menzion rather less than double the dry weather flow of the stream being 0.018 m^3 s^{-1} (Anon, 1953). However, during negotiations, the Edinburgh Corporation stressed that abstraction would only occur when there was more than twice the dry weather flow in the burns, as determined on the basis of half a century of gauge records (namely 0.132 m^3 s^{-1} on the Fruid Burn and 0.033 m^3 s^{-1} on the Menzion Burn) (Sheail, 1985; 1987). In addition, subject to the natural flow of the two streams being sufficient for the purpose, the Order required the provision of flows of specified amounts and duration (‘freshets’) below the two intakes during each period of seven days between September 28th and November 30th in each year to facilitate the passage upstream of migratory fish (Anon, 1953). In practice, the required timing of these freshets could mimic natural higher flows during periods of wet weather.

In 1958 the Edinburgh Corporation Waterworks Committee commissioned a report on what should be the next phase in the development of the Tweed works (Sheail, 1985; 1987). The report by the Corporation’s water engineer and Baxter, by then a consultant, estimated that the long-term average daily flow of the Fruid Burn was 0.831 m^3 s^{-1}, of which it was economically practicable to impound 0.721 m^3 s^{-1} (approximately 0.237 m^3 s^{-1} was already abstracted under the Order of 1948). However, due to the importance of the fisheries and the inroads already made by the Talla scheme, rather more compensation water would have to be given than was ‘customary’ at that time (Sheail, 1987).

Baxter calculated that, on average, flow fell ‘to below a quarter of the long-term average flow for 60 days a year on the Fruid, with variations from 20 to 100 days, and 0.105 m^3 s^{-1} or just on an eighth of the long-term average was a commonly occurring figure’ (Sheail, 1987). Baxter therefore proposed that 0.216 m^3 s^{-1} should be set aside as compensation water, namely double the normal minimum flow and almost 3.5 times the minimum flow previously recorded at the site of the proposed dam (Sheail, 1987). In order to make the greatest use of the water for salmon spawning purposes, Baxter proposed a daily allocation equivalent to 0.184 m^3 s^{-1}, and an additional block allocation of 0.029 m^3 s^{-1} in the form of 28 freshets (Sheail, 1985; 1987).

With these deductions made, the scheme would only obtain an additional 0.268 m^3 s^{-1}, an amount insufficient to warrant the cost of constructing the works (Sheail, 1985; 1987). The report therefore recommended that the flow to Fruid reservoir should be augmented by an additional 0.110 m^3s^{-1} from the Hawkshaw and Fingland Burns. The severe drought of 1959, when the Edinburgh Corporation’s reservoirs were reduced to approximately 35 days’ supply, persuaded the Corporation to promote the scheme with the minimum of delay (Sheail, 1985; 1987). An Order was approved in 1962; in order to satisfy the opposition to the scheme, the amount of water allocated for public supply was reduced to 0.362 m^3 s^{-1} (Sheail, 1985; 1987).

The Tweed River Purification Board, acted on behalf of all the major river interests during negotiations over the compensation water issue. The Board criticised the scheme for exacerbating an already unsatisfactory position caused by the absence of any compensation water from the Talla reservoir in winter (Sheail, 1985). During the previous 60 years, the volume of water discharged from that part of the catchment had fallen from 33.3% to 10 % of the annual gross yield of River Tweed causing heavy silting to occur.

The Board accepted the concept of a basic allowance but also demanded that a block allocation of 0.029 m^3 s^{-1} should be made from the Talla reservoir in the form of freshets (Sheail, 1985) to provide flushing flows. The basic allocation was to be 0.167 m^3 s^{-1}, or an average of 0.167 m^3 s^{-1}. Additionally a block allocation of 0.026 m^3 s^{-1} or an average of 0.026 m^3 s^{-1} was to be made for up to 28 freshets each year. The Corporation was to be given at least 48 hours notice of a freshet being required, except in an acknowledged emergency. Unless otherwise agreed, each freshet was to extend over 12 hours at full rate and 6 hours at half rate. Table A1 summarises the schedule of flows for the Fruid Scheme.

During the development of the Scheme it was recognised that the original estimates of an annual rainfall of 1651 mm had been set far too low with data suggesting it was approximately 1778 mm. Although the Corporation had already paid large sums in compensation for the earlier schemes, the Corporation accepted that it could now afford to make some concessions (Sheail, 1985). The Order implementing the Fruid scheme was therefore extended to give the Purification Board the right to request up to 0.031 m^3 s^{-1} or an average of 0.003 m^3 s^{-1} from the Talla or Fruid reservoirs or partly from both (Sheail, 1985). This discharge was not to exceed 0.789 m^3 s^{-1} in any 7 consecutive days, or 25 % of the annual allocation in a month. In any one day, 4/5ths of the water was to be discharged in a uniform flow over 12 hours and the remainder over the ensuing 6 hours at a gradually reducing rate (Sheail, 1985).

Table A1: Schedule of Flows – Fruid Scheme

Month	Basic Allocation % adf	Block Allocation for freshets % adf	Comments
January	12	-	
February	12	-	
March	20	70*	
April	20	70*	
May	25	100*	25% adf between May and August when ‘the needs of the river and of the fry and parr life are at their maximum’
June	25	100*	
July	25	100*	
August	25	100*	
September	20	100*	
October	20	70*	
November	20	-	
December	20 - 12	-	

*Included the basic compensation water.

Based on information contained within Sheail (1985; 1987).

Appendix 4.2: Summary of Baxter’s (1961) flow analyses

River	**Severn**	**Lower Spey**	**Dee**	**Wye**	**Garry**	**Moriston**		**Shin**
Period of years covered by record	15 (1921-36)	7 (1938-45)	10 (1939-49)	8 (1937-45)	7[1] (1935-44)	6[2] (1935-44)	27	7 (1949-56)
Catchment area (square miles)	1650	1020	528	495	149	151	-	191
Height of highest point above OD (feet)	2713	4300	4300	2468	3410	3670	-	2864
Approximate (long term) average annual rainfall (inches)	35.5	N/A	45(e)	53.7	100(e)	82.2	-	57.5
Average daily flows (cusecs)	2255	2132	1254	1203	930	739	742	590
Flow range (percentage of days per year)								
(1) between 4 adf and nm	2.5	1	2	4.5	3	3.5	3	1
(2) between 2 adf and 4 adf	11	8	8.5	10.5	10	10	10	10.5
(3) between adf and 2 adf	18	27	23.5	14	20.5	17.5	16	23.5
(4) between ¾ adf and adf	10.5	14	10.5	8	10	8	8	13
(5) between ½ adf and ¾ adf	13	21.5	26.5	14	14	14	14	18
(6) between ¼ adf and ½ adf	31.5	26.5	24	29	19	22	23	23.5
(7) between ⅛ adf and ¼ adf	12.5	2	5	17.5	15	16	17	7.5
(8) below ⅛ adf	1	Nil	Nil	2.5	8	9	8	3
Ratio of nm to adf	6.3	5.6	8.7	9	7.2	8	-	4.3
Peak discharge (cusecs per square mile)	14	18	76	45	68	109	109	N/A
Minimum flow (cusecs per square mile)	0.12	0.37	0.33	0.21	0.09	0.25	0.09	0.09
River	**Upper Lyon**	**Upper Spey**	**Upper Cassley**	**Melgam**	**Allt Bhlaraidth**	**Fruid**	**Inzion**	**Allt Uaine**
Period of years covered by record	7 (1949-56)	1 (1936-37)	7 (1949-56)	10 (1927-37)	5 (1952-56)	11 (1947-58)	10 (1927-37)	6
Catchment area (square miles)	62.3	85	27.9	15.8	10.6	9.14	9.5	1.2
Height of highest point above OD (feet)	3540	3298	3273	2070	2224	2650	2196	2900
Approximate (long term) average annual rainfall (inches)	99(e)	N/A	104	43	57(e)	62.2	40.7	140(e)
Average daily flows (cusecs)	393	327	183	35	33	32	20.5	12
Flow range (percentage of days per year)								
(1) between 4 adf and nm	5	4	3.5	5	4	3.5	1.5	4
(2) between 2 adf and 4 adf	8	10	9.5	6	8	8	8	8
(3) between adf and 2 adf	16	15	21	21	17	18	24	11
(4) between ¾ adf and adf	8.5	8	11	16	9	11.5	16	6
(5) between ½ adf and ¾ adf	13	11	15.5	18	15	15.5	16	9
(6) between ¼ adf and ½ adf	21	23	23	24	24	27	25	19
(7) between ⅛ adf and ¼ adf	19	25	11.5	10.7	14	13.5	9	22
(8) below ⅛ adf	9.5	4	5	0.2	9	3	0.5	20
Ratio of nm to adf	10	10	8.2	7	9	8.5	5	5.5
Peak discharge (cusecs per square mile)	185	72	123	43	72	95	30	N/A
Minimum flow (cusecs per square mile)	0.10	0.33	0.11	0.23	0.01	0.23	0.25	N/A

Appendix 4.2: Summary of Baxter's (1961) flow analyses (continued)

River	**Severn**	**Lower Spey**	**Dee**	**Wye**	**Garry**	**Moriston**		**Shin**
Period of years covered by record	15 (1921-36)	7 (1938-45)	10 (1939-49)	8 (1937-45)	7[1] (1935-44)	6[2] (1935-44)	27	7 (1949-56)
Catchment area (km^2)	4273.5	2641.8	1367.5	1282.0	385.9	391.1	-	494.7
Height of highest point above OD (m)	826.9	1310.6	1310.6	752.3	1039.4	1118.6	-	873.0
Approximate (long term) average annual rainfall (mm)	901.7	N/A	1143(e)	1364.0	2540(e)	2087.9	-	1460.5
Average daily flows (m^3/s)	63.9	60.4	35.5	34.1	26.3	20.9	21.0	16.7
Flow range (percentage of days per year)								
(1) between 4 adf and nm	2.5	1	2	4.5	3	3.5	3	1
(2) between 2 adf and 4 adf	11	8	8.5	10.5	10	10	10	10.5
(3) between adf and 2 adf	18	27	23.5	14	20.5	17.5	16	23.5
(4) between ¾ adf and adf	10.5	14	10.5	8	10	8	8	13
(5) between ½ adf and ¾ adf	13	21.5	26.5	14	14	14	14	18
(6) between ¼ adf and ½ adf	31.5	26.5	24	29	19	22	23	23.5
(7) between ⅛ adf and ¼ adf	12.5	2	5	17.5	15	16	17	7.5
(8) below ⅛ adf	1	Nil	Nil	2.5	8	9	8	3
Ratio of nm to adf	6.3	5.6	8.7	9	7.2	8	-	4.3
Peak discharge (cumecs per square kilometre)	1.020	1.321	5.574	3.300	4.988	7.995	7.995	N/A
Minimum flow (cumecs per square kilometre)	0.009	0.027	0.024	0.015	0.006	0.018	0.006	0.006
River	**Upper Lyon**	**Upper Spey**	**Upper Cassley**	**Melgam**	**Allt Bhlaraidth**	**Fruid**	**Inzion**	**Allt Uaine**
Period of years covered by record	7 (1949-56)	1 (1936-37)	7 (1949-56)	10 (1927-37)	5 (1952-56)	11 (1947-58)	10 (1927-37)	6
Catchment area (km^2)	161.4	220.2	72.3	40.9	27.5	23.7	24.6	3.1
Height of highest point above OD (m)	1051.6	1005.2	997.6	630.9	677.9	807.7	669.3	883.9
Approximate (long term) average annual rainfall (mm)	2514.6(e)	N/A	2641.6	1092.2	1447.8(e)	1579.9	1033.8	3556(e)
Average daily flows (m^3/s)	11.1	9.36	5.18	0.99	0.93	0.91	0.58	0.34
Flow range (percentage of days per year)								
(1) between 4 adf and nm	5	4	3.5	5	4	3.5	1.5	4
(2) between 2 adf and 4 adf	8	10	9.5	6	8	8	8	8
(3) between adf and 2 adf	16	15	21	21	17	18	24	11
(4) between ¾ adf and adf	8.5	8	11	16	9	11.5	16	6
(5) between ½ adf and ¾ adf	13	11	15.5	18	15	15.5	16	9
(6) between ¼ adf and ½ adf	21	23	23	24	24	27	25	19
(7) between ⅛ adf and ¼ adf	19	25	11.5	10.7	14	13.5	9	22
(8) below ⅛ adf	9.5	4	5	0.2	9	3	0.5	20
Ratio of nm to adf	10	10	8.2	7	9	8.5	5	5.5
Peak discharge (cumecs per square kilometre)	13.569	5.281	9.021	3.155	5.281	6.967	2.202	N/A
Minimum flow (cumecs per square kilometre)	0.007	0.024	0.008	0.017	0.008	0.017	0.018	N/A

Notes: adf = average daily flow; nm = mean daily maximum flow; (e) estimated fall; [1]omitting 1940-42; [2]omitting 1937-1940.

Adapted from Baxter (1961) pages 228-229.

Appendix 4.3: The impact of Baxter (1961): selected papers citing Baxter (1961) between 1961 and 1969

Year	Theme	Reference
1961	Baxter's (1961) conclusions were quickly reported in both UK and USA: "the traditional fixed rate of discharge of compensation water based quantitatively on yield and unrelated to biological need is unsuitable for fish life and should be replaced by a variable compensation flow regime based on the seasonal needs of the fish and of the river and incorporating provision for the release of freshets.	HMSO (1961) Okun *et al.* (1962)
1963	Considering the water requirements of fisheries and fishing below the Elan reservoir, Risbridger supported Baxter's (1961) conclusion that the water needs of migratory fish are less than generally thought suggesting that the needs of migratory fish would be satisfied by a basic discharge of compensation water of 5 mgd, increased in periods of hot weather to 17.5 mgd, with a few freshets in late summer and early autumn at rates from 30% adf (42 mgd) to 70% adf (98 mgd) so that the average daily compensation water from Elan would be little more than 9 mgd, substantially lower than the current (1940 Act) compensation water of 29 mgd.	Risbridger (1963)
1964	Highlighted the work of Baxter (1961) stating 'the amount of water which fish require, in order to thrive, provided it is pure, is not easily determined, but it may be proved to be much less than anglers had previously thought necessary'.	Nixon (1964)
1965	"George Baxter (1961) has made a valuable contribution to our knowledge of this matter; his principal conclusions that the water needs of migratory fish are smaller than is perhaps generally supposed'. He concluded '...it appeared that a minimum flow of one-eighth the average daily flow was not unsatisfactory during periods of hot weather, provided that there were freshets at intervals'.	Boulton (1965)
1966	Discussing the operation fish-passes at hydro-electric works in Scotland, advocated Baxter's (1961) approach: compensation water is normally divided into a steady flow which may be varied during the different periods of the year and a volume of water from which additional flows (freshets) can be given from time to time as seems best in the fishery interest.'	Aitken *et al.* (1966)
1966	At the 1965 *Man-Made Lakes* symposium (Lowe McConnell) Law highlighted the dangers of following Baxter (1961, 1963) suggesting that one-eighth ADF, one-quarter ADF may be used rather rigidly.	Law (1966)
1967	"Baxter (1961) soundly justified describing discharges as a proportion of the average daily flow (a.d.f.) and stated that 'salmon will ascend most rivers in flows varying from 30% to 50% of the a.d.f. in the lower and middle reaches to 70% in the upper reaches and streams of headwaters'". While his statement is substantially correct that salmon will ascend most rivers in flows varying from 30-50% of the a.d.f., migration reaches a peak at much higher discharges'.	Brayshaw (1967)
1969	Banks (1969) reproduced Baxter's (1961) *Schedule of Flows* stating that although the schedule did not provide adequate conditions for the ascent of migratory fish, it was intended that sufficient stored compensation water should be available to provide freshets. 'Baxter (1961) was of the opinion that fish would respond as readily to sluice water as to a natural rise, in Baxter (1963) this is modified to show that compensation water, including freshets, should be withdrawn from the upper levels of reservoirs'. He noted that although the regime outlined in Baxter's (1961) *Schedule of Flows* may well be sufficient to maintain the stock of fish, it would reduce the time during which angling was likely to be successful.	Banks (1969)
1969	Stewart (1964) pioneered electronic fish-counting, and the results from his instrumentation on the Rivers Leven and Lune in Lancashire and other rivers in the country confirmed that '...Baxter (1961) was never more correct than when he said "The water needs of migratory fish are smaller than is perhaps generally supposed"'.	Stewart (1969)

Appendix 5.1: Timings of the most extreme drought event at each study site (droughts defined using minimum flow in 30-year period)

Study Site	Min Flow in study period (m^3s^{-1})	Date of min flow	20% ADF Start Date[1]	20% ADF End Date[2]	Days Below 20% ADF[3]	Q_{95} Start Date[1]	Q_{95} End Date[2]	Days Below Q_{95}[3]	MAM7 Start Date[1]	MAM7 End Date[2]	Days Below MAM7[3]
River Granta - Linton	0.000	21/09/1991	19/06/1991	09/01/1992	205	08/08/1991	09/01/1992	155	26/06/1991	09/01/1992	198
River Kym - Meagre Farm	0.005	30/06/1986	04/06/1986	26/08/1986	84	28/06/1986	05/07/1986	8	28/06/1986	05/07/1986	8
River Stringside - Whitebridge	0.000	27/08/1995	25/07/1995	22/12/1995	151	30/07/1995	26/09/1995	59	25/07/1995	22/12/1995	151
River Wittle - Quidenham	0.000	15/11/1990	03/11/1990	02/01/1991	61	05/11/1990	26/11/1990	22	04/11/1990	26/11/1990	23
River Tove - Cappenham Bridge	0.109	04/10/1990	01/10/1990	17/10/1990	17	01/10/1990	17/10/1990	17	01/10/1990	17/10/1990	17
Bedford Ouse - Bedford	1.000	17/09/1982	17/09/1982	22/09/1982	6	17/09/1982	21/09/1982	5	17/09/1982	22/09/1982	6
River Rhee - Burnt Mill	0.145	25/07/2006	08/07/2006	27/07/2006	20	20/06/2006	27/07/2006	38	16/06/2006	27/07/2006	42
River Heacham - Heacham	0.015	12/12/1991	30/09/1991	09/01/1992	102	08/08/1991	22/02/1992	199	07/06/1991	05/12/1992	549
River Little Ouse - Knettishall	0.045	31/08/1990	14/07/1990	16/10/1990	95	11/07/1990	18/10/1990	100	08/07/1990	19/10/1990	104
River Thet - Melford Bridge	0.245	13/09/2009	20/08/2009	09/10/2009	51	07/08/2009	23/10/2009	78	06/08/2009	23/10/2009	79
River Cam - Dernford	0.104	24/08/1997	07/08/1997	10/10/1997	65	19/07/1997	05/11/1997	110	29/06/1997	05/12/1997	160
River Lark - Temple	0.127	18/08/1997	18/08/1997	25/08/1997	8	21/07/1997	12/09/1997	54	03/07/1997	07/11/1997	128
River Nar - Marham	0.150	20/09/1991	09/09/1991	27/09/1991	19	29/07/1991	30/10/1991	94	25/07/1991	21/12/1991	150
River Babingley - Castle Rising	0.078	09/08/1996	02/08/1996	11/08/1996	10	18/07/1996	12/08/1996	26	12/06/1996	12/11/1996	154
River Ivel - Blunham	0.586	20/08/1997	-	-	-	02/08/1997	28/08/1997	27	02/08/1997	07/10/1997	67
River Flit - Shefford	0.322	03/09/1982	-	-	-	-	-	-	-	-	-
River Hiz - Arlesey	0.241	09/09/1997	-	-	-	31/08/1997	07/10/1997	38	28/08/1997	07/10/1997	41

At sites with multiple zero flows (e.g. Granta at Linton) the minimum flow in the 30-year period was taken as the earliest date a zero flow was recorded.

[1] Start date: earliest date that daily mean flows fell below each flow threshold.

[2] End date: earliest date that daily mean flows crossed back above each flow threshold.

[3] Days below each flow threshold during drought event i.e. the number of days between the start and end dates.

Appendix 5.2: Timings of the drought/low-flow event at each study site in 1990 (drought/low flow period defined using minimum flow in 1990)

Study Site	Min Flow in 1990 (m^{3}s^{-1})	Date of min flow	20% ADF Start Date[1]	20% ADF End Date[2]	Days Below 20% ADF[3]	Q_{95} Start Date[1]	Q_{95} End Date[2]	Days Below Q_{95}[3]	MAM7 Start Date[1]	MAM7 End Date[2]	Days Below MAM7[3]
River Granta - Linton	0.001	23/10/1990	12/06/1990	15/02/1991	249	24/09/1990	10/01/1991	109	14/07/1990	15/02/1991	217
River Kym - Meagre Farm	0.016	22/07/1990	25/04/1990	10/12/1990	230	13/07/1990	30/07/1990	18	17/07/1990	30/07/1990	14
River Stringside - Whitebridge	0.008	06/09/1990	27/06/1990	09/01/1991	197	18/07/1990	18/11/1990	124	26/06/1990	10/01/1991	199
River Wittle - Quidenham	0.000	15/11/1990	03/11/1990	02/01/1991	61	05/11/1990	26/11/1990	22	04/11/1990	26/11/1990	23
River Tove - Cappenham Bridge	0.109	04/10/1990	01/10/1990	17/10/1990	17	01/10/1990	17/10/1990	17	01/10/1990	17/10/1990	17
Bedford Ouse - Bedford	1.100	07/08/1990	12/07/1990	20/08/1990	40	13/07/1990	20/08/1990	39	13/07/1990	20/08/1990	39
River Rhee - Burnt Mill	0.204	22/07/1990	21/07/1990	08/08/1990	19	20/07/1990	10/08/1990	22	08/07/1990	30/09/1990	85
River Heacham - Heacham	0.027	23/12/1990	21/11/1990	09/01/1991	50	05/11/1990	18/01/1991	75	05/06/1990	27/02/1991	268
River Little Ouse - Knettishall	0.045	31/08/1990	14/07/1990	16/10/1990	95	11/07/1990	18/10/1990	100	08/07/1990	19/10/1990	104
River Thet - Melford Bridge	0.325	16/07/1990	13/07/1990	18/07/1990	6	10/07/1990	19/07/1990	10	10/07/1990	19/07/1990	10
River Cam - Dernford	0.228	06/12/1990	-	-	-	-	-	-	21/11/1990	21/12/1990	31
River Lark - Temple	0.282	14/08/1990	-	-	-	01/08/1990	19/08/1990	19	08/07/1990	18/10/1990	103
River Nar - Marham	0.166	05/09/1990	03/09/1990	10/09/1990	8	10/07/1990	25/09/1990	78	23/06/1990	26/12/1990	187
River Babingley - Castle Rising	0.109	11/08/1990	-	-	-	31/07/1990	19/08/1990	20	05/06/1990	09/01/1991	219
River Ivel - Blunham	0.845	12/08/1990	-	-	-	01/08/1990	15/08/1990	15	17/07/1990	16/08/1990	31
River Flit - Shefford	0.373	07/08/1990	-	-	-	31/07/1990	15/08/1990	16	31/07/1990	15/08/1990	16
River Hiz - Arlesey	0.319	13/09/1990	-	-	-	12/09/1990	23/09/1990	12	26/08/1990	29/09/1990	35

At sites with multiple zero flows (e.g. Granta at Linton) the minimum flow in the 30-year period was taken as the earliest date a zero flow was recorded.

[1] Start date: earliest date that daily mean flows fell below each flow threshold.

[2] End date: earliest date that daily mean flows crossed back above each flow threshold.

[3] Days below each flow threshold during drought event i.e. the number of days between the start and end dates.

Appendix 6.1: Information on gauging stations used in initial flow assessments - Great Ouse and Trent catchments (38 study sites ranked by Q_{95} % Mean Flow) study sites highlighted were used in the more detailed flow assessments

Watercourse	Station Name	Basin	Catchment Area (km^2)	Sensitivity[1] (%)	Factors Affecting Runoff[2]	BFI[3]	Long-term[4]		1988 – 2012[5]		
							Mean Flow (m^3/s)	Q_{95} (m^3/s)	Mean Flow (m^3/s)	Q_{95} (m^3/s)	Q_{95} (% Mean Flow)
River Granta	Linton	GO	59.8	25	GEI	0.45	0.190	0.008	0.181	0.004	2.0
River Kym	Meagre Farm	GO	137.5	66	EI	0.26	0.617	0.020	0.595	0.023	3.8
River Stringside	Whitebridge	GO	98.8	21	GI	0.84	0.507	0.053	0.467	0.036	7.7
River Wittle	Quidenham	GO	28.3	32	GI	0.65	0.138	0.016	0.137	0.014	10.2
River Wreake	Syston Mill	T	413.8	16	GE	0.40	2.855	0.314	2.841	0.328	11.5
River Sence	South Wigston	T	113.0	-	EI	0.41	0.960	0.141	0.907	0.142	15.6
Rothley Brook	Rothley	T	94.0	18	SE	0.45	0.743	0.123	0.724	0.113	15.7
River Manifold	Ilam	T	148.5	18	N	0.53	3.575	0.634	3.529	0.594	16.8
River Tove	Cappenham Bridge	GO	138.1	12	EI	0.54	1.067	0.190	1.066	0.185	17.4
Bedford Ouse	Bedford	GO	1460.0	-	SPGEI	0.53	10.717	1.133	12.143	2.262	18.6
River Cole	Coleshill	T	130.0	27	EI	0.42	0.958	0.190	0.946	0.179	18.9
River Soar	Littlethorpe	T	183.9	-	E	0.49	1.371	0.263	1.297	0.246	19.0
Meece Brook	Shallowford	T	86.3	-	EI	0.62	0.665	0.142	0.675	0.137	20.3
River Ryton	Worksop	T	77.0	-	GE	0.62	0.455	0.089	0.416	0.087	20.8
River Churnet	Basford Bridge	T	139.0	35	SP	0.44	1.971	0.435	1.963	0.413	21.0
River Rhee	Burnt Mill	GO	303.0	19	GEI	0.74	1.176	0.254	1.095	0.239	21.9
River Derwent	Yorkshire Bridge	T	126.0	9	SRP	0.47	2.109	0.521	2.080	0.467	22.4
River Heacham	Heacham	GO	59.0	34	GI	0.96	0.209	0.053	0.202	0.046	22.6
Little Ouse	Knettishall	GO	101.0	19	GEI	0.65	0.483	0.118	0.470	0.109	23.2
River Thet	Melford Bridge	GO	316.0	14	GEI	0.78	1.903	0.465	1.928	0.452	23.4
River Anker	Polesworth	T	368.0	15	GE	0.51	3.154	0.714	3.371	0.848	25.2
River Amber	Wingfield Park	T	139.0	22	SRPG	0.49	1.391	0.349	1.372	0.355	25.8
River Rea	Calthorpe Park	T	74.0	12	E	0.45	0.778	0.211	0.736	0.197	26.7
River Cam	Dernford	GO	198.0	15	GEI	0.77	0.917	0.267	0.812	0.222	27.3
River Dove	Izaak Walton	T	83.0	9	N	0.79	1.920	0.547	1.903	0.521	27.4
River Sow	Great Bridgford	T	163.0	12	GE	0.65	1.164	0.333	1.168	0.325	27.8
Dover Beck	Lowdham	T	69.0	8	G	0.75	0.161	0.049	0.158	0.047	29.9
River Lark	Temple	GO	272.0	7	GEI	0.77	1.283	0.456	1.247	0.376	30.2

River Nar	Marham	GO	153.3	12	PGEI	0.91	1.134	0.387	1.039	0.314	30.2
River Trent	North Muskham	T	8231.0	8	SRPGEI	0.65	89.162	28.330	87.148	27.339	31.4
River Greet	Southwell	T	46.2	-	GI	0.70	0.303	0.099	0.294	0.093	31.6
River Babingley	Castle Rising	GO	47.7	67	GEI	0.95	0.513	0.178	0.493	0.159	32.4
River Ivel	Blunham	GO	541.3	9	GEI	0.73	2.979	1.050	2.855	1.023	35.8
River Idle	Mattersey	T	529.0	-	SRGE	0.78	2.363	0.833	2.190	0.798	36.4
River Torne	Auckley	T	135.5	13	GE	0.70	0.896	0.332	0.845	0.320	37.9
River Flit	Shefford	GO	119.6	11	GEI	0.73	0.884	0.359	0.970	0.468	48.2
River Hiz	Arlesey	GO	108.0	19	GEI	0.85	0.672	0.326	0.667	0.328	49.1
River Tame	Lea Marston Lakes	T	799.0	-	EI	0.68	13.876	7.290	14.109	7.453	52.8

Notes:

[1] Sensitivity: The sensitivity index used here is the percentage change in flow associated with a 10mm increase in stage at the Q_{95} flow; the higher the percentage change, the greater the uncertainty in computed flows associated with a given systematic error in stage measurement. A high percentage change is therefore indicative of an insensitive gauging station. The sensitivity index provides a guide to the susceptibility of low flows at individual stations to errors arising from imprecise stage measurement. Where available, sensitivity values were obtained from Marsh and Hannaford (2008).

[2] Factors Affecting Runoff (FAR) information was obtained from the NRFA to provide an indication of the types of artificial influences within each catchment.

S – reservoir(s) in catchment affect runoff
R – regulation from surface water and/or ground water
P – runoff reduced by public water supply abstraction
G – runoff influenced by groundwater abstraction and/or recharge
E – runoff increased by effluent returns
I – runoff reduced by industrial and/or agricultural abstraction
N - natural to within 10% at the 95 percentile flow

.

[3] BFI: The Base Flow Index (BFI) may be thought of as a measure of the proportion of the river runoff that derives from stored sources; the more permeable the rock, superficial deposits and soils in a catchment, the higher the baseflow and the more sustained the river's flow during periods of dry weather. BFI information was obtained from the National River Flow Archive in July 2014.

[4] Long-term mean flow and Q_{95} flow information was obtained from the National River Flow Archive in July 2014.

[5] Mean flows and Q_{95} flows were calculated from daily mean flows recorded between 01/01/1988 and 31/12/2012 (i.e. from 25 years of daily mean flow data).

Appendix 6.2: Flow data availability and station type - Great Ouse and Trent catchments (38 study sites ranked by Q_{95} % mean flow)

Watercourse	Gauging Station	Basin	Station Type[1]	Period(s) of Missing Data	Total Number Days of Missing Data	1988-2012 25-year data availability (%)	Future Flows Site[2]
River Granta	Linton	GO	CC	-	-	100	N
River Kym	Meagre Farm	GO	CB	-	-	100	Y
River Stringside	Whitebridge	GO	FL	12/10/1993-15/10/1993 06/01/1994-09/01/1994	8	99.9	Y
River Wittle	Quidenham	GO	CB	20/07/1995-01/08/1995 25/11/1995-26/11/1995	15	99.8	N
River Wreake	Syston Mill	T	EM	-	-	100	N
River Sence	South Wigston	T	EM	-	-	100	N
Rothley Brook	Rothley	T	FV/VA	-	-	100	N
River Manifold	Ilam	T	C	-	-	100	Y
River Tove	Cappenham Bridge	GO	CB	-	-	100	Y
Bedford Ouse	Bedford	GO	MIS	-	-	100	N
River Cole	Coleshill	T	FV/VA	14/07/2012-09/08/2012	27	99.7	Y
River Soar	Littlethorpe	T	EM	-	-	100	N
Meece Brook	Shallowford	T	FV/VA	-	-	100	N
River Ryton	Worksop	T	FV	-	-	100	N
River Churnet	Basford Bridge	T	FV/VA	-	-	100	N
River Rhee	Burnt Mill	GO	C	02/01/1995-03/01/1995	2	99.9	N
River Derwent	Yorkshire Bridge	T	FL	-	-	100	N
River Heacham	Heacham	GO	CC	28/01/1993-21/02/1993 03/02/1994 31/08/1995-18/09/1995	45	99.5	N
Little Ouse	Knettishall	GO	MIS	-	-	100	Y
River Thet	Melford Bridge	GO	C	-	-	100	Y
River Anker	Polesworth	T	C/VA	01/08/1992-31/08/1992	31	99.7	N
River Amber	Wingfield Park	T	FV/VA	-	-	100	N
River Rea	Calthorpe Park	T	C/B	-	-	100	N
River Cam	Dernford	GO	TP	-	-	100	N
River Dove	Izaak Walton	T	FV	-	-	100	Y
River Sow	Great Bridgford	T	FV/VA	-	-	100	N

Dover Beck	Lowdham	T	FV/VA	-	-	100	N
River Lark	Temple	GO	CB	12/04/1991-25/04/1991 21/07/1992-09/08/1992 09/09/1996-11/09/1996	37	99.6	Y
River Nar	Marham	GO	FL	25/11/1992-29/11/1992 01/01/2002-03/01/2002 17/06/2002-21/06/2002 24/06/2002-25/06/2002	15	99.8	N
River Trent	North Muskham	T	US	-	-	100	Y
River Greet	Southwell	T	FV	-	-	100	N
River Babingley	Castle Rising	GO	FV	13/05/2001-24/06/2001	43	99.5	N
River Ivel	Blunham	GO	C	-	-	100	N
River Idle	Mattersey	T	EM	-	-	100	N
River Torne	Auckley	T	FV/VA	21/06/2012-15/09/2012	87	99.0	N
River Flit	Shefford	GO	FL	21/12/1989 02/11/1994 19/11/1994-21/11/1994 29/05/1995-01/06/1995	9	99.9	N
River Hiz	Arlesey	GO	C	-	-	100	N
River Tame	Lea Marston Lakes	T	MIS	-	-	100	N

[1]Station Type

B – Broad-crested weir
C – Crump profile single-crest weir
CB – Compound broad-crested weir.
CC – Compound crump weir
EM – Electromagnetic gauging station
FL – Flume
FV – Flat V triangular profile weir
MIS – Miscellaneous
TP – Rectangular thin-plate weir
US – Ultrasonic gauging station
VA – Velocity-area gauging station

[2] Future Flows Site

At each Future Flows site, an ensemble of 11 realisations of daily flows have been modelled for the period 1951-2098 based on the Medium emission scenario (A1B). This provides a dataset for understanding the influence of climate variability on river flow at each site and how this might change in the future. http://www.ceh.ac.uk/sci_programmes/water/futureflowsandgroundwaterlevels.html

Appendix 6.3: Information on the descriptors of ecological drought

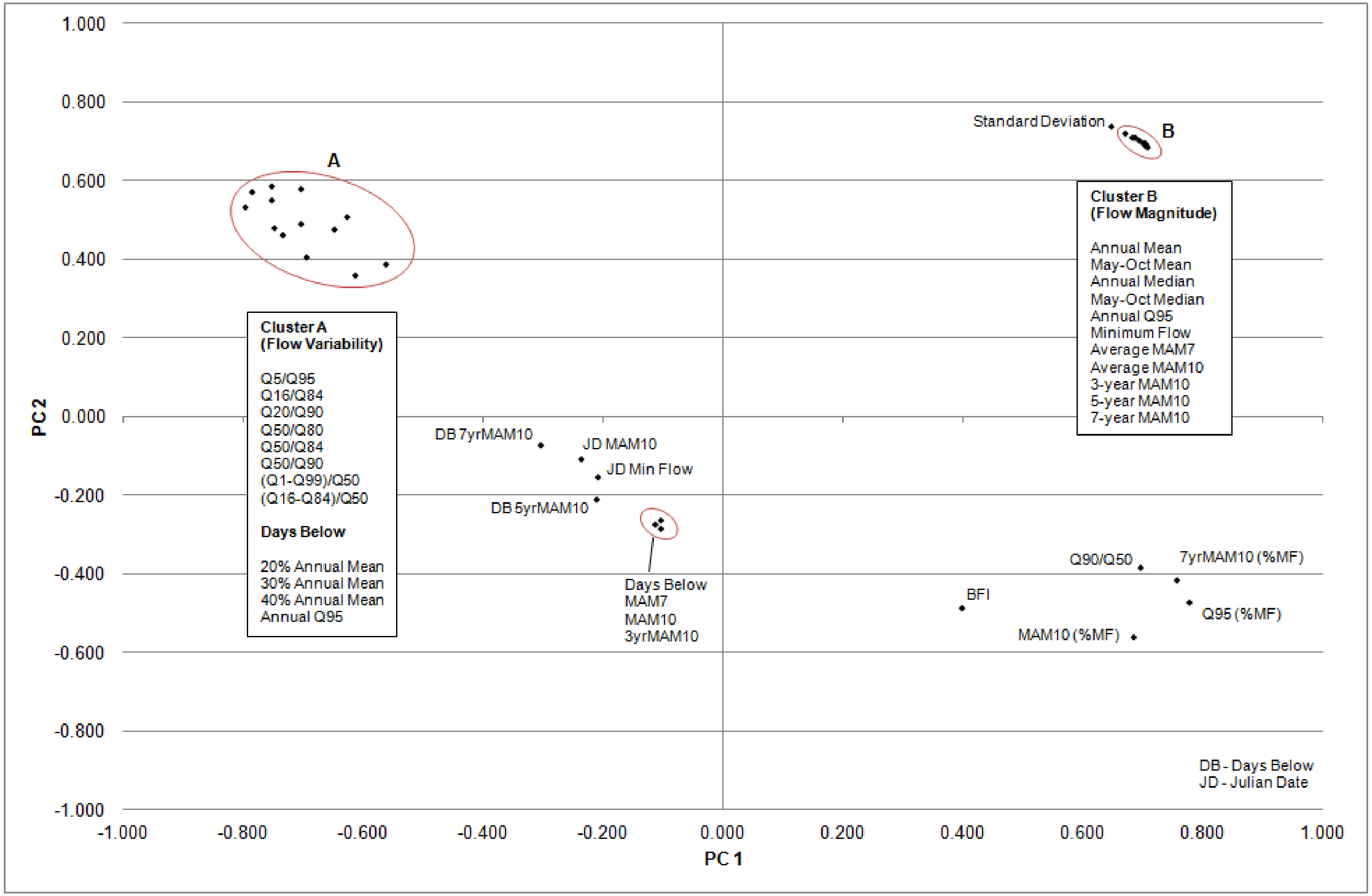
Ecological Drought Descriptor	**Definition of Ecological Drought Descriptor**	**Calculation of Ecological Drought Descriptor**
Annual Q_{95} exceedence probability (Q_{95})	The Q_{95} exceedence probability; the flow that is equalled or exceeded for 95% of the time.	The annual Q_{95} was calculated within Excel using the daily mean flow record for each study site.
Annual Q_{84} exceedence probability (Q_{84})	The Q_{84} exceedence probability; the flow that is equalled or exceeded for 84% of the time.	The annual Q_{84} was calculated within Excel using the daily mean flow record for each study site.
10% long-term average daily flow (10%ADF)	10% of the long-term average daily flow for each study site.	The value of 10% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 10% ADF. Included to assess the utility of Baxter's (1961) approach.
15% long-term average daily flow (15%ADF)	15% of the long-term average daily flow for each study site.	The value of 15% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 15% ADF. Included to assess the utility of Baxter's (1961) approach.
20% long-term average daily flow (20%ADF)	20% of the long-term average daily flow for each study site.	The value of 20% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 20% ADF. Included to assess the utility of Baxter's (1961) approach.
25% long-term average daily flow (25%ADF)	25% of the long-term average daily flow for each study site.	The value of 25% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 25% ADF. Included to assess the utility of Baxter's (1961) approach.
30% long-term average daily flow (30%ADF)	30% of the long-term average daily flow for each study site.	The value of 30% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 30% ADF. Included to assess the utility of Baxter's (1961) approach.
35% long-term average daily flow (35%ADF)	35% of the long-term average daily flow for each study site.	The value of 35% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 35% ADF. Included to assess the utility of Baxter's (1961) approach.
40% long-term average daily flow (35%ADF)	40% of the long-term average daily flow for each study site.	The value of 40% ADF was calculated using the daily mean flow record at each study site. The long-term average daily flow was calculated and then used to determine 40% ADF. Included to

		assess the utility of Baxter's (1961) approach.
Annual 1-day minimum flow Annual Minimum Flow	The annual minimum daily mean flow for each study site.	At each study site for each year in the study period the annual minimum flow was identified within Excel (n=30).
Annual 7-day minimum flow (average for study period) Average MAM(7)	The average value taken from the series of annual values of the mean annual 7-day minimum flow at each study site. The MAM(7) is defined as the mean annual 7-day minimum flow and describes the lowest consecutive 7-day flow period each year.	At each study site the MAM(7) for each year in the study period was calculated within Excel. The average value of the series of MAM(7) values was then identified and used as the average mean annual 7-day minimum flow descriptor for each study site.
Annual 7-day minimum flow (minimum for study period) Minimum MAM(7)	The minimum value taken from the series of annual values of the mean annual 7-day minimum flow at each study site. The MAM(7) is defined as the mean annual 7-day minimum flow and describes the lowest consecutive 7-day flow period each year.	At each study site the MAM(7) for each year in the study period was calculated within Excel. The minimum value from the series of MAM(7) values was then identified and used as the minimum mean annual 7-day minimum flow descriptor for each study site.
Annual 10-day minimum flow (average for study period) Average MAM(10)	The average value taken from the series of annual values of the mean annual 10-day minimum flow at each study site. The MAM(10) is defined as the mean annual 10-day minimum flow and describes the lowest consecutive 10-day flow period (month) each year.	At each study site the MAM(30) for each year in the study period was calculated within Excel. The average value of the series of MAM(10) values was then identified and used as the average mean annual 10-day minimum flow descriptor for each study site.
Annual 10-day minimum flow (minimum for study period) Minimum MAM(10)	The minimum value taken from the series of annual values of the mean annual 10-day minimum flow at each study site. The MAM(10) is defined as the mean annual 10-day minimum flow and describes the lowest consecutive 10-day flow period each year.	At each study site the MAM(10) for each year in the study period was calculated within Excel. The minimum value from the series of MAM(10) values was then identified and used as the minimum mean annual 10-day minimum flow descriptor for each study site.
Annual 20-day minimum flow (average for study period) Average MAM(20)	The average value taken from the series of annual values of the mean annual 20-day minimum flow at each study site. The MAM(20) is defined as the mean annual 20-day minimum flow and describes the lowest consecutive 20-day flow period (month) each year.	At each study site the MAM(20) for each year in the study period was calculated within Excel. The average value of the series of MAM(20) values was then identified and used as the average mean annual 20-day minimum flow descriptor for each study site.
Annual 20-day minimum flow (minimum for study period) Minimum MAM(20)	The minimum value taken from the series of annual values of the mean annual 20-day minimum flow at each study site. The MAM(20) is defined as the mean annual 20-day minimum flow and describes the lowest consecutive 20-day flow period each year.	At each study site the MAM(20) for each year in the study period was calculated within Excel. The minimum value from the series of MAM(20) values was then identified and used as the minimum mean annual 20-day minimum flow descriptor for each study site.
Annual 30-day minimum flow (average for study period) Average MAM(30)	The average value taken from the series of annual values of the mean annual 30-day minimum flow at each study site. The MAM(30) is defined as the mean annual 30-day	At each study site the MAM(30) for each year in the study period was calculated within Excel. The average value of the series of MAM(30) values was then identified and used as the

	minimum flow and describes the lowest consecutive 30-day flow period (month) each year.	average mean annual 30-day minimum flow descriptor for each study site.
Annual 30-day minimum flow (minimum for study period) Minimum MAM(30)	The minimum value taken from the series of annual values of the mean annual 30-day minimum flow at each study site. The MAM(30) is defined as the mean annual 30-day minimum flow and describes the lowest consecutive 30-day flow period each year.	At each study site the MAM(30) for each year in the study period was calculated within Excel. The minimum value from the series of MAM(30) values was then identified and used as the minimum mean annual 30-day minimum flow descriptor for each study site.
Annual 50-day minimum flow (average for study period) Average MAM(50)	The average value taken from the series of annual values of the mean annual 50-day minimum flow at each study site. The MAM(50) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 50-day flow period (month) each year.	At each study site the MAM(50) for each year in the study period was calculated within Excel. The average value of the series of MAM(50) values was then identified and used as the average mean annual 50-day minimum flow descriptor for each study site.
Annual 50-day minimum flow (minimum for study period) Minimum MAM(50)	The minimum value taken from the series of annual values of the mean annual 50-day minimum flow at each study site. The MAM(50) is defined as the mean annual 50-day minimum flow and describes the lowest consecutive 50-day flow period each year.	At each study site the MAM(50) for each year in the study period was calculated within Excel. The minimum value from the series of MAM(50) values was then identified and used as the minimum mean annual 50-day minimum flow descriptor for each study site.
Annual 100-day minimum flow (average for study period) Average MAM(100)	The average value taken from the series of annual values of the mean annual 100-day minimum flow at each study site. The MAM(100) is defined as the mean annual 100-day minimum flow and describes the lowest consecutive 100-day flow period (month) each year.	At each study site the MAM(100) for each year in the study period was calculated within Excel. The average value of the series of MAM(100) values was then identified and used as the average mean annual 100-day minimum flow descriptor for each study site.
Annual 100-day minimum flow (minimum for study period) Minimum MAM(100)	The minimum value taken from the series of annual values of the mean annual 50-day minimum flow at each study site. The MAM(100) is defined as the mean annual 100-day minimum flow and describes the lowest consecutive 100-day flow period each year.	At each study site the MAM(100) for each year in the study period was calculated within Excel. The minimum value from the series of MAM(100) values was then identified and used as the minimum mean annual 100-day minimum flow descriptor for each study site.
Annual Q_{95} exceedence probability standardised by the long-term mean flow Q_{95}(% Mean Flow)	The Q_{95} exceedence probability i.e. the flow that is equalled or exceeded for 95% of the time standardised by the long-term mean flow.	The annual Q_{95} was calculated within Excel using the daily mean flow record for each study site and standardised by the long-term mean flow. (The annual Q_{95} flow divided by the long-term mean flow multiplied by 100 (Q_{95}/Q_{MEAN}) * 100)
Annual 7-day minimum flow (average for study period) standardised by the long-term mean flow Average MAM(7) (% Mean Flow)	The average value taken from the series of annual values of the mean annual 7-day minimum flow at each study site standardised by the long-term mean flow.	At each study site the MAM(7) for each year in the study period was calculated. The average value of the series of MAM(7) values was identified and used as the average mean annual 7-day minimum flow descriptor for each study site and standardised by the long-term mean flow.

Annual 7-day minimum flow (minimum for study period) standardised by the long-term mean flow Minimum MAM(7) (% Mean Flow)	The minimum value taken from the series of annual values of the mean annual 7-day minimum flow at each study site standardised by the long-term mean flow.	At each study site the MAM(7) for each year in the study period was calculated. The minimum value of the series of MAM(7) values was identified and used as the minimum mean annual 7-day minimum flow descriptor for each study site and standardised by the long-term mean flow.
Annual 7-day minimum flow standardised by the average Annual 7-day minimum flow MAM(7) (% Average MAM7)	The series of annual values of the mean annual 7-day minimum flow at each study site i.e. the lowest consecutive 7-day flow period each year standardised by the average of the series of MAM(7) values.	At each study site the MAM(7) for each year in the study period was calculated and standardised by the average of the series of MAM(7) values.
Julian Date of the ecological drought descriptor	The Julian Date of the occurrence of each ecological drought descriptor listed above was identified for each study site. Julian dates represent calendar dates with integer values, which start with 1 on January 1st and end with 366 on December 31st.	In this Chapter the Julian Date is calculated as the last day of the low flow series (e.g. average MAM(7)) for each ecological drought descriptor.
Total Number of days below each ecological drought descriptor	The total number of days average daily flows at each study site in the 1990-2009 study period were lower than each ecological drought descriptor.	The total number of days average daily flows fell below each ecological drought descriptor was determined using daily mean flow data within Excel.
Consecutive Number of days below each ecological drought descriptor	Low flow persistence defined as the occurrence of daily mean flows below an ecological drought descriptor for more than 5 consecutive days.	The number of consecutive days average daily flows fell below each ecological drought descriptor was determined using daily mean flow data within Excel.

Appendix 6.4: Unrotated plot of loadings of the first two principal components of 37 low-flow metrics (38 study sites; River Trent and River Great Ouse catchments)



Appendix 6.5: Correlation Matrixes illustrating hydrological dependency defined using the inter-annual variability in the occurrence of flows equal to or lower than the Annual Q_{95} and Average MAM10 (38 study sites River Trent and River Great Ouse catchments ranked by Q_{95} % mean flow; cells highlighted red indicate a correlation coefficient of between 0.700-0.799 and blue a correlation coefficient of >0.800)

Days Below Annual Q_{95}

	LI	MF	WH	QU	SM	SW	RO	IL	CB	BE	CO	LT	SH	WO	BB	BM	YB	HE	KN	MB	PO	WP	CP	DE	IW	GB	LO	TE	MA	NM	SO	CR	BL	MT	AU	SE	AR	LM
LI	--															🟥												🟦										
MF		--									🟥																									🟥		
WH			--											🟥			🟥				🟥										🟥	🟦						
QU			🟥	--										🟥				🟥			🟥										🟦							
SM					--																															🟥		
SW						--																																
RO					🟥		--					🟦																					🟥					
IL			🟥					--			🟥										🟥				🟦					🟦								🟥
CB		🟥	🟥	🟥	🟥				--		🟦	🟥		🟥		🟥					🟦				🟦					🟥						🟦		🟥
BE										--				🟦																	🟥							
CO		🟥					🟥		🟥	🟥	--	🟥									🟥				🟦					🟦				🟥				🟥
LT					🟥		🟦				🟥	--																										
SH			🟥	🟥				🟥					--													🟦					🟦				🟥			
WO			🟦					🟥	🟥	🟥			🟥	--							🟦				🟥		🟥			🟥	🟦	🟥		🟥	🟦			
BB			🟥	🟥				🟥					🟦	🟥	--											🟥					🟥							
BM									🟦	🟥				🟥		--					🟥			🟦				🟥					🟦	🟥	🟥	🟥	🟥	
YB															🟥		--										🟥					🟦						
HE	🟥		🟥	🟦					🟥							🟥		--													🟥	🟦						
KN	🟥	🟥	🟥	🟦					🟦							🟥		🟦	--							🟥		🟥	🟥							🟦		
MB		🟥	🟥	🟥					🟦										🟦	--																🟥		
PO			🟦			🟥		🟥	🟦	🟥	🟥		🟦	🟥	🟥	🟥		🟥	🟥		--				🟦	🟥				🟥	🟦			🟥	🟥	🟦		🟥
WP																						--																
CP																							--															
DE									🟥							🟥		🟥	🟥					--				🟥									🟦	
IW			🟥		🟥			🟦	🟥		🟦		🟥								🟦				--	🟥				🟦	🟥					🟥		🟥
GB								🟦					🟥								🟦				🟥	--			🟥		🟥				🟥			
LO														🟥							🟥						--					🟥						
TE	🟦		🟥	🟥					🟥						🟥	🟥		🟦	🟦		🟥			🟦				--										
MA	🟥		🟦	🟦					🟦										🟦	🟥	🟥							🟦	--									
NM			🟥					🟦	🟥		🟦		🟥	🟥							🟦				🟦	🟦			🟥	--								🟦
SO			🟥						🟥	🟥				🟦		🟦		🟥			🟦							🟥	🟥		--	🟥			🟥			
CR			🟦	🟦									🟥	🟥	🟥			🟥	🟥		🟥						🟥	🟥	🟥			--						
BL							🟥		🟦	🟥	🟥	🟥				🟥					🟥							🟥					--	🟦	🟥		🟥	
MT							🟥				🟥			🟥		🟥					🟦				🟥	🟥		🟥		🟥	🟦		🟥	--	🟦	🟥		
AU			🟥					🟥					🟥	🟦		🟥					🟦				🟥	🟦		🟥		🟥	🟦			🟦	--			
SE		🟥	🟦	🟥	🟥				🟦		🟥					🟥		🟦	🟦	🟦	🟦			🟥	🟥			🟦	🟥		🟥		🟥	🟥	🟥	--		🟦
AR									🟦							🟦			🟥					🟥							🟥		🟥			🟥	--	
LM			🟥						🟦		🟥					🟥		🟥	🟥		🟥				🟥	🟥			🟥	🟦						🟦		--

Days Below MAM10

Appendix 6.6: Correlation Matrixes illustrating hydrological dependency defined using the inter-annual variability in the occurrence of flows equal to or lower than 20% and 30% of the annual mean flow (38 study sites River Trent and River Great Ouse catchments ranked by Q_{95} % mean flow; cells highlighted red indicate a correlation coefficient of between 0.700-0.799 and blue a correlation coefficient of >0.800)

Days Below 20% ADF

	LI	MF	WH	QU	SM	SW	RO	IL	CB	BE	CO	LT	SH	WO	BB	BM	YB	HE	KN	MB	PO	WP	CP	DE	IW	GB	LO	TE	MA	NM	SO	CR	BL	MT	AU	SE	AR	LM
LI	--	🟥							🟥							🟦																						
MF	🟥	--	🟥		🟥				🟦		🟥																											
WH		🟥	--	🟥					🟥					🟥	🟥					🟥																		
QU			🟥	--																🟥																		
SM		🟥	🟥		--	🟥					🟥																											
SW		🟥	🟥		🟦	--			🟥											🟥																		
RO		🟥			🟦		--		🟥		🟥	🟦																										
IL								--																														
CB		🟦	🟦		🟦	🟦	🟥		--		🟦	🟥		🟥		🟥			🟥	🟥																		
BE		🟥	🟥						🟦	--	🟥			🟥																								
CO		🟥			🟥	🟥	🟦	🟥	🟦	🟦	--	🟥																										
LT							🟥				🟥	--																										
SH			🟥					🟥		🟥			--								🟥																	
WO			🟥					🟥	🟥	🟦			🟥	--																								
BB		🟥	🟥					🟦		🟥	🟥		🟦	🟥	--																							
BM	🟦	🟦	🟥	🟥					🟥	🟥				🟥		--			🟥																			
YB																	--																					
HE				🟥														--			🟦								🟥									
KN		🟥	🟥	🟦					🟥							🟦			--																			
MB		🟥	🟥		🟥				🟥										🟦	--																		
PO		🟥	🟦		🟥	🟥		🟦	🟦	🟥	🟥		🟥	🟦	🟥						--																	
WP																						--																
CP																							--															
DE	🟥															🟦			🟥					--														
IW		🟥	🟥		🟦	🟥		🟦	🟥	🟥	🟥		🟥	🟥	🟦						🟦				--	🟦					🟥							
GB								🟥					🟥	🟥	🟥						🟥				🟥	--												
LO																											--											
TE	🟦															🟥			🟥					🟦				--										
MA																													--			🟥						
NM			🟥					🟥	🟥	🟥	🟥			🟥							🟥				🟥	🟥				--								
SO			🟦	🟥				🟥					🟦	🟦				🟥			🟥										--							
CR																		🟦													🟦	--						
BL																																	--					
MT		🟥														🟥								🟥									🟦	--				
AU			🟥											🟥												🟥								🟥	--			
SE																																				--		
AR																																					--	
LM																																						--

Days Below 30% ADF

Sites: LI (River Granta Linton), MF (River Kym Meagre Farm), WH (River Stringside Whitebridge), QU (River Wittle Quidenham), SM (River Wreake Syston Mill), SW (River Sence South Wigston), RO (Rothley Brook Rothley), IL (River Manifold Ilam), CB (River Tove Cappenham Bridge), BE (Bedford Ouse Bedford), CO (River Cole Coleshill), LT (River Soar Littlethorpe), SH (Meece Brook Shallowford), WO (River Ryton Worksop), BB (River Churnet Basford Bridge), BM (River Rhee Burnt Mill), YB (River Derwent Yorkshire Bridge), HE (River Heacham Heacham), KN (Little Ouse Knettishall), MB (River Thet Melford Bridge), PO (River Anker Polesworth), WP (River Amber Wingfield Park), CP (River Rea Calthorpe Park), DE (River Cam Dernford), IW (River Dove Izaak Walton), GB (River Sow Great Bridgford), LO (Dover Beck Lowdham), TE (River Lark Temple), MA (River Nar Marham), NM (River Trent North Muskham), SO (River Greet Southwell), CR (River Babingley Castle Rising), BL (River Ivel Blunham), MT (River Idle Mattersey), AU (River Torne Auckley), SE (River Flit Shefford), AR (River Hiz Arlesey) and LM (River Tame Lea Marston Lakes).

Appendix 6.7a: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Kym at Meagre Farm

May

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.054	0.065	0.123	0.037	**0.070**
HOF1: Annual Q95 (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Volume to supply (Ml)	83.03	112.49	267.84	37.50	**125.22**
HOF2: Month Q95 (m^3s^{-1})	0.033	0.033	0.033	0.033	**0.033**
HOF2: Flow to river (m^3s^{-1})	0.033	0.033	0.033	0.033	**0.033**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.010	+0.010	+0.010	+0.010	**+0.010**
HOF2: Volume to supply (Ml)	56.25	85.71	241.06	10.72	**98.44**
HOF2: Difference from HOF1 (Ml)	-26.78	-26.78	-26.78	-26.78	**-26.78**
HOF3: Month Q90 (m^3s^{-1})	0.037	0.037	0.037	0.037	**0.037**
HOF3: Flow to river (m^3s^{-1})	0.037	0.037	0.037	0.037	**0.037**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.014	+0.014	+0.014	+0.014	**+0.014**
HOF3: Volume to supply (Ml)	45.53	74.99	230.34	0.00	**87.72**
HOF3: Difference from HOF1 (Ml)	-37.50	-37.50	-37.50	-37.50	**-37.50**
HOF4: Month Q84 (m^3s^{-1})	0.045	0.045	0.045	0.045	**0.045**
HOF4: Flow to river (m^3s^{-1})	0.045	0.045	0.045	0.037	**0.043**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.022	+0.022	+0.022	+0.014	**+0.020**
HOF4: Volume to supply (Ml)	24.10	53.56	208.91	0.00	**71.64**
HOF4: Difference from HOF1 (Ml)	-58.93	-58.93	-58.93	-37.50	**-53.57**

June

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.052	0.039	0.045	0.035	**0.043**
HOF1: Annual Q95 (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Volume to supply (Ml)	75.17	41.47	57.02	31.10	**51.19**
HOF2: Month Q95 (m^3s^{-1})	0.025	0.025	0.025	0.025	**0.025**
HOF2: Flow to river (m^3s^{-1})	0.025	0.025	0.025	0.025	**0.025**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.002	+0.002	+0.002	+0.002	**+0.002**
HOF2: Volume to supply (Ml)	69.99	36.29	51.84	25.92	**46.01**
HOF2: Difference from HOF1 (Ml)	-5.18	-5.18	-5.18	-5.18	**-5.18**
HOF3: Month Q90 (m^3s^{-1})	0.028	0.028	0.028	0.028	**0.028**
HOF3: Flow to river (m^3s^{-1})	0.028	0.028	0.028	0.028	**0.028**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.005	+0.005	+0.005	+0.005	**+0.005**
HOF3: Volume to supply (Ml)	62.21	28.51	44.06	18.14	**38.23**
HOF3: Difference from HOF1 (Ml)	-12.96	-12.96	-12.96	-12.96	**-12.96**
HOF4: Month Q84 (m^3s^{-1})	0.031	0.031	0.031	0.031	**0.031**
HOF4: Flow to river (m^3s^{-1})	0.031	0.031	0.031	0.031	**0.031**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.008	+0.008	+0.008	+0.008	**+0.008**
HOF4: Volume to supply (Ml)	54.43	20.73	36.28	10.36	**30.45**
HOF4: Difference from HOF1 (Ml)	-20.74	-20.74	-20.74	-20.74	**-20.74**

July

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	0.051	0.018	0.041	0.028	**0.035**
HOF1: Annual Q95 (m^{3}s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^{3}s^{-1})	0.023	0.018	0.023	0.023	**0.022**
HOF1: Volume to supply (Ml)	75.00	0.00	48.21	13.39	**34.15**
HOF2: Month Q95 (m^{3}s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF2: Flow to river (m^{3}s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.006	-0.001	-0.006	-0.006	**-0.005**
HOF2: Volume to supply (Ml)	91.07	2.68	64.28	29.46	**46.87**
HOF2: Difference from HOF1 (Ml)	+16.07	+2.68	+16.07	+16.07	**+12.72**
HOF3: Month Q98 (m^{3}s^{-1})	0.014	0.014	0.014	0.014	**0.014**
HOF3: Flow to river (m^{3}s^{-1})	0.014	0.014	0.014	0.014	**0.014**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.009	-0.004	-0.009	-0.009	**-0.008**
HOF3: Volume to supply (Ml)	99.11	10.71	72.32	37.50	**54.91**
HOF3: Difference from HOF1 (Ml)	+24.11	+10.71	+24.11	+24.11	**+20.76**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4: Flow to river (m^{3}s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.006	-0.001	-0.006	-0.006	**-0.005**
HOF4: Volume to supply (Ml)	91.07	2.68	64.28	29.46	**46.87**
HOF4: Difference from HOF1 (Ml)	+16.07	+2.68	+16.07	+16.07	**+12.72**

August

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	0.220	0.165	0.119	0.030	**0.134**
HOF1: Annual Q95 (m^{3}s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^{3}s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Volume to supply (Ml)	527.65	380.33	257.13	18.75	**295.97**
HOF2: Month Q95 (m^{3}s^{-1})	0.018	0.018	0.018	0.018	**0.018**
HOF2: Flow to river (m^{3}s^{-1})	0.018	0.018	0.018	0.018	**0.018**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.005	-0.005	-0.005	-0.005	**-0.005**
HOF2: Volume to supply (Ml)	541.04	393.72	270.52	32.14	**309.36**
HOF2: Difference from HOF1 (Ml)	+13.39	+13.39	+13.39	+13.39	**+13.39**
HOF3: Month Q98 (m^{3}s^{-1})	0.016	0.016	0.016	0.016	**0.016**
HOF3: Flow to river (m^{3}s^{-1})	0.016	0.016	0.016	0.016	**0.016**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.007	-0.007	-0.007	-0.007	**-0.007**
HOF3: Volume to supply (Ml)	546.40	399.08	275.88	37.50	**314.72**
HOF3: Difference from HOF1 (Ml)	+18.75	+18.75	+18.75	+18.75	**+18.75**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4: Flow to river (m^{3}s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.006	-0.006	-0.006	-0.006	**-0.006**
HOF4: Volume to supply (Ml)	543.72	396.40	273.20	34.82	**312.04**
HOF4: Difference from HOF1 (Ml)	+16.07	+16.07	+16.07	+16.07	**+16.07**

September

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.020	0.051	0.064	0.026	**0.040**
HOF1: Annual Q95 (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^3s^{-1})	0.020	0.023	0.023	0.023	**0.022**
HOF1: Volume to supply (Ml)	0.00	72.58	106.27	7.78	**46.66**
HOF2: Month Q95 (m^3s^{-1})	0.019	0.019	0.019	0.019	**0.019**
HOF2: Flow to river (m^3s^{-1})	0.019	0.019	0.019	0.019	**0.019**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.001	-0.004	-0.004	-0.004	**-0.003**
HOF2: Volume to supply (Ml)	2.59	82.95	116.64	18.15	**55.08**
HOF2: Difference from HOF1 (Ml)	+2.59	+10.37	+10.37	+10.37	**+8.43**
HOF3: Month Q98 (m^3s^{-1})	0.016	0.016	0.016	0.016	**0.016**
HOF3: Flow to river (m^3s^{-1})	0.016	0.016	0.016	0.016	**0.016**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.004	-0.007	-0.007	-0.007	**-0.006**
HOF3: Volume to supply (Ml)	10.37	90.72	124.41	25.92	**62.86**
HOF3: Difference from HOF1 (Ml)	+10.37	+18.14	+18.14	+18.14	**+16.20**
HOF4: 5-year MAM10 (m^3s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4: Flow to river (m^3s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.003	-0.006	-0.006	-0.006	**-0.005**
HOF4: Volume to supply (Ml)	7.78	88.13	121.82	23.33	**60.27**
HOF4: Difference from HOF1 (Ml)	+7.78	+15.55	+15.55	+15.55	**+13.61**

October

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.025	0.112	0.889	0.022	**0.262**
HOF1: Annual Q95 (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^3s^{-1})	0.023	0.023	0.023	0.022	**0.023**
HOF1: Volume to supply (Ml)	5.36	238.38	2319.49	0.00	**640.81**
HOF2: Month Q95 (m^3s^{-1})	0.022	0.022	0.022	0.022	**0.022**
HOF2: Flow to river (m^3s^{-1})	0.022	0.022	0.022	0.022	**0.022**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.001	-0.001	-0.001	0.000	**-0.001**
HOF2: Volume to supply (Ml)	8.04	241.06	2322.17	0.00	**642.82**
HOF2: Difference from HOF1 (Ml)	+2.68	+2.68	+2.68	0.00	**+2.01**
HOF3: Month Q90 (m^3s^{-1})	0.024	0.024	0.024	0.024	**0.024**
HOF3: Flow to river (m^3s^{-1})	0.024	0.024	0.024	0.022	**0.024**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.001	+0.001	+0.001	0.000	**+0.001**
HOF3: Volume to supply (Ml)	2.68	0.00	2316.81	0.00	**579.87**
HOF3: Difference from HOF1 (Ml)	-2.68	-238.38	-2.68	0.00	**-60.94**
HOF4: Month Q84 (m^3s^{-1})	0.027	0.027	0.027	0.027	**0.027**
HOF4: Flow to river (m^3s^{-1})	0.025	0.027	0.027	0.022	**0.025**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.002	+0.004	+0.004	0.000	**+0.003**
HOF4: Volume to supply (Ml)	0.00	227.67	2308.78	0.00	**634.11**
HOF4: Difference from HOF1 (Ml)	-5.36	-10.71	-10.71	0.00	**-6.70**

November

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.209	0.185	2.801	0.037	**0.808**
HOF1: Annual Q95 (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Flow to river (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Volume to supply (Ml)	482.11	419.90	7200.58	36.29	**2034.72**
HOF2: Month Q95 (m^3s^{-1})	0.035	0.035	0.035	0.035	**0.035**
HOF2: Flow to river (m^3s^{-1})	0.035	0.035	0.035	0.035	**0.035**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.012	+0.012	+0.012	+0.012	**+0.012**
HOF2: Volume to supply (Ml)	451.01	388.80	7169.48	5.19	**2003.62**
HOF2: Difference from HOF1 (Ml)	-31.10	-31.10	-31.10	-31.10	**-31.10**
HOF3: Month Q90 (m^3s^{-1})	0.041	0.041	0.041	0.041	**0.041**
HOF3: Flow to river (m^3s^{-1})	0.041	0.041	0.041	0.037	**0.040**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.018	+0.018	+0.018	+0.014	**+0.017**
HOF3: Volume to supply (Ml)	435.45	373.24	7153.92	0.00	**1990.65**
HOF3: Difference from HOF1 (Ml)	-46.66	-46.66	-46.66	-36.29	**-44.07**
HOF4: Month Q84 (m^3s^{-1})	0.048	0.048	0.048	0.048	**0.048**
HOF4: Flow to river (m^3s^{-1})	0.048	0.048	0.048	0.037	**0.045**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.025	+0.025	+0.025	+0.025	**+0.025**
HOF4: Volume to supply (Ml)	417.31	355.10	7135.78	0.00	**1977.05**
HOF4: Difference from HOF1 (Ml)	-64.80	-64.80	-64.80	-36.29	**-57.67**

Appendix 6.7b: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Manifold at Ilam

May

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	1.216	1.525	1.128	1.133	**1.251**
HOF1: Annual Q95 (m^{3}s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^{3}s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Volume to supply (Ml)	1665.97	2493.59	1430.27	1443.66	**1758.37**
HOF2: Month Q95 (m^{3}s^{-1})	0.769	0.769	0.769	0.769	**0.769**
HOF2: Flow to river (m^{3}s^{-1})	0.769	0.769	0.769	0.769	**0.769**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.175	+0.175	+0.175	+0.175	**+0.175**
HOF2: Volume to supply (Ml)	1197.25	2024.87	961.55	974.94	**1289.65**
HOF2: Difference from HOF1 (Ml)	-468.72	-468.72	-468.72	-468.72	**-468.72**
HOF3: Month Q90 (m^{3}s^{-1})	0.877	0.877	0.877	0.877	**0.877**
HOF3: Flow to river (m^{3}s^{-1})	0.877	0.877	0.877	0.877	**0.877**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.283	+0.283	+0.283	+0.283	**+0.283**
HOF3: Volume to supply (Ml)	907.98	1735.60	672.28	685.67	**1000.38**
HOF3: Difference from HOF1 (Ml)	-757.99	-757.99	-757.99	-757.99	**-757.99**
HOF4: Month Q84 (m^{3}s^{-1})	0.984	0.984	0.984	0.984	**0.984**
HOF4: Flow to river (m^{3}s^{-1})	0.984	0.984	0.984	0.984	**0.984**
HOF4: Difference from HOF1 (m^{3}s^{-1})	+0.390	+0.390	+0.390	+0.390	**+0.390**
HOF4: Volume to supply (Ml)	621.39	1449.01	385.69	399.08	**713.79**
HOF4: Difference from HOF1 (Ml)	-1044.58	-1044.58	-1044.58	-1044.58	**-1044.58**

June

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.812	1.132	1.101	0.887	**0.983**
HOF1: Annual Q95 (m^{3}s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^{3}s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Volume to supply (Ml)	565.06	1394.50	1314.14	759.46	**1008.29**
HOF2: Month Q95 (m^{3}s^{-1})	0.640	0.640	0.640	0.640	**0.640**
HOF2: Flow to river (m^{3}s^{-1})	0.640	0.640	0.640	0.640	**0.640**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.046	+0.046	+0.046	+0.046	**+0.046**
HOF2: Volume to supply (Ml)	445.83	1275.27	1194.91	640.23	**889.06**
HOF2: Difference from HOF1 (Ml)	-119.23	-119.23	-119.23	-119.23	**-119.23**
HOF3: Month Q90 (m^{3}s^{-1})	0.699	0.699	0.699	0.699	**0.699**
HOF3: Flow to river (m^{3}s^{-1})	0.699	0.699	0.699	0.699	**0.699**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.105	+0.105	+0.105	+0.105	**+0.105**
HOF3: Volume to supply (Ml)	292.90	1122.34	1041.98	487.30	**736.13**
HOF3: Difference from HOF1 (Ml)	-272.16	-272.16	-272.16	-272.16	**-272.16**
HOF4: Month Q84 (m^{3}s^{-1})	0.770	0.770	0.770	0.770	**0.770**
HOF4: Flow to river (m^{3}s^{-1})	0.770	0.770	0.770	0.770	**0.770**
HOF4: Difference from HOF1 (m^{3}s^{-1})	+0.176	+0.176	+0.176	+0.176	**+0.176**
HOF4: Volume to supply (Ml)	108.87	938.31	857.95	303.27	**552.10**
HOF4: Difference from HOF1 (Ml)	-456.19	-456.19	-456.19	-456.19	**-456.19**

July

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	0.577	1.157	0.793	0.783	**0.828**
HOF1: Annual Q95 (m^{3}s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^{3}s^{-1})	0.577	0.594	0.594	0.594	**0.590**
HOF1: Volume to supply (Ml)	0.00	1507.94	533.00	506.22	**636.79**
HOF2: Month Q95 (m^{3}s^{-1})	0.548	0.548	0.548	0.548	**0.548**
HOF2: Flow to river (m^{3}s^{-1})	0.548	0.548	0.548	0.548	**0.548**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.029	-0.046	-0.046	-0.046	**-0.042**
HOF2: Volume to supply (Ml)	77.67	1631.15	656.21	629.43	**748.62**
HOF2: Difference from HOF1 (Ml)	+77.67	+123.21	+123.21	+123.21	**+111.83**
HOF3: Month Q98 (m^{3}s^{-1})	0.483	0.483	0.483	0.483	**0.483**
HOF3: Flow to river (m^{3}s^{-1})	0.483	0.483	0.483	0.483	**0.483**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.094	-0.111	-0.111	-0.111	**-0.107**
HOF3: Volume to supply (Ml)	251.77	1805.24	830.30	803.52	**922.71**
HOF3: Difference from HOF1 (Ml)	+251.77	+297.30	+297.30	+297.30	**+285.92**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.465	0.465	0.465	0.465	**0.465**
HOF4: Flow to river (m^{3}s^{-1})	0.465	0.465	0.465	0.465	**0.465**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.112	-0.129	-0.129	-0.129	**-0.125**
HOF4: Volume to supply (Ml)	299.98	1853.45	878.51	851.73	**970.92**
HOF4: Difference from HOF1 (Ml)	+299.98	+345.51	+345.51	+345.51	**+334.13**

August

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	0.559	0.560	0.583	0.474	**0.544**
HOF1: Annual Q95 (m^{3}s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^{3}s^{-1})	0.559	0.560	0.583	0.474	**0.544**
HOF1: Volume to supply (Ml)	0.00	0.00	0.00	0.00	**0.00**
HOF2: Month Q95 (m^{3}s^{-1})	0.478	0.478	0.478	0.478	**0.478**
HOF2: Flow to river (m^{3}s^{-1})	0.478	0.478	0.478	0.474	**0.477**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.081	-0.082	-0.105	0.000	**-0.067**
HOF2: Volume to supply (Ml)	216.95	219.63	281.23	0.00	**179.45**
HOF2: Difference from HOF1 (Ml)	+216.95	+291.63	+281.23	0.00	**+197.45**
HOF3: Month Q98 (m^{3}s^{-1})	0.436	0.436	0.436	0.436	**0.436**
HOF3: Flow to river (m^{3}s^{-1})	0.436	0.436	0.436	0.436	**0.436**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.123	-0.124	-0.147	-0.038	**-0.108**
HOF3: Volume to supply (Ml)	329.44	332.12	393.72	101.78	**289.27**
HOF3: Difference from HOF1 (Ml)	+329.44	+332.12	+393.72	+101.78	**+289.27**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.465	0.465	0.465	0.465	**0.465**
HOF4: Flow to river (m^{3}s^{-1})	0.465	0.465	0.465	0.465	**0.465**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.094	-0.095	-0.118	-0.009	**-0.079**
HOF4: Volume to supply (Ml)	251.77	254.45	316.05	24.11	**211.60**
HOF4: Difference from HOF1 (Ml)	+251.77	+254.45	+316.05	+24.11	**+211.60**

September

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.434	0.465	0.468	0.623	**0.498**
HOF1: Annual Q95 (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^3s^{-1})	0.434	0.465	0.468	0.594	**0.490**
HOF1: Volume to supply (Ml)	0.00	0.0	0.00	75.17	**18.79**
HOF2: Month Q95 (m^3s^{-1})	0.436	0.436	0.436	0.436	**0.436**
HOF2: Flow to river (m^3s^{-1})	0.434	0.436	0.436	0.436	**0.436**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.029	-0.032	-0.158	**-0.055**
HOF2: Volume to supply (Ml)	0.00	75.17	82.94	484.71	**160.71**
HOF2: Difference from HOF1 (Ml)	0.00	+75.17	+82.94	+409.54	**+141.91**
HOF3: Month Q98 (m^3s^{-1})	0.399	0.399	0.399	0.399	**0.399**
HOF3: Flow to river (m^3s^{-1})	0.399	0.399	0.399	0.399	**0.399**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.035	-0.066	-0.069	-0.195	**-0.091**
HOF3: Volume to supply (Ml)	90.72	171.07	178.85	579.61	**255.06**
HOF3: Difference from HOF1 (Ml)	+90.72	+171.07	+178.85	+504.44	**+236.27**
HOF4: 5-year MAM10 (m^3s^{-1})	0.465	0.465	0.465	0.465	**0.465**
HOF4: Flow to river (m^3s^{-1})	0.434	0.465	0.465	0.465	**0.457**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	0.000	-0.003	-0.129	**-0.033**
HOF4: Volume to supply (Ml)	0.00	0.00	7.78	409.54	**104.33**
HOF4: Difference from HOF1 (Ml)	0.00	0.00	+7.78	+334.37	**+85.54**

October

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	1.084	1.404	0.726	0.674	**0.972**
HOF1: Annual Q95 (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Volume to supply (Ml)	1312.42	2169.50	353.55	214.27	**1012.44**
HOF2: Month Q95 (m^3s^{-1})	0.520	0.520	0.520	0.520	**0.520**
HOF2: Flow to river (m^3s^{-1})	0.520	0.520	0.520	0.520	**0.520**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.074	-0.074	-0.074	-0.074	**-0.074**
HOF2: Volume to supply (Ml)	1510.62	2367.70	551.75	412.47	**1210.64**
HOF2: Difference from HOF1 (Ml)	+198.20	+198.20	+198.20	+198.20	**+198.20**
HOF3: Month Q90 (m^3s^{-1})	0.598	0.598	0.598	0.598	**0.598**
HOF3: Flow to river (m^3s^{-1})	0.598	0.598	0.598	0.598	**0.598**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.004	+0.004	+0.004	+0.004	**+0.004**
HOF3: Volume to supply (Ml)	1301.71	2158.79	342.84	203.56	**1001.73**
HOF3: Difference from HOF1 (Ml)	-10.71	-10.71	-10.71	-10.71	**-10.71**
HOF4: Month Q84 (m^3s^{-1})	0.765	0.765	0.765	0.765	**0.765**
HOF4: Flow to river (m^3s^{-1})	0.765	0.765	0.726	0.674	**0.733**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.171	+0.171	+0.132	+0.080	**+0.139**
HOF4: Volume to supply (Ml)	854.41	1711.49	0.00	0.00	**641.48**
HOF4: Difference from HOF1 (Ml)	-458.01	-458.01	-353.55	-214.27	**-370.96**

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	5.882	3.287	3.766	1.246	**3.545**
HOF1: Annual Q95 (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Flow to river (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Volume to supply (Ml)	13706.50	6980.26	8221.82	1689.98	**7649.64**
HOF2: Month Q95 (m^3s^{-1})	1.250	1.250	1.250	1.250	**1.250**
HOF2: Flow to river (m^3s^{-1})	1.250	1.250	1.250	1.246	**1.249**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.656	+0.656	+0.656	+0.652	**+0.655**
HOF2: Volume to supply (Ml)	12006.15	5279.91	6521.47	0.00	**5951.88**
HOF2: Difference from HOF1 (Ml)	-1700.35	-1700.35	-1700.35	-1689.98	**-1697.76**
HOF3: Month Q90 (m^3s^{-1})	1.510	1.510	1.510	1.510	**1.510**
HOF3: Flow to river (m^3s^{-1})	1.510	1.510	1.510	1.246	**1.444**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.916	+0.916	+0.916	+0.652	**+0.850**
HOF3: Volume to supply (Ml)	11332.23	4605.99	5847.55	0.00	**5446.44**
HOF3: Difference from HOF1 (Ml)	-2374.27	-2374.27	-2374.27	-1689.98	**-2203.20**
HOF4: Month Q84 (m^3s^{-1})	1.870	1.870	1.870	1.870	**1.870**
HOF4: Flow to river (m^3s^{-1})	1.870	1.870	1.870	1.246	**1.714**
HOF4: Difference from HOF1 (m^3s^{-1})	+1.276	+1.276	+1.276	+0.652	**+1.120**
HOF4: Volume to supply (Ml)	10399.11	3672.87	4914.43	0.00	**4746.60**
HOF4: Difference from HOF1 (Ml)	-3307.39	-3307.39	-3307.39	-1689.98	**-2903.04**

Appendix 6.7c: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Tove at Cappenham Bridge

May

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.419	0.265	0.325	0.420	**0.357**
HOF1: Annual Q95 (m^{3}s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^{3}s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Volume to supply (Ml)	626.75	214.27	374.98	629.42	**461.36**
HOF2: Month Q95 (m^{3}s^{-1})	0.273	0.273	0.273	0.273	**0.273**
HOF2: Flow to river (m^{3}s^{-1})	0.273	0.265	0.273	0.273	**0.271**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.088	+0.080	+0.088	+0.088	**+0.086**
HOF2: Volume to supply (Ml)	391.05	0.00	139.28	393.72	**231.01**
HOF2: Difference from HOF1 (Ml)	-235.70	-214.27	-235.70	-235.70	**-230.34**
HOF3: Month Q90 (m^{3}s^{-1})	0.308	0.308	0.308	0.308	**0.308**
HOF3: Flow to river (m^{3}s^{-1})	0.308	0.265	0.308	0.308	**0.297**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.123	+0.080	+0.123	+0.123	**+0.112**
HOF3: Volume to supply (Ml)	297.31	0.00	45.54	299.98	**160.71**
HOF3: Difference from HOF1 (Ml)	-329.44	-214.27	-329.44	-329.44	**-300.65**
HOF4: Month Q84 (m^{3}s^{-1})	0.351	0.351	0.351	0.351	**0.351**
HOF4: Flow to river (m^{3}s^{-1})	0.351	0.265	0.325	0.351	**0.323**
HOF4: Difference from HOF1 (m^{3}s^{-1})	+0.166	+0.080	+0.140	+0.166	**+0.138**
HOF4: Volume to supply (Ml)	182.14	0.00	0.00	187.81	**92.49**
HOF4: Difference from HOF1 (Ml)	-441.61	-214.27	-374.98	-441.61	**-368.12**

June

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.313	0.210	0.274	0.386	**0.296**
HOF1: Annual Q95 (m^{3}s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^{3}s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Volume to supply (Ml)	331.78	64.80	230.69	520.99	**287.07**
HOF2: Month Q95 (m^{3}s^{-1})	0.218	0.218	0.218	0.218	**0.218**
HOF2: Flow to river (m^{3}s^{-1})	0.218	0.210	0.218	0.218	**0.216**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.033	+0.025	+0.033	+0.033	**+0.031**
HOF2: Volume to supply (Ml)	246.24	0.00	145.15	435.45	**206.71**
HOF2: Difference from HOF1 (Ml)	-85.54	-64.80	-85.54	-85.54	**-80.36**
HOF3: Month Q90 (m^{3}s^{-1})	0.252	0.252	0.252	0.252	**0.252**
HOF3: Flow to river (m^{3}s^{-1})	0.252	0.210	0.252	0.252	**0.242**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.067	+0.025	+0.067	+0.067	**+0.057**
HOF3: Volume to supply Ml (Ml)	158.12	0.00	57.03	347.33	**140.62**
HOF3: Difference from HOF1 (Ml)	-173.66	-64.80	-173.66	-173.66	**-146.45**
HOF4: Month Q84 (m^{3}s^{-1})	0.269	0.269	0.269	0.269	**0.269**
HOF4: Flow to river (m^{3}s^{-1})	0.269	0.210	0.269	0.269	**0.254**
HOF4: Difference from HOF1 (m^{3}s^{-1})	+0.084	+0.025	+0.084	+0.084	**+0.069**
HOF4: Volume to supply Ml (Ml)	114.05	0.00	12.96	303.26	**107.57**
HOF4: Difference from HOF1 (Ml)	-217.73	-64.80	-217.73	-217.73	**-179.50**

July

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.188	0.199	0.207	0.454	**0.262**
HOF1: Annual Q95 (m^3s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^3s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Volume to supply (Ml)	8.04	37.50	58.92	720.49	**206.24**
HOF2: Month Q95 (m^3s^{-1})	0.170	0.170	0.170	0.170	**0.170**
HOF2: Flow to river (m^3s^{-1})	0.170	0.170	0.170	0.170	**0.170**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.015	-0.015	-0.015	-0.015	**-0.015**
HOF2: Volume to supply (Ml)	48.22	77.68	99.10	760.67	**246.42**
HOF2: Difference from HOF1 (Ml)	+40.18	+40.18	+40.18	+40.18	**+40.18**
HOF3: Month Q97 (m^3s^{-1})	0.162	0.162	0.162	0.162	**0.162**
HOF3: Flow to river (m^3s^{-1})	0.162	0.162	0.162	0.162	**0.162**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.023	-0.023	-0.023	-0.023	**-0.023**
HOF3: Volume to supply (Ml)	69.64	99.10	120.52	782.09	**267.84**
HOF3: Difference from HOF1 (Ml)	+61.60	+61.60	+61.60	+61.60	**+61.60**
HOF4: 5-year MAM10 (m^3s^{-1})	0.167	0.167	0.167	0.167	**0.167**
HOF4: Flow to river (m^3s^{-1})	0.167	0.167	0.167	0.167	**0.167**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.018	-0.018	-0.018	-0.018	**-0.018**
HOF4: Volume to supply (Ml)	56.25	85.71	107.13	768.70	**254.45**
HOF4: Difference from HOF1 (Ml)	+48.21	+48.21	+48.21	+48.21	**+48.21**

August

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.166	0.179	0.169	0.200	**0.179**
HOF1: Annual Q95 (m^3s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^3s^{-1})	0.166	0.179	0.169	0.185	**0.175**
HOF1: Volume to supply (Ml)	0.00	0.00	0.00	40.18	**10.05**
HOF2: Month Q95 (m^3s^{-1})	0.154	0.154	0.154	0.154	**0.154**
HOF2: Flow to river (m^3s^{-1})	0.154	0.154	0.154	0.154	**0.154**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.012	-0.025	-0.015	-0.031	**-0.021**
HOF2: Volume to supply (Ml)	32.14	66.96	40.18	123.21	**65.62**
HOF2: Difference from HOF1 (Ml)	+32.14	+66.96	+40.18	+83.03	**+55.58**
HOF3: Month Q97 (m^3s^{-1})	0.142	0.142	0.142	0.142	**0.142**
HOF3: Flow to river (m^3s^{-1})	0.142	0.142	0.142	0.142	**0.142**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.024	-0.037	-0.027	-0.043	**-0.033**
HOF3: Volume to supply (Ml)	64.28	99.10	72.32	155.35	**97.76**
HOF3: Difference from HOF1 (Ml)	+64.28	+99.10	+72.32	+115.17	**+87.72**
HOF4: 5-year MAM10 (m^3s^{-1})	0.167	0.167	0.167	0.167	**0.167**
HOF4: Flow to river (m^3s^{-1})	0.166	0.167	0.167	0.167	**0.167**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	-0.012	-0.002	-0.018	**-0.008**
HOF4: Volume to supply (Ml)	0.00	32.14	5.36	88.39	**+31.47**
HOF4: Difference from HOF1 (Ml)	0.00	+32.14	+5.36	+48.21	**21.43**

September

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.164	0.165	0.165	0.245	**0.185**
HOF1: Annual Q95 (m^{3}s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^{3}s^{-1})	0.164	0.165	0.165	0.185	**0.170**
HOF1: Volume to supply (Ml)	0.00	0.00	0.00	155.52	**38.88**
HOF2: Month Q95 (m^{3}s^{-1})	0.154	0.154	0.154	0.154	**0.154**
HOF2: Flow to river (m^{3}s^{-1})	0.154	0.154	0.154	0.154	**0.154**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.010	-0.011	-0.011	-0.031	**-0.016**
HOF2: Volume to supply (Ml)	25.92	28.51	28.51	235.87	**79.70**
HOF2: Difference from HOF1 (Ml)	+25.92	+28.51	+28.51	+80.35	**+40.82**
HOF3: Month Q97 (m^{3}s^{-1})	0.149	0.149	0.149	0.149	**0.149**
HOF3: Flow to river (m^{3}s^{-1})	0.149	0.149	0.149	0.149	**0.149**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.015	-0.016	-0.016	-0.036	**-0.021**
HOF3: Volume to supply (Ml)	38.88	41.47	41.47	248.83	**92.66**
HOF3: Difference from HOF1 (Ml)	+38.88	+41.47	+41.47	+93.31	**+53.78**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.167	0.167	0.167	0.167	**0.167**
HOF4: Flow to river (m^{3}s^{-1})	0.164	0.165	0.165	0.167	**0.165**
HOF4: Difference from HOF1 (m^{3}s^{-1})	0.000	0.000	0.000	-0.018	**-0.005**
HOF4: Volume to supply (Ml)	0.00	0.00	0.00	202.18	**50.55**
HOF4: Difference from HOF1 (Ml)	0.00	0.00	0.00	+46.66	**+11.67**

October

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.251	0.162	0.261	0.234	**0.227**
HOF1: Annual Q95 (m^{3}s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^{3}s^{-1})	0.185	0.162	0.185	0.185	**0.179**
HOF1: Volume to supply (Ml)	176.77	0.00	203.56	131.24	**127.89**
HOF2: Month Q95 (m^{3}s^{-1})	0.163	0.163	0.163	0.163	**0.163**
HOF2: Flow to river (m^{3}s^{-1})	0.163	0.162	0.163	0.163	**0.163**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.022	0.000	-0.022	-0.022	**-0.017**
HOF2: Volume to supply (Ml)	235.69	0.00	262.48	190.16	**172.08**
HOF2: Difference from HOF1 (Ml)	+58.92	0.00	+58.92	+58.92	**+44.19**
HOF3: Month Q90 (m^{3}s^{-1})	0.181	0.181	0.181	0.181	**0.181**
HOF3: Flow to river (m^{3}s^{-1})	0.181	0.162	0.181	0.181	**0.176**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.004	0.000	-0.004	-0.004	**-0.003**
HOF3: Volume to supply (Ml)	187.48	0.00	214.27	141.95	**135.93**
HOF3: Difference from HOF1 (Ml)	+10.71	0.00	+10.71	+10.71	**+8.03**
HOF4: Month Q84 (m^{3}s^{-1})	0.197	0.197	0.197	0.197	**0.197**
HOF4: Flow to river (m^{3}s^{-1})	0.197	0.162	0.197	0.197	**0.188**
HOF4: Difference from HOF1 (m^{3}s^{-1})	+0.012	0.000	+0.012	+0.012	**+0.009**
HOF4: Volume to supply (Ml)	144.63	0.00	171.42	99.10	**103.79**
HOF4: Difference from HOF1 (Ml)	-32.14	0.00	-32.14	-32.14	**-24.11**

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.843	0.198	0.255	1.041	**0.584**
HOF1: Annual Q95 (m^3s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Flow to river (m^3s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Volume to supply (Ml)	1705.54	33.70	181.44	2218.75	**1034.86**
HOF2: Month Q95 (m^3s^{-1})	0.206	0.206	0.206	0.206	**0.206**
HOF2: Flow to river (m^3s^{-1})	0.206	0.198	0.206	0.206	**0.204**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.021	+0.013	+0.021	+0.021	**+0.019**
HOF2: Volume to supply (Ml)	1651.11	0.00	127.01	2164.32	**985.61**
HOF2: Difference from HOF1 (Ml)	-54.43	-33.70	-54.43	-54.43	**-49.25**
HOF3: Month Q90 (m^3s^{-1})	0.247	0.247	0.247	0.247	**0.247**
HOF3: Flow to river (m^3s^{-1})	0.247	0.198	0.247	0.247	**0.235**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.062	+0.013	+0.062	+0.062	**+0.050**
HOF3: Volume to supply (Ml)	1544.84	0.00	20.74	2058.05	**905.91**
HOF3: Difference from HOF1 (Ml)	-160.70	-33.70	-160.70	-160.70	**-128.95**
HOF4: Month Q84 (m^3s^{-1})	0.283	0.283	0.283	0.283	**0.283**
HOF4: Flow to river (m^3s^{-1})	0.283	0.198	0.255	0.283	**0.255**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.098	+0.013	+0.070	+0.098	**+0.070**
HOF4: Volume to supply (Ml)	1451.52	0.00	0.00	1964.73	**854.06**
HOF4: Difference from HOF1 (Ml)	-254.02	-33.70	-181.44	-254.02	**-180.80**

Appendix 6.7d: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Dove at Izaak Walton

May

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.706	0.921	1.130	1.327	**1.021**
HOF1: Annual Q95 (m^3s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^3s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Volume to supply (Ml)	495.50	1071.36	1631.50	2158.79	**1339.29**
HOF2: Month Q95 (m^3s^{-1})	0.837	0.837	0.837	0.837	**0.837**
HOF2: Flow to river (m^3s^{-1})	0.706	0.837	0.837	0.837	**0.804**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.185	+0.136	+0.136	+0.136	**+0.148**
HOF2: Volume to supply (Ml)	0.00	224.99	785.14	1312.42	**580.64**
HOF2: Difference from HOF1 (Ml)	-495.50	-846.37	-846.37	-846.37	**-758.65**
HOF3: Month Q90 (m^3s^{-1})	0.935	0.935	0.935	0.935	**0.935**
HOF3: Flow to river (m^3s^{-1})	0.706	0.921	0.935	0.935	**0.874**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.185	+0.400	+0.414	+0.414	**+0.353**
HOF3: Volume to supply (Ml)	0.00	0.00	522.64	1049.93	**393.14**
HOF3: Difference from HOF1 (Ml)	-495.50	-1071.36	-1108.86	-1108.86	**-946.15**
HOF4: Month Q84 (m^3s^{-1})	1.025	1.025	1.025	1.025	**1.025**
HOF4: Flow to river (m^3s^{-1})	0.706	0.921	1.025	1.025	**0.919**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.185	+0.400	+0.504	+0.504	**+0.398**
HOF4: Volume to supply (Ml)	0.00	0.00	281.59	808.88	**272.62**
HOF4: Difference from HOF1 (Ml)	-495.50	-1071.36	-1349.91	-1349.91	**-1066.67**

June

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.561	0.689	0.919	0.989	**0.790**
HOF1: Annual Q95 (m^3s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^3s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Volume to supply (Ml)	103.68	435.46	1031.62	1231.06	**700.46**
HOF2: Month Q95 (m^3s^{-1})	0.609	0.609	0.609	0.609	**0.609**
HOF2: Flow to river (m^3s^{-1})	0.561	0.609	0.609	0.609	**0.597**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.040	+0.088	+0.088	+0.088	**+0.076**
HOF2: Volume to supply (Ml)	0.00	207.36	803.52	1002.96	**503.46**
HOF2: Difference from HOF1 (Ml)	-103.68	-228.10	-228.10	-228.10	**-197.00**
HOF3: Month Q90 (m^3s^{-1})	0.754	0.754	0.754	0.754	**0.754**
HOF3: Flow to river (m^3s^{-1})	0.561	0.689	0.754	0.754	**0.690**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.040	+0.168	+0.233	+0.233	**+0.169**
HOF3: Volume to supply (Ml)	0.00	0.00	427.68	627.12	**263.70**
HOF3: Difference from HOF1 (Ml)	-103.68	-435.46	-603.94	-603.94	**-436.76**
HOF4: Month Q84 (m^3s^{-1})	0.817	0.817	0.817	0.817	**0.817**
HOF4: Flow to river (m^3s^{-1})	0.561	0.689	0.817	0.817	**0.721**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.040	+0.168	+0.296	+0.296	**+0.200**
HOF4: Volume to supply (Ml)	0.00	0.00	264.39	463.83	**182.06**
HOF4: Difference from HOF1 (Ml)	-103.68	-435.46	-767.23	-767.23	**-518.40**

July

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.655	0.498	0.751	0.814	**0.680**
HOF1: Annual Q95 (m^{3}s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^{3}s^{-1})	0.521	0.498	0.521	0.521	**0.515**
HOF1: Volume to supply (Ml)	358.91	0.00	616.03	784.77	**439.93**
HOF2: Month Q95 (m^{3}s^{-1})	0.507	0.507	0.507	0.507	**0.507**
HOF2: Flow to river (m^{3}s^{-1})	0.507	0.498	0.507	0.507	**0.505**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.014	0.000	-0.014	-0.014	**-0.011**
HOF2: Volume to supply (Ml)	396.41	0.00	653.53	825.27	**468.80**
HOF2: Difference from HOF1 (Ml)	+37.50	0.00	+37.50	+37.50	**+28.13**
HOF3: Month Q98 (m^{3}s^{-1})	0.436	0.436	0.436	0.436	**0.436**
HOF3: Flow to river (m^{3}s^{-1})	0.436	0.436	0.436	0.436	**0.436**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.085	-0.062	-0.085	-0.085	**-0.079**
HOF3: Volume to supply (Ml)	586.77	166.06	843.69	1012.43	**652.24**
HOF3: Difference from HOF1 (Ml)	+227.66	+166.06	+227.66	+227.66	**+212.26**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.431	0.431	0.431	0.431	**0.431**
HOF4: Flow to river (m^{3}s^{-1})	0.431	0.431	0.431	0.431	**0.431**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.090	-0.067	-0.090	-0.090	**-0.084**
HOF4: Volume to supply (Ml)	599.97	179.45	857.09	1025.83	**665.59**
HOF4: Difference from HOF1 (Ml)	+241.06	+179.45	+241.06	+241.06	**+225.66**

August

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.432	0.458	0.576	0.599	**0.516**
HOF1: Annual Q95 (m^{3}s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^{3}s^{-1})	0.432	0.458	0.521	0.521	**0.483**
HOF1: Volume to supply (Ml)	0.00	0.00	147.31	208.92	**89.06**
HOF2: Month Q95 (m^{3}s^{-1})	0.429	0.429	0.429	0.429	**0.429**
HOF2: Flow to river (m^{3}s^{-1})	0.429	0.429	0.429	0.429	**0.429**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.003	-0.029	-0.092	-0.092	**-0.054**
HOF2: Volume to supply (Ml)	8.04	77.67	393.72	455.33	**233.69**
HOF2: Difference from HOF1 (Ml)	+8.04	+77.67	+246.41	+246.41	**+144.63**
HOF3: Month Q98 (m^{3}s^{-1})	0.405	0.405	0.405	0.405	**0.405**
HOF3: Flow to river (m^{3}s^{-1})	0.405	0.405	0.405	0.405	**0.405**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.027	-0.053	-0.116	-0.116	**-0.078**
HOF3: Volume to supply (Ml)	72.32	141.96	458.00	519.61	**297.97**
HOF3: Difference from HOF1 (Ml)	+72.32	+141.96	+310.69	+310.69	**+208.92**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.431	0.431	0.431	0.431	**0.431**
HOF4: Flow to river (m^{3}s^{-1})	0.431	0.431	0.431	0.431	**0.431**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.001	-0.027	-0.090	-0.090	**-0.052**
HOF4: Volume to supply (Ml)	2.68	72.32	388.37	449.98	**228.34**
HOF4: Difference from HOF1 (Ml)	+2.68	+72.32	+241.06	+241.06	**+139.28**

September

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.381	0.373	0.443	0.542	**0.435**
HOF1: Annual Q95 (m^{3}s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^{3}s^{-1})	0.381	0.373	0.443	0.521	**0.430**
HOF1: Volume to supply (Ml)	0.00	0.00	0.00	54.43	**13.61**
HOF2: Month Q95 (m^{3}s^{-1})	0.376	0.376	0.376	0.376	**0.376**
HOF2: Flow to river (m^{3}s^{-1})	0.376	0.373	0.376	0.376	**0.375**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.005	0.000	-0.067	-0.145	**-0.054**
HOF2: Volume to supply (Ml)	12.96	0.00	173.66	430.27	**154.22**
HOF2: Difference from HOF1 (Ml)	+12.96	0.00	+173.66	+375.84	**+140.62**
HOF3: Month Q98 (m^{3}s^{-1})	0.349	0.349	0.349	0.349	**0.349**
HOF3: Flow to river (m^{3}s^{-1})	0.349	0.349	0.349	0.349	**0.349**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.032	-0.024	-0.094	-0.172	**-0.081**
HOF3: Volume to supply (Ml)	82.94	62.21	243.65	500.25	**222.26**
HOF3: Difference from HOF1 (Ml)	+82.94	+62.21	+243.65	+445.82	**+208.66**
HOF4: 5-year MAM10 (m^{3}s^{-1})	0.431	0.431	0.431	0.431	**0.431**
HOF4: Flow to river (m^{3}s^{-1})	0.381	0.373	0.431	0.431	**0.404**
HOF4: Difference from HOF1 (m^{3}s^{-1})	0.000	0.000	-0.012	-0.090	**-0.026**
HOF4: Volume to supply (Ml)	0.00	0.00	31.10	287.71	**79.70**
HOF4: Difference from HOF1 (Ml)	0.00	0.00	+31.10	+233.28	**+66.10**

October

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	0.758	0.524	0.495	0.485	**0.566**
HOF1: Annual Q95 (m^{3}s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^{3}s^{-1})	0.521	0.521	0.495	0.485	**0.506**
HOF1: Volume to supply (Ml)	634.78	8.04	0.00	0.00	**160.71**
HOF2: Month Q95 (m^{3}s^{-1})	0.415	0.415	0.415	0.415	**0.415**
HOF2: Flow to river (m^{3}s^{-1})	0.415	0.415	0.415	0.415	**0.415**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.106	-0.106	-0.080	-0.070	**-0.091**
HOF2: Volume to supply (Ml)	918.69	291.95	214.27	187.49	**403.10**
HOF2: Difference from HOF1 (Ml)	+283.91	+283.91	+214.27	+187.49	**+242.40**
HOF3: Month Q90 (m^{3}s^{-1})	0.463	0.463	0.463	0.463	**0.463**
HOF3: Flow to river (m^{3}s^{-1})	0.463	0.463	0.463	0.463	**0.463**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.058	-0.058	-0.032	-0.022	**-0.043**
HOF3: Volume to supply (Ml)	790.13	163.39	85.71	58.92	**274.54**
HOF3: Difference from HOF1 (Ml)	+155.35	+155.35	+85.71	+58.92	**+113.83**
HOF4: Month Q84 (m^{3}s^{-1})	0.517	0.517	0.517	0.517	**0.517**
HOF4: Flow to river (m^{3}s^{-1})	0.517	0.517	0.495	0.485	**0.504**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.004	-0.004	0.000	0.000	**-0.002**
HOF4: Volume to supply (Ml)	645.49	18.75	0.00	0.00	**166.06**
HOF4: Difference from HOF1 (Ml)	+10.71	+10.71	0.00	0.00	**+5.36**

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.731	1.916	1.600	0.562	**1.202**
HOF1: Annual Q95 (m^3s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Flow to river (m^3s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Volume to supply (Ml)	544.32	3615.84	2976.77	106.27	**1810.80**
HOF2: Month Q95 (m^3s^{-1})	0.598	0.598	0.598	0.598	**0.598**
HOF2: Flow to river (m^3s^{-1})	0.598	0.598	0.598	0.562	**0.589**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.077	+0.077	+0.077	+0.041	**+0.068**
HOF2: Volume to supply (Ml)	344.74	3416.26	2777.19	0.00	**1634.55**
HOF2: Difference from HOF1 (Ml)	-199.58	-199.58	-199.58	-106.27	**-176.25**
HOF3: Month Q90 (m^3s^{-1})	0.775	0.775	0.775	0.775	**0.775**
HOF3: Flow to river (m^3s^{-1})	0.775	0.775	0.775	0.562	**0.722**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.210	+0.254	+0.254	+0.041	**+0.190**
HOF3: Volume to supply (Ml)	0.00	2957.47	2318.40	0.00	**1318.97**
HOF3: Difference from HOF1 (Ml)	-544.32	-658.37	-658.37	-106.27	**-491.83**
HOF4: Month Q84 (m^3s^{-1})	0.959	0.959	0.959	0.959	**0.959**
HOF4: Flow to river (m^3s^{-1})	0.731	0.959	0.959	0.562	**0.803**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.210	+0.438	+0.438	+0.041	**+0.282**
HOF4: Volume to supply (Ml)	0.00	2480.54	1841.47	0.00	**1080.50**
HOF4: Difference from HOF1 (Ml)	-544.32	-1135.30	-1135.30	-106.27	**-730.30**

Appendix 6.7e: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Sow at Great Bridgford

May

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.367	0.516	0.575	0.575	**0.508**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Volume to supply (Ml)	112.49	511.57	669.60	669.60	**490.82**
HOF2: Month Q95 (m^3s^{-1})	0.424	0.424	0.424	0.424	**0.424**
HOF2: Flow to river (m^3s^{-1})	0.367	0.424	0.424	0.424	**0.410**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.042	+0.099	+0.099	+0.099	**+0.085**
HOF2: Volume to supply (Ml)	0.00	246.41	404.44	404.44	**263.82**
HOF2: Difference from HOF1 (Ml)	-112.49	-265.16	-265.16	-265.16	**-226.99**
HOF3: Month Q90 (m^3s^{-1})	0.470	0.470	0.470	0.470	**0.470**
HOF3: Flow to river (m^3s^{-1})	0.367	0.470	0.470	0.470	**0.444**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.042	+0.145	+0.145	+0.145	**+0.119**
HOF3: Volume to supply (Ml)	0.00	123.20	281.23	281.23	**171.42**
HOF3: Difference from HOF1 (Ml)	-112.49	-388.37	-388.37	-388.37	**-319.40**
HOF4: Month Q84 (m^3s^{-1})	0.526	0.526	0.526	0.526	**0.526**
HOF4: Flow to river (m^3s^{-1})	0.367	0.516	0.526	0.526	**0.484**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.042	+0.191	+0.201	+0.201	**+0.159**
HOF4: Volume to supply (Ml)	0.00	0.00	131.24	131.24	**65.62**
HOF4: Difference from HOF1 (Ml)	-112.49	-511.57	-538.36	-538.36	**-425.20**

June

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.323	0.467	0.406	0.555	**0.438**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.323	0.325	0.325	0.325	**0.325**
HOF1: Volume to supply (Ml)	0.00	368.06	209.95	596.16	**293.54**
HOF2: Month Q95 (m^3s^{-1})	0.349	0.349	0.349	0.349	**0.349**
HOF2: Flow to river (m^3s^{-1})	0.323	0.349	0.349	0.349	**0.343**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	+0.024	+0.024	+0.024	**+0.018**
HOF2: Volume to supply (Ml)	0.00	305.85	147.74	533.95	**246.89**
HOF2: Difference from HOF1 (Ml)	0.00	-62.21	-62.21	-62.21	**-46.66**
HOF3: Month Q90 (m^3s^{-1})	0.413	0.413	0.413	0.413	**0.413**
HOF3: Flow to river (m^3s^{-1})	0.323	0.413	0.406	0.413	**0.389**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	+0.088	+0.081	+0.088	**+0.064**
HOF3: Volume to supply (Ml)	0.00	139.96	0.00	368.06	**127.01**
HOF3: Difference from HOF1 (Ml)	0.00	-228.10	-209.95	-228.10	**-166.54**
HOF4: Month Q84 (m^3s^{-1})	0.445	0.445	0.445	0.445	**0.445**
HOF4: Flow to river (m^3s^{-1})	0.323	0.445	0.406	0.445	**0.405**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	+0.120	+0.081	+0.120	**+0.080**
HOF4: Volume to supply (Ml)	0.00	57.02	0.00	285.12	**85.54**
HOF4: Difference from HOF1 (Ml)	0.00	-311.04	-209.95	-311.04	**-208.01**

July

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.253	0.345	0.301	0.424	**0.331**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.253	0.325	0.301	0.325	**0.301**
HOF1: Volume to supply (Ml)	0.00	53.57	0.00	265.16	**79.68**
HOF2: Month Q95 (m^3s^{-1})	0.268	0.268	0.268	0.268	**0.268**
HOF2: Flow to river (m^3s^{-1})	0.253	0.268	0.268	0.268	**0.264**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.057	-0.033	-0.057	**-0.037**
HOF2: Volume to supply (Ml)	0.00	206.24	88.39	417.83	**178.12**
HOF2: Difference from HOF1 (Ml)	0.00	+152.67	+88.39	+152.67	**+98.43**
HOF3: Month Q97 (m^3s^{-1})	0.251	0.251	0.251	0.251	**0.251**
HOF3: Flow to river (m^3s^{-1})	0.251	0.251	0.251	0.251	**0.251**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.002	-0.074	-0.050	-0.074	**-0.050**
HOF3: Volume to supply (Ml)	5.36	251.77	133.92	463.36	**213.60**
HOF3: Difference from HOF1 (Ml)	+5.36	+198.20	+133.92	+198.20	**+133.92**
HOF4: 5-year MAM10 (m^3s^{-1})	0.262	0.262	0.262	0.262	**0.262**
HOF4: Flow to river (m^3s^{-1})	0.253	0.262	0.262	0.262	**0.260**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	-0.063	-0.039	-0.063	**-0.041**
HOF4: Volume to supply (Ml)	0.00	222.31	104.46	433.90	**190.17**
HOF4: Difference from HOF1 (Ml)	0.00	+168.74	+104.46	+168.74	**+110.49**

August

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.197	0.297	0.537	0.350	**0.345**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.197	0.297	0.325	0.325	**0.286**
HOF1: Volume to supply (Ml)	0.00	0.00	567.82	66.96	**158.70**
HOF2: Month Q95 (m^3s^{-1})	0.244	0.244	0.244	0.244	**0.244**
HOF2: Flow to river (m^3s^{-1})	0.197	0.244	0.244	0.244	**0.232**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.053	-0.081	-0.081	**-0.054**
HOF2: Volume to supply (Ml)	0.00	141.96	784.77	283.91	**302.66**
HOF2: Difference from HOF1 (Ml)	0.00	+141.96	+216.95	+216.95	**+143.97**
HOF3: Month Q97 (m^3s^{-1})	0.203	0.203	0.203	0.203	**0.203**
HOF3: Flow to river (m^3s^{-1})	0.197	0.203	0.203	0.203	**0.202**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	-0.094	-0.122	-0.122	**-0.085**
HOF3: Volume to supply (Ml)	0.00	251.77	894.58	393.72	**385.02**
HOF3: Difference from HOF1 (Ml)	0.00	+251.77	+326.76	+326.76	**+226.32**
HOF4: 5-year MAM10 (m^3s^{-1})	0.262	0.262	0.262	0.262	**0.262**
HOF4: Flow to river (m^3s^{-1})	0.197	0.262	0.262	0.262	**0.246**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	-0.035	-0.063	-0.063	**-0.040**
HOF4: Volume to supply (Ml)	0.00	93.74	736.56	235.70	**266.50**
HOF4: Difference from HOF1 (Ml)	0.00	+93.74	+168.74	+168.74	**+107.81**

September

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.191	0.349	0.336	0.278	**0.289**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.191	0.325	0.325	0.278	**0.280**
HOF1: Volume to supply (Ml)	0.00	62.21	28.51	0.00	**22.68**
HOF2: Month Q95 (m^3s^{-1})	0.250	0.250	0.250	0.250	**0.250**
HOF2: Flow to river (m^3s^{-1})	0.191	0.250	0.250	0.250	**0.235**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.075	-0.075	-0.028	**-0.045**
HOF2: Volume to supply (Ml)	0.00	256.61	222.91	72.58	**138.03**
HOF2: Difference from HOF1 (Ml)	0.00	+194.40	+194.40	+72.58	**+115.35**
HOF3: Month Q97 (m^3s^{-1})	0.204	0.204	0.204	0.204	**0.204**
HOF3: Flow to river (m^3s^{-1})	0.191	0.204	0.204	0.204	**0.201**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	-0.121	-0.121	-0.074	**-0.079**
HOF3: Volume to supply (Ml)	0.00	375.84	342.14	191.81	**227.45**
HOF3: Difference from HOF1 (Ml)	0.00	+313.63	+313.63	+191.81	**+204.77**
HOF4: 5-year MAM10 (m^3s^{-1})	0.262	0.262	0.262	0.262	**0.262**
HOF4: Flow to river (m^3s^{-1})	0.191	0.262	0.262	0.262	**0.244**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	-0.063	-0.063	-0.016	**-0.036**
HOF4: Volume to supply (Ml)	0.00	225.51	191.81	41.47	**114.70**
HOF4: Difference from HOF1 (Ml)	0.00	+163.30	+163.30	+41.47	**+92.02**

October

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.208	0.442	0.385	0.317	**0.338**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.208	0.325	0.325	0.317	**0.294**
HOF1: Volume to supply (Ml)	0.00	313.37	160.70	0.00	**118.52**
HOF2: Month Q95 (m^3s^{-1})	0.305	0.305	0.305	0.305	**0.305**
HOF2: Flow to river (m^3s^{-1})	0.208	0.305	0.305	0.305	**0.281**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.020	-0.020	-0.012	**-0.013**
HOF2: Volume to supply (Ml)	0.00	366.94	214.27	32.14	**153.34**
HOF2: Difference from HOF1 (Ml)	0.00	+53.57	+53.57	+32.14	**+34.82**
HOF3: Month Q90 (m^3s^{-1})	0.345	0.345	0.345	0.345	**0.345**
HOF3: Flow to river (m^3s^{-1})	0.208	0.345	0.345	0.317	**0.304**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	+0.020	+0.020	0.000	**+0.010**
HOF3: Volume to supply Ml (Ml)	0.00	259.80	107.13	0.00	**91.73**
HOF3: Difference from HOF1 (Ml)	0.00	-53.57	-53.57	0.00	**-26.79**
HOF4: Month Q84 (m^3s^{-1})	0.375	0.375	0.375	0.375	**0.375**
HOF4: Flow to river (m^3s^{-1})	0.208	0.375	0.375	0.317	**0.319**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	+0.050	+0.050	0.000	**+0.025**
HOF4: Volume to supply (Ml)	0.00	179.45	26.78	0.00	**51.56**
HOF4: Difference from HOF1 (Ml)	0.00	-133.92	-133.92	0.00	**-66.96**

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.262	0.633	0.806	0.564	**0.566**
HOF1: Annual Q95 (m^3s^{-1})	0.325	0.325	0.325	0.325	**0.325**
HOF1: Flow to river (m^3s^{-1})	0.262	0.325	0.325	0.325	**0.309**
HOF1: Volume to supply (Ml)	0.00	798.34	1246.75	619.49	**666.15**
HOF2: Month Q95 (m^3s^{-1})	0.373	0.373	0.373	0.373	**0.373**
HOF2: Flow to river (m^3s^{-1})	0.262	0.373	0.373	0.373	**0.345**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	+0.048	+0.048	+0.048	**+0.036**
HOF2: Volume to supply (Ml)	0.00	673.92	1122.33	495.07	**572.83**
HOF2: Difference from HOF1 (Ml)	0.00	-124.42	-124.42	-124.42	**-93.32**
HOF3: Month Q90 (m^3s^{-1})	0.444	0.444	0.444	0.444	**0.444**
HOF3: Flow to river (m^3s^{-1})	0.262	0.444	0.444	0.444	**0.399**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	+0.119	+0.119	+0.119	**+0.089**
HOF3: Volume to supply (Ml)	0.00	489.89	938.30	311.04	**434.81**
HOF3: Difference from HOF1 (Ml)	0.00	-308.45	-308.45	-308.45	**-231.34**
HOF4: Month Q84 (m^3s^{-1})	0.477	0.477	0.477	0.477	**0.477**
HOF4: Flow to river (m^3s^{-1})	0.262	0.477	0.477	0.477	**0.423**
HOF4: Difference from HOF1 (m^3s^{-1})	0.000	+0.152	+0.152	+0.152	**+0.114**
HOF4: Volume to supply (Ml)	0.00	404.36	852.52	225.51	**370.60**
HOF4: Difference from HOF1 (Ml)	0.00	-393.98	-393.98	-393.98	**-295.49**

Appendix 6.8a: Change in water allocation during the four driest years – River Kym at Meagre Farm (totals aggregated by season)

May and June

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Volume to supply (Ml)	158.20	153.96	324.86	68.60	**176.41**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.029	0.029	0.029	0.029	**0.029**
HOF2 % change from HOF1	26.1	26.1	26.1	26.1	**26.1**
HOF2: Volume to supply (Ml)	126.24	122.00	292.90	36.64	**144.45**
HOF2 % change from HOF1	-20.2	-20.8	-9.8	-46.6	**-18.1**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.033	0.033	0.033	0.033	**0.033**
HOF3 % change from HOF1	41.3	41.3	41.3	41.3	**41.3**
HOF3: Volume to supply (Ml)	107.74	103.50	274.40	18.14	**125.95**
HOF3 % change from HOF1	-31.9	-32.8	-15.5	-73.6	**-28.6**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.038	0.038	0.038	0.034	**0.037**
HOF4 % change from HOF1	65.2	65.2	65.2	47.8	**60.9**
HOF4: Volume to supply (Ml)	78.53	74.29	245.19	10.36	**102.09**
HOF4 % change from HOF1	-50.4	-51.7	-24.5	-84.9	**-42.1**

July to September

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.022	0.021	0.023	0.023	**0.022**
HOF1: Volume to supply (Ml)	602.65	452.91	411.61	39.92	**376.77**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.018	0.018	0.018	0.018	**0.018**
HOF2 % change from HOF1	-18.2	-15.6	-21.7	-21.7	**-19.4**
HOF2: Volume to supply (Ml)	634.70	479.35	451.44	79.75	**411.31**
HOF2 % change from HOF1	5.3	5.8	9.7	99.8	**9.2**
HOF3: Month Q98 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.015	0.015	0.015	0.015	**0.015**
HOF3 % change from HOF1	-30.3	-28.1	-33.3	-33.3	**-31.3**
HOF3: Volume to supply (Ml)	655.88	500.51	472.61	100.92	**432.48**
HOF3 % change from HOF1	8.8	10.5	14.8	152.8	**14.8**
HOF4: 5 year MAM10 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.017	0.017	0.017	0.017	**0.017**
HOF4 % change from HOF1	-22.7	-20.3	-26.1	-26.1	**-23.9**
HOF4: Volume to supply (Ml)	642.57	487.21	459.30	87.61	**419.17**
HOF4 % change from HOF1	6.6	7.6	11.6	119.5	**11.3**

October and November

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.023	0.023	0.023	0.023	**0.023**
HOF1: Volume to supply (Ml)	487.47	658.28	9520.07	36.29	**2675.53**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.029	0.029	0.029	0.029	**0.029**
HOF2 % change from HOF1	23.9	23.9	23.9	26.7	**24.6**
HOF2: Volume to supply (Ml)	459.05	629.86	9491.65	5.19	**2646.44**
HOF2 % change from HOF1	-5.8	-4.3	-0.3	-85.7	**-1.1**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.033	0.033	0.033	0.030	**0.032**
HOF3 % change from HOF1	41.3	41.3	41.3	31.1	**38.8**
HOF3: Volume to supply (Ml)	438.13	373.24	9470.73	0.00	**2570.53**
HOF3 % change from HOF1	-10.1	-43.3	-0.5	-100.0	**-3.9**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.037	0.038	0.038	0.030	**0.035**
HOF4 % change from HOF1	58.7	63.0	63.0	31.1	**54.1**
HOF4: Volume to supply (Ml)	417.31	582.77	9444.56	0.00	**2611.16**
HOF4 % change from HOF1	-14.4	-11.5	-0.8	-100.0	**-2.4**

Appendix 6.8b: Change in water allocation during the four driest years – River Manifold at Ilam (totals aggregated by season)

May and June

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Volume to supply (Ml)	2231.03	3888.09	2744.41	2203.12	**2766.66**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.705	0.705	0.705	0.705	**0.705**
HOF2 % change from HOF1	18.6	18.6	18.6	18.6	**18.6**
HOF2: Volume to supply (Ml)	1643.08	3300.14	2156.46	1615.17	**2178.71**
HOF2 % change from HOF1	-26.4	-15.1	-21.4	-26.7	**-21.3**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.788	0.788	0.788	0.788	**0.788**
HOF3 % change from HOF1	32.7	32.7	32.7	32.7	**32.7**
HOF3: Volume to supply (Ml)	1200.88	2857.94	1714.26	1172.97	**1736.51**
HOF3 % change from HOF1	-46.2	-26.5	-37.5	-46.8	**-37.2**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.877	0.877	0.877	0.877	**0.877**
HOF4 % change from HOF1	47.6	47.6	47.6	47.6	**47.6**
HOF4: Volume to supply (Ml)	730.26	2387.32	1243.64	702.35	**1265.89**
HOF4 % change from HOF1	-67.3	-38.6	-54.7	-68.1	**-54.2**

July to September

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.523	0.540	0.548	0.554	**0.541**
HOF1: Volume to supply (Ml)	0	1507.94	533	581.39	**655.58**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.487	0.487	0.487	0.486	**0.487**
HOF2 % change from HOF1	-7.0	-9.7	-11.1	-12.3	**-10.1**
HOF2: Volume to supply (Ml)	294.62	1925.95	1020.38	1114.14	**1088.77**
HOF2 % change from HOF1		27.7	91.4	91.6	**66.1**
HOF3: Month Q98 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.439	0.439	0.439	0.439	**0.439**
HOF3 % change from HOF1	-16.1	-18.6	-19.9	-20.7	**-18.8**
HOF3: Volume to supply (Ml)	671.93	2308.43	1402.87	1484.91	**1467.04**
HOF3 % change from HOF1		53.1	163.2	155.4	**123.8**
HOF4: 5 year MAM10 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.455	0.465	0.465	0.465	**0.462**
HOF4 % change from HOF1	-13.1	-13.8	-15.2	-16.1	**-14.6**
HOF4: Volume to supply (Ml)	551.75	2107.9	1202.34	1285.38	**1286.84**
HOF4 % change from HOF1		39.8	125.6	121.1	**96.3**

October and November

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.594	0.594	0.594	0.594	**0.594**
HOF1: Volume to supply (Ml)	15018.92	9149.76	8575.37	1904.25	**8662.08**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.885	0.885	0.885	0.883	**0.885**
HOF2 % change from HOF1	49.0	49.0	49.0	48.7	**48.9**
HOF2: Volume to supply (Ml)	13516.77	7647.61	7073.22	412.47	**7162.52**
HOF2 % change from HOF1	-10.0	-16.4	-17.5	-78.3	**-17.3**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	1.054	1.054	1.054	0.922	**1.021**
HOF3 % change from HOF1	77.4	77.4	77.4	55.2	**71.9**
HOF3: Volume to supply (Ml)	12633.94	6764.78	6190.39	203.56	**6448.17**
HOF3 % change from HOF1	-15.9	-26.1	-27.8	-89.3	**-25.6**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	1.318	1.318	1.298	0.960	**1.223**
HOF4 % change from HOF1	121.8	121.8	118.5	61.6	**105.9**
HOF4: Volume to supply (Ml)	11253.52	5384.36	4914.43	0	**5388.08**
HOF4 % change from HOF1	-25.1	-41.2	-42.7	-100.0	**-37.8**

Appendix 6.8c: Change in water allocation during the four driest years – River Tove at Cappenham Bridge (totals aggregated by season)

May and June

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.185	0.185	0.185	0.185	**0.185**
HOF1: Volume to supply (Ml)	958.53	279.07	605.67	1150.41	**748.42**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.246	0.238	0.246	0.246	**0.244**
HOF2 % change from HOF1	32.7	28.4	32.7	32.7	**31.6**
HOF2: Volume to supply (Ml)	637.29	0	284.43	829.17	**437.72**
HOF2 % change from HOF1	-33.5	-100.0	-53.0	-27.9	**-41.5**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.280	0.238	0.280	0.280	**0.269**
HOF3 % change from HOF1	51.4	28.4	51.4	51.4	**45.6**
HOF3: Volume to supply (Ml)	455.43	0	102.57	647.31	**301.33**
HOF3 % change from HOF1	-52.5	-100.0	-83.1	-43.7	**-59.7**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.310	0.238	0.297	0.310	**0.289**
HOF4 % change from HOF1	67.6	28.4	60.5	67.6	**56.0**
HOF4: Volume to supply (Ml)	296.19	0	12.96	491.07	**200.06**
HOF4 % change from HOF1	-69.1	-100.0	-97.9	-57.3	**-73.3**

July to September

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.172	0.176	0.173	0.185	**0.177**
HOF1: Volume to supply (Ml)	8.04	37.5	58.92	916.19	**255.16**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.159	0.159	0.159	0.159	**0.159**
HOF2 % change from HOF1	-7.2	-9.6	-7.9	-13.9	**-9.7**
HOF2: Volume to supply (Ml)	106.28	173.15	167.79	1119.75	**391.74**
HOF2 % change from HOF1	1221.9	361.7	184.8	22.2	**53.5**
HOF3: Month Q97 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.151	0.151	0.151	0.151	**0.151**
HOF3 % change from HOF1	-12.0	-14.4	-12.7	-18.4	**-14.4**
HOF3: Volume to supply (Ml)	172.8	239.67	234.31	1186.27	**458.26**
HOF3 % change from HOF1	2049.3	539.1	297.7	29.5	**79.6**
HOF4: 5 year MAM10 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.166	0.166	0.166	0.167	**0.166**
HOF4 % change from HOF1	-3.5	-5.7	-3.9	-9.7	**-5.8**
HOF4: Volume to supply (Ml)	56.25	117.85	112.49	1059.27	**336.47**
HOF4 % change from HOF1	599.6	214.3	90.9	15.6	**31.9**

October and November

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.185	0.174	0.185	0.185	**0.182**
HOF1: Volume to supply (Ml)	1882.31	33.7	385	2349.99	**1162.75**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.185	0.180	0.185	0.185	**0.183**
HOF2 % change from HOF1	-0.3	3.7	-0.3	-0.3	**0.7**
HOF2: Volume to supply (Ml)	1886.8	0	389.49	2354.48	**1157.69**
HOF2 % change from HOF1	0.2	-100.0	1.2	0.2	**-0.4**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.214	0.180	0.214	0.214	**0.206**
HOF3 % change from HOF1	15.7	3.7	15.7	15.7	**12.8**
HOF3: Volume to supply (Ml)	1732.32	0	235.01	2200	**1041.83**
HOF3 % change from HOF1	-8.0	-100.0	-39.0	-6.4	**-10.4**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.240	0.180	0.226	0.240	**0.222**
HOF4 % change from HOF1	29.7	3.7	22.2	29.7	**21.6**
HOF4: Volume to supply (Ml)	1596.15	0	171.42	2063.83	**957.85**
HOF4 % change from HOF1	-15.2	-100.0	-55.5	-12.2	**-17.6**

Appendix 6.8d: Change in water allocation during the four driest years – River Dove at Izaak Walton (totals aggregated by season)

May and June

HOF1: Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	0.521	0.521	0.521	0.521	**0.521**
HOF1: Volume to supply (Ml)	599.18	1506.82	2663.12	3389.85	**2039.74**
HOF2: Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	0.634	0.723	0.723	0.723	**0.701**
HOF2 % change from HOF1	21.6	38.8	38.8	38.8	**34.5**
HOF2: Volume to supply (Ml)	0	432.35	1588.66	2315.38	**1084.10**
HOF2 % change from HOF1	-100.0	-71.3	-40.3	-31.7	**-46.9**
HOF3: Month Q90 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	0.634	0.805	0.845	0.845	**0.782**
HOF3 % change from HOF1	21.6	54.5	62.1	62.1	**50.1**
HOF3: Volume to supply (Ml)	0	0	950.32	1677.05	**656.84**
HOF3 % change from HOF1	-100.0	-100.0	-64.3	-50.5	**-67.8**
HOF4: Month Q84 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	0.634	0.805	0.921	0.921	**0.820**
HOF4 % change from HOF1	21.6	54.5	76.8	76.8	**57.4**
HOF4: Volume to supply (Ml)	0	0	545.98	1272.71	**454.67**
HOF4 % change from HOF1	-100.0	-100.0	-79.5	-62.5	**-77.7**

July to September

HOF1: Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	0.445	0.443	0.495	0.521	**0.476**
HOF1: Volume to supply (Ml)	358.91	0	763.34	1048.12	**542.59**
HOF2: Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	0.437	0.433	0.437	0.437	**0.436**
HOF2 % change from HOF1	-1.6	-2.2	-11.6	-16.1	**-8.3**
HOF2: Volume to supply (Ml)	417.41	77.67	1220.91	1710.87	**856.72**
HOF2 % change from HOF1	16.3		59.9	63.2	**57.9**
HOF3: Month Q98 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	0.397	0.397	0.397	0.397	**0.397**
HOF3 % change from HOF1	-10.8	-10.5	-19.9	-23.9	**-16.7**
HOF3: Volume to supply (Ml)	742.03	370.23	1545.34	2032.29	**1172.47**
HOF3 % change from HOF1	106.7		102.4	93.9	**116.1**
HOF4: 5 year MAM10 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	0.414	0.412	0.431	0.431	**0.422**
HOF4 % change from HOF1	-6.8	-7.1	-12.9	-17.3	**-11.3**
HOF4: Volume to supply (Ml)	602.65	251.77	1276.56	1763.52	**973.63**
HOF4 % change from HOF1	67.9		67.2	68.3	**79.4**

October and November

HOF1: Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	0.521	0.521	0.508	0.503	**0.513**
HOF1: Volume to supply (Ml)	1179.1	3623.88	2976.77	106.27	**1971.51**
HOF2: Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	0.507	0.507	0.507	0.489	**0.502**
HOF2 % change from HOF1	-2.8	-2.8	-0.3	-2.9	**-2.2**
HOF2: Volume to supply (Ml)	1263.43	3708.21	2991.46	187.49	**2037.65**
HOF2 % change from HOF1	7.2	2.3	0.5	76.4	**3.4**
HOF3: Month Q90 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	0.619	0.619	0.619	0.513	**0.592**
HOF3 % change from HOF1	18.8	18.8	21.9	1.9	**15.4**
HOF3: Volume to supply (Ml)	790.13	3120.86	2404.11	58.92	**1593.51**
HOF3 % change from HOF1	-33.0	-13.9	-19.2	-44.6	**-19.2**
HOF4: Month Q84 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	0.624	0.738	0.727	0.524	**0.653**
HOF4 % change from HOF1	19.8	41.7	43.1	4.1	**27.3**
HOF4: Volume to supply (Ml)	645.49	2499.29	1841.47	0	**1246.56**
HOF4 % change from HOF1	-45.3	-31.0	-38.1	-100.0	**-36.8**

Appendix 6.8e: Change in water allocation during the four driest years – River Sow at Great Bridgford (totals aggregated by season)

May and June

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.324	0.325	0.325	0.325	**0.325**
HOF1: Volume to supply (Ml)	112.49	879.63	879.55	1265.76	**784.36**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.345	0.387	0.387	0.387	**0.376**
HOF2 % change from HOF1	6.5	18.9	18.9	18.9	**15.8**
HOF2: Volume to supply (Ml)	0	552.26	552.18	938.39	**510.71**
HOF2 % change from HOF1	-100.0	-37.2	-37.2	-25.9	**-34.9**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.345	0.442	0.438	0.442	**0.417**
HOF3 % change from HOF1	6.5	35.8	34.8	35.8	**28.3**
HOF3: Volume to supply (Ml)	0	263.16	281.23	649.29	**298.42**
HOF3 % change from HOF1	-100.0	-70.1	-68.0	-48.7	**-62.0**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.345	0.481	0.466	0.486	**0.444**
HOF4 % change from HOF1	6.5	47.8	43.4	49.4	**36.8**
HOF4: Volume to supply (Ml)	0	57.02	131.24	416.36	**151.16**
HOF4 % change from HOF1	-100.0	-93.5	-85.1	-67.1	**-80.7**

July to September

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.214	0.316	0.317	0.309	**0.289**
HOF1: Volume to supply (Ml)	0	115.78	596.33	332.12	**261.06**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.214	0.254	0.254	0.254	**0.244**
HOF2 % change from HOF1	0.0	-19.5	-19.9	-17.9	**-15.6**
HOF2: Volume to supply (Ml)	0	604.81	1096.07	774.32	**618.80**
HOF2 % change from HOF1		422.4	83.8	133.1	**137.0**
HOF3: Month Q97 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.213	0.219	0.219	0.219	**0.218**
HOF3 % change from HOF1	-0.3	-30.5	-30.8	-29.1	**-24.6**
HOF3: Volume to supply (Ml)	5.36	879.38	1370.64	1048.89	**826.07**
HOF3 % change from HOF1		659.5	129.8	215.8	**216.4**
HOF4: 5 year MAM10 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.214	0.262	0.262	0.262	**0.250**
HOF4 % change from HOF1	0.0	-17.0	-17.4	-15.3	**-13.5**
HOF4: Volume to supply (Ml)	0	541.56	1032.83	711.07	**571.37**
HOF4 % change from HOF1		367.7	73.2	114.1	**118.9**

October and November

HOF1: Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.235	0.325	0.325	0.321	**0.302**
HOF1: Volume to supply (Ml)	0	1111.71	1407.45	619.49	**784.66**
HOF2: Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.235	0.339	0.339	0.339	**0.313**
HOF2 % change from HOF1	0.0	4.3	4.3	5.6	**3.8**
HOF2: Volume to supply (Ml)	0	1040.86	1336.6	527.21	**726.17**
HOF2 % change from HOF1		-6.4	-5.0	-14.9	**-7.5**
HOF3: Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.235	0.395	0.395	0.381	**0.351**
HOF3 % change from HOF1	0.0	21.4	21.4	18.5	**16.5**
HOF3: Volume to supply (Ml)	0	749.69	1045.43	311.04	**526.54**
HOF3 % change from HOF1		-32.6	-25.7	-49.8	**-32.9**
HOF4: Month Q84 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.235	0.426	0.426	0.397	**0.371**
HOF4 % change from HOF1	0.0	31.1	31.1	23.7	**23.1**
HOF4: Volume to supply (Ml)	0	583.81	879.3	225.51	**422.16**
HOF4 % change from HOF1		-47.5	-37.5	-63.6	**-46.2**

Appendix 6.9a: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Hiz at Arlesey

May

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.323	0.452	0.486	0.474	**0.434**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.323	0.328	0.328	0.328	**0.327**
HOF1: Volume to supply (Ml)	0.00	332.12	423.19	391.05	**286.59**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.351	0.351	0.351	0.351	**0.351**
HOF2: Flow to river (m^3s^{-1})	0.323	0.351	0.351	0.351	**0.344**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	+0.023	+0.023	+0.023	**+0.017**
HOF2: Volume to supply (Ml)	0.00	270.52	361.58	329.44	**240.39**
HOF2: Difference from HOF1 (Ml)	0.00	-61.60	-61.61	-61.61	**-46.21**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.405	0.405	0.405	0.405	**0.405**
HOF3: Flow to river (m^3s^{-1})	0.323	0.405	0.405	0.405	**0.385**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	+0.077	+0.077	+0.077	**+0.058**
HOF3: Volume to supply (Ml)	0.00	125.88	216.95	184.81	**131.91**
HOF3: Difference from HOF1 (Ml)	0.00	-206.24	-206.24	-206.24	**-154.68**
HOF4: Natural Month Q95 (m^3s^{-1})	0.251	0.251	0.251	0.251	**0.251**
HOF4: Flow to river (m^3s^{-1})	0.251	0.251	0.251	0.251	**0.251**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.072	-0.077	-0.077	-0.077	**-0.076**
HOF4: Volume to supply (Ml)	192.84	538.36	629.42	597.28	**489.48**
HOF4: Difference from HOF1 (Ml)	+192.84	+206.24	+206.23	+206.23	**+202.89**
HOF5: Natural Month Q90 (m^3s^{-1})	0.284	0.284	0.284	0.284	**0.284**
HOF5: Flow to river (m^3s^{-1})	0.284	0.284	0.284	0.284	**0.284**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.039	-0.044	-0.044	-0.044	**-0.043**
HOF5: Volume to supply (Ml)	104.46	449.97	541.04	508.90	**401.09**
HOF5: Difference from HOF1 (Ml)	+104.46	+117.85	+117.85	+117.85	**+114.50**

June

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.374	0.335	0.416	0.488	**0.403**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Volume to supply (Ml)	119.23	18.14	228.10	414.72	**195.05**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.336	0.336	0.336	0.336	**0.336**
HOF2: Flow to river (m^3s^{-1})	0.336	0.335	0.336	0.336	**0.336**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.008	+0.007	+0.008	+0.008	**+0.008**
HOF2: Volume to supply (Ml)	98.50	0.00	207.36	393.98	**174.96**
HOF2: Difference from HOF1 (Ml)	-20.73	-18.14	-20.74	-20.74	**-20.09**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.381	0.381	0.381	0.381	**0.381**
HOF3: Flow to river (m^3s^{-1})	0.374	0.335	0.381	0.381	**0.368**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.046	+0.007	+0.053	+0.053	**+0.040**
HOF3: Volume to supply (Ml)	0.00	0.00	90.72	277.34	**92.02**
HOF3: Difference from HOF1 (Ml)	-119.23	-18.14	-137.38	-137.38	**-103.03**
HOF4: Natural Month Q95 (m^3s^{-1})	0.223	0.223	0.223	0.223	**0.223**
HOF4: Flow to river (m^3s^{-1})	0.223	0.223	0.223	0.223	**0.223**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.105	-0.105	-0.105	-0.105	**-0.105**
HOF4: Volume to supply (Ml)	391.39	290.30	500.26	686.88	**467.21**
HOF4: Difference from HOF1 (Ml)	+272.16	+272.16	+272.16	+272.16	**+272.16**
HOF5: Natural Month Q90 (m^3s^{-1})	0.277	0.277	0.277	0.277	**0.277**
HOF5: Flow to river (m^3s^{-1})	0.277	0.277	0.277	0.277	**0.277**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.051	-0.051	-0.051	-0.051	**-0.051**
HOF5: Volume to supply (Ml)	251.42	150.34	360.29	546.91	**327.24**
HOF5: Difference from HOF1 (Ml)	+132.19	+132.20	+132.19	+132.19	**+132.19**

July

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.324	0.284	0.366	0.361	**0.334**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.324	0.284	0.328	0.328	**0.316**
HOF1: Volume to supply (Ml)	0.00	0.00	101.78	88.39	**47.54**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.306	0.306	0.306	0.306	**0.306**
HOF2: Flow to river (m^3s^{-1})	0.306	0.284	0.306	0.306	**0.301**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.018	0.000	-0.022	-0.022	**-0.016**
HOF2: Volume to supply (Ml)	48.21	0.00	160.70	147.31	**89.06**
HOF2: Difference from HOF1 (Ml)	+48.21	0.00	+58.92	+58.92	**+41.51**
HOF3: Gauged Month Q97 (m^3s^{-1})	0.280	0.280	0.280	0.280	**0.280**
HOF3: Flow to river (m^3s^{-1})	0.280	0.280	0.280	0.280	**0.280**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.044	-0.004	-0.048	-0.048	**-0.036**
HOF3: Volume to supply (Ml)	117.85	10.71	230.34	216.95	**143.963**
HOF3: Difference from HOF1 (Ml)	+117.85	+10.71	+128.56	+128.56	**+96.42**
HOF4: Natural Month Q95 (m^3s^{-1})	0.225	0.225	0.225	0.225	**0.225**
HOF4: Flow to river (m^3s^{-1})	0.225	0.225	0.225	0.225	**0.225**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.099	-0.059	-0.103	-0.103	**-0.091**
HOF4: Volume to supply (Ml)	265.16	158.03	377.65	364.26	**291.28**
HOF4: Difference from HOF1 (Ml)	+265.16	+158.03	+275.87	+275.87	**+243.73**
HOF5: Natural Month Q97 (m^3s^{-1})	0.210	0.210	0.210	0.210	**0.210**
HOF5: Flow to river (m^3s^{-1})	0.210	0.210	0.210	0.210	**0.210**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.114	-0.074	-0.118	-0.118	**-0.106**
HOF5: Volume to supply (Ml)	305.34	198.20	417.83	404.44	**331.45**
HOF5: Difference from HOF1 (Ml)	+305.34	+198.20	+316.05	+316.05	**+283.91**

August

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.296	0.335	0.443	0.331	**0.351**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.296	0.328	0.328	0.328	**0.320**
HOF1: Volume to supply (Ml)	0.00	18.75	308.02	8.04	**83.70**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.299	0.299	0.299	0.299	**0.299**
HOF2: Flow to river (m^3s^{-1})	0.296	0.299	0.299	0.299	**0.298**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.029	-0.029	-0.029	**-0.022**
HOF2: Volume to supply (Ml)	0.00	96.42	385.69	85.71	**141.96**
HOF2: Difference from HOF1 (Ml)	0.00	+77.67	+77.67	+77.67	**+58.25**
HOF3: Gauged Month Q97 (m^3s^{-1})	0.270	0.270	0.270	0.270	**0.270**
HOF3: Flow to river (m^3s^{-1})	0.270	0.270	0.270	0.270	**0.270**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.026	-0.058	-0.058	-0.058	**-0.050**
HOF3: Volume to supply (Ml)	69.64	174.10	463.36	163.38	**217.62**
HOF3: Difference from HOF1 (Ml)	+69.64	+155.35	+155.34	+155.34	**+133.92**
HOF4: Natural Month Q95 (m^3s^{-1})	0.209	0.209	0.209	0.209	**0.209**
HOF4: Flow to river (m^3s^{-1})	0.209	0.209	0.209	0.209	**0.209**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.087	-0.119	-0.119	-0.119	**-0.111**
HOF4: Volume to supply (Ml)	233.02	337.48	626.75	326.76	**381.00**
HOF4: Difference from HOF1 (Ml)	+233.02	+318.73	+318.73	+318.72	**+297.30**
HOF5: Natural Month Q97 (m^3s^{-1})	0.183	0.183	0.183	0.183	**0.183**
HOF5: Flow to river (m^3s^{-1})	0.183	0.183	0.183	0.183	**0.183**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.113	-0.145	-0.145	-0.145	**-0.137**
HOF5: Volume to supply (Ml)	302.66	407.12	696.38	396.40	**450.64**
HOF5: Difference from HOF1 (Ml)	+302.66	+388.37	+388.36	+388.36	**+366.94**

September

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.262	0.331	0.361	0.409	**0.341**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.262	0.328	0.328	0.328	**0.312**
HOF1: Volume to supply (Ml)	0.00	7.78	85.54	209.95	**75.82**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.286	0.286	0.286	0.286	**0.286**
HOF2: Flow to river (m^3s^{-1})	0.262	0.286	0.286	0.286	**0.280**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.042	-0.042	-0.042	**-0.032**
HOF2: Volume to supply (Ml)	0.00	116.64	194.40	318.82	**157.47**
HOF2: Difference from HOF1 (Ml)	0.00	+108.86	+108.86	+108.87	**+81.65**
HOF3: Gauged Month Q97 (m^3s^{-1})	0.265	0.265	0.265	0.265	**0.265**
HOF3: Flow to river (m^3s^{-1})	0.262	0.265	0.265	0.265	**0.264**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	-0.063	-0.063	-0.063	**-0.047**
HOF3: Volume to supply (Ml)	0.00	171.07	248.83	373.25	**198.29**
HOF3: Difference from HOF1 (Ml)	0.00	+163.29	+163.29	+163.30	**+122.47**
HOF4: Natural Month Q95 (m^3s^{-1})	0.216	0.216	0.216	0.216	**0.216**
HOF4: Flow to river (m^3s^{-1})	0.216	0.216	0.216	0.216	**0.216**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.046	-0.112	-0.112	-0.112	**-0.096**
HOF4: Volume to supply (Ml)	119.23	298.08	375.84	500.26	**323.35**
HOF4: Difference from HOF1 (Ml)	+119.23	+290.30	+290.30	+290.31	**+247.54**
HOF5: Natural Month Q97 (m^3s^{-1})	0.194	0.194	0.194	0.194	**0.194**
HOF5: Flow to river (m^3s^{-1})	0.194	0.194	0.194	0.194	**0.194**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.068	-0.134	-0.134	-0.134	**-0.1175**
HOF5: Volume to supply (Ml)	176.26	355.10	432.86	557.28	**380.38**
HOF5: Difference from HOF1 (Ml)	+176.26	+347.32	+347.32	+347.33	**+304.56**

October

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	0.301	0.381	0.284	0.531	**0.374**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.301	0.328	0.284	0.328	**0.310**
HOF1: Volume to supply (Ml)	0.00	141.96	0.00	543.72	**171.42**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.284	0.284	0.284	0.284	**0.284**
HOF2: Flow to river (m^3s^{-1})	0.284	0.284	0.284	0.284	**0.284**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.017	-0.044	0.000	-0.044	**-0.026**
HOF2: Volume to supply (Ml)	45.33	295.80	0.00	661.56	**250.67**
HOF2: Difference from HOF1 (Ml)	+45.33	+153.84	0.00	+117.84	**+79.25**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.338	0.338	0.338	0.338	**0.338**
HOF3: Flow to river (m^3s^{-1})	0.301	0.338	0.284	0.338	**0.315**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	+0.010	+0.000	+0.010	**+0.005**
HOF3: Volume to supply (Ml)	0.00	115.17	0.00	516.93	**158.03**
HOF3: Difference from HOF1 (Ml)	0.00	-26.79	0.00	-26.79	**-13.40**
HOF4: Natural Month Q95 (m^3s^{-1})	0.245	0.245	0.245	0.245	**0.245**
HOF4: Flow to river (m^3s^{-1})	0.245	0.245	0.245	0.245	**0.245**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.056	-0.083	-0.039	-0.083	**-0.065**
HOF4: Volume to supply (Ml)	149.99	364.26	104.46	766.02	**346.18**
HOF4: Difference from HOF1 (Ml)	+149.99	+222.30	+104.46	+222.30	**+174.76**
HOF5: Natural Month Q90 (m^3s^{-1})	0.255	0.255	0.255	0.255	**0.255**
HOF5: Flow to river (m^3s^{-1})	0.255	0.255	0.255	0.255	**0.255**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.046	-0.073	-0.029	-0.073	**-0.055**
HOF5: Volume to supply (Ml)	123.21	337.48	77.67	739.24	**319.40**
HOF5: Difference from HOF1 (Ml)	+123.21	+195.52	+77.67	+195.52	**+147.98**

November

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.321	0.487	0.321	0.991	**0.530**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.328	0.328	0.328	0.328	**0.328**
HOF1: Flow to river (m^3s^{-1})	0.321	0.328	0.321	0.328	**0.325**
HOF1: Volume to supply (Ml)	0.00	412.13	0.00	1718.50	**532.66**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.307	0.307	0.307	0.307	**0.307**
HOF2: Flow to river (m^3s^{-1})	0.307	0.307	0.307	0.307	**0.307**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.014	-0.021	-0.014	-0.021	**-0.018**
HOF2: Volume to supply (Ml)	36.29	466.56	36.29	1772.93	**578.02**
HOF2: Difference from HOF1 (Ml)	+36.29	+54.43	+36.29	+54.43	**+45.36**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.344	0.344	0.344	0.344	**0.344**
HOF3: Flow to river (m^3s^{-1})	0.321	0.344	0.321	0.344	**0.333**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	+0.016	0.000	+0.016	**+0.008**
HOF3: Volume to supply (Ml)	0.00	370.66	0.00	1677.02	**511.92**
HOF3: Difference from HOF1 (Ml)	0.00	-41.47	0.00	-41.48	**-20.74**
HOF4: Natural Month Q95 (m^3s^{-1})	0.253	0.253	0.253	0.253	**0.253**
HOF4: Flow to river (m^3s^{-1})	0.253	0.253	0.253	0.253	**0.253**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.068	-0.075	-0.068	-0.075	**-0.072**
HOF4: Volume to supply (Ml)	176.26	606.53	176.26	1912.90	**717.99**
HOF4: Difference from HOF1 (Ml)	+176.26	+194.40	+176.26	+194.40	**+185.33**
HOF5: Natural Month Q90 (m^3s^{-1})	0.267	0.267	0.267	0.267	**0.267**
HOF5: Flow to river (m^3s^{-1})	0.267	0.267	0.267	0.267	**0.267**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.054	-0.061	-0.054	-0.061	**-0.058**
HOF5: Volume to supply (Ml)	139.97	570.24	139.97	1876.61	**681.70**
HOF5: Difference from HOF1 (Ml)	+139.97	+158.11	+139.97	+158.11	**+149.04**

Appendix 6.9b: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Trent at North Muskham

May

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	54.883	33.911	33.858	46.164	**42.204**
HOF1: Gauged Annual Q95 (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	73773.85	17602.44	17460.49	50420.88	**39814.42**
HOF2: Gauged Month Q95 (m^3s^{-1})	32.300	32.300	32.300	32.300	**32.300**
HOF2: Flow to river (m^3s^{-1})	32.300	32.300	32.300	32.300	**32.300**
HOF2: Difference from HOF1 (m^3s^{-1})	+4.961	+4.961	+4.961	+4.961	**+4.961**
HOF2: Volume to supply (Ml)	60486.31	4314.90	4172.95	37133.34	**26526.88**
HOF2: Difference from HOF1 (Ml)	-13287.54	-13287.54	-13287.54	-13287.54	**-13287.54**
HOF3: Gauged Month Q90 (m^3s^{-1})	34.320	34.320	34.320	34.320	**34.320**
HOF3: Flow to river (m^3s^{-1})	34.320	33.911	33.858	34.320	**34.102**
HOF3: Difference from HOF1 (m^3s^{-1})	+6.981	+6.572	+6.519	+6.981	**+6.763**
HOF3: Volume to supply (Ml)	55075.94	0.00	0.00	31722.97	**21699.73**
HOF3: Difference from HOF1 (Ml)	-18697.91	-17602.44	-17460.49	-18697.91	**-18114.69**
HOF4: Natural Month Q95 (m^3s^{-1})	18.910	18.910	18.910	18.910	**18.910**
HOF4: Flow to river (m^3s^{-1})	18.910	18.910	18.910	18.910	**18.910**
HOF4: Difference from HOF1 (m^3s^{-1})	-8.429	-8.429	-8.429	-8.429	**-8.429**
HOF4: Volume to supply (Ml)	96350.08	40178.68	40036.72	72997.11	**62390.65**
HOF4: Difference from HOF1 (Ml)	+22576.23	+22576.24	+22576.23	+22576.23	**+22576.23**
HOF5: Natural Month Q90 (m^3s^{-1})	21.290	21.290	21.290	21.290	**21.290**
HOF5: Flow to river (m^3s^{-1})	21.290	21.290	21.290	21.290	**21.290**
HOF5: Difference from HOF1 (m^3s^{-1})	-6.049	-6.049	-6.049	-6.049	**-6.049**
HOF5: Volume to supply (Ml)	89975.49	33804.09	33662.13	66622.52	**56016.06**
HOF5: Difference from HOF1 (Ml)	+16201.64	+16201.65	+16201.64	+16201.64	**+16201.64**

June

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	38.226	35.740	32.820	35.449	**35.559**
HOF1: Gauged Annual Q95 (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	28219.10	21775.39	14206.75	21021.12	**21305.59**
HOF2: Gauged Month Q95 (m^3s^{-1})	28.310	28.310	28.310	28.310	**28.310**
HOF2: Flow to river (m^3s^{-1})	28.310	28.310	28.310	28.310	**28.310**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.971	+0.971	+0.971	+0.971	**+0.971**
HOF2: Volume to supply (Ml)	25702.27	19258.56	11689.92	18504.29	**18788.76**
HOF2: Difference from HOF1 (Ml)	-2516.83	-2516.83	-2516.83	-2516.83	**-2516.83**
HOF3: Gauged Month Q90 (m^3s^{-1})	30.000	30.000	30.000	30.000	**30.000**
HOF3: Flow to river (m^3s^{-1})	30.000	30.000	30.000	30.000	**30.000**
HOF3: Difference from HOF1 (m^3s^{-1})	+2.661	+2.661	+2.661	+2.661	**+2.661**
HOF3: Volume to supply (Ml)	21321.79	14878.08	7309.44	14123.81	**14408.28**
HOF3: Difference from HOF1 (Ml)	-6897.31	-6897.31	-6897.31	-6897.31	**-6897.31**
HOF4: Natural Month Q95 (m^3s^{-1})	14.510	14.510	14.510	14.510	**14.510**
HOF4: Flow to river (m^3s^{-1})	14.510	14.510	14.510	14.510	**14.510**
HOF4: Difference from HOF1 (m^3s^{-1})	-12.829	-12.829	-12.829	-12.829	**-12.829**
HOF4: Volume to supply (Ml)	61471.87	55028.16	47459.52	54273.89	**54558.36**
HOF4: Difference from HOF1 (Ml)	+33252.77	+33252.77	+33252.77	+33252.77	**+33252.77**
HOF5: Natural Month Q90 (m^3s^{-1})	16.330	16.330	16.330	16.330	**16.330**
HOF5: Flow to river (m^3s^{-1})	16.330	16.330	16.330	16.330	**16.330**
HOF5: Difference from HOF1 (m^3s^{-1})	-11.009	-11.009	-11.009	-11.009	**-11.009**
HOF5: Volume to supply (Ml)	56754.43	50310.72	42742.08	49556.45	**49840.92**
HOF5: Difference from HOF1 (Ml)	+28535.33	+28535.33	+28535.33	+28535.33	**+28535.33**

July

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	33.986	31.276	30.771	31.470	**31.876**
HOF1: Gauged Annual Q95 (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	17803.32	10544.86	9192.27	11064.47	**12151.23**
HOF2: Gauged Month Q95 (m^3s^{-1})	25.110	25.110	25.110	25.110	**25.110**
HOF2: Flow to river (m^3s^{-1})	25.110	25.110	25.110	25.110	**25.110**
HOF2: Difference from HOF1 (m^3s^{-1})	-2.229	-2.229	-2.229	-2.229	**-2.229**
HOF2: Volume to supply (Ml)	23773.48	16515.01	15162.42	17034.62	**18121.38**
HOF2: Difference from HOF1 (Ml)	+5970.16	+5970.15	+5970.15	+5970.15	**+5970.15**
HOF3: Gauged Month Q97 (m^3s^{-1})	24.420	24.420	24.420	24.420	**24.420**
HOF3: Flow to river (m^3s^{-1})	24.420	24.420	24.420	24.420	**24.420**
HOF3: Difference from HOF1 (m^3s^{-1})	-2.919	-2.919	-2.919	-2.919	**-2.919**
HOF3: Volume to supply (Ml)	25621.57	18363.11	17010.52	18882.72	**19969.480**
HOF3: Difference from HOF1 (Ml)	+7818.25	+7818.25	+7818.25	+7818.25	**+7818.25**
HOF4: Natural Month Q95 (m^3s^{-1})	11.370	11.370	11.370	11.370	**11.370**
HOF4: Flow to river (m^3s^{-1})	11.370	11.370	11.370	11.370	**11.370**
HOF4: Difference from HOF1 (m^3s^{-1})	-15.969	-15.969	-15.969	-15.969	**-15.969**
HOF4: Volume to supply (Ml)	60574.69	53316.23	51963.64	53835.84	**54922.60**
HOF4: Difference from HOF1 (Ml)	+42771.37	+42771.37	+42771.37	+42771.37	**+42771.37**
HOF5: Natural Month Q97 (m^3s^{-1})	10.080	10.080	10.080	10.080	**10.08**
HOF5: Flow to river (m^3s^{-1})	10.080	10.080	10.080	10.080	**10.08**
HOF5: Difference from HOF1 (m^3s^{-1})	-17.259	-17.259	-17.259	-17.259	**-17.259**
HOF5: Volume to supply (Ml)	64029.83	56771.37	55418.77	57290.98	**58377.74**
HOF5: Difference from HOF1 (Ml)	+46226.51	+46226.51	+46226.50	+46226.51	**+46226.51**

August

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	29.079	27.112	27.913	35.322	**29.857**
HOF1: Gauged Annual Q95 (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^3s^{-1})	27.339	27.112	27.339	27.339	**27.282**
HOF1: Volume to supply (Ml)	4660.42	0.00	1537.40	21381.67	**6894.87**
HOF2: Gauged Month Q95 (m^3s^{-1})	24.100	24.100	24.100	24.100	**24.100**
HOF2: Flow to river (m^3s^{-1})	24.100	24.100	24.100	24.100	**24.100**
HOF2: Difference from HOF1 (m^3s^{-1})	-3.239	-3.012	-3.239	-3.239	**-3.182**
HOF2: Volume to supply (Ml)	13335.75	8067.34	10212.74	30057.00	**15418.21**
HOF2: Difference from HOF1 (Ml)	+8675.33	+8067.34	+8675.34	+8675.33	**+8523.34**
HOF3: Gauged Month Q97 (m^3s^{-1})	23.170	23.170	23.170	23.170	**23.170**
HOF3: Flow to river (m^3s^{-1})	23.170	23.170	23.170	23.170	**23.170**
HOF3: Difference from HOF1 (m^3s^{-1})	-4.169	-3.942	-4.169	-4.169	**-4.112**
HOF3: Volume to supply (Ml)	15826.67	10558.25	12703.65	32547.92	**17909.12**
HOF3: Difference from HOF1 (Ml)	+11166.25	+10558.25	+11166.25	+11166.25	**+11014.25**
HOF4: Natural Month Q95 (m^3s^{-1})	9.306	9.306	9.306	9.306	**9.306**
HOF4: Flow to river (m^3s^{-1})	9.306	9.306	9.306	9.306	**9.306**
HOF4: Difference from HOF1 (m^3s^{-1})	-18.033	-17.806	-18.033	-18.033	**-17.976**
HOF4: Volume to supply (Ml)	52960.00	47691.59	49836.99	69681.25	**55042.46**
HOF4: Difference from HOF1 (Ml)	+48299.58	+47691.59	+48299.59	+48299.58	**+48147.59**
HOF5: Natural Month Q97 (m^3s^{-1})	8.130	8.130	8.130	8.130	**8.130**
HOF5: Flow to river (m^3s^{-1})	8.130	8.130	8.130	8.130	**8.130**
HOF5: Difference from HOF1 (m^3s^{-1})	-19.209	-18.982	-19.209	-19.209	**-19.152**
HOF5: Volume to supply (Ml)	56109.80	50841.39	52986.79	72831.05	**58192.26**
HOF5: Difference from HOF1 (Ml)	+51449.38	+50841.39	+51449.39	+51449.38	**+51297.39**

September

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	28.060	26.472	26.700	40.555	**30.447**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^{3}s^{-1})	27.339	26.472	26.700	27.339	**26.963**
HOF1: Volume to supply (Ml)	1868.83	0.00	0.00	34255.87	**9031.18**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	24.660	24.660	24.660	24.660	**24.660**
HOF2: Flow to river (m^{3}s^{-1})	24.660	24.660	24.660	24.660	**24.660**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-2.679	-1.812	-2.040	-2.679	**-2.303**
HOF2: Volume to supply (Ml)	8812.80	4696.70	5287.68	41199.84	**14999.26**
HOF2: Difference from HOF1 (Ml)	+6943.97	+4696.70	+5287.68	+6943.97	**+5968.08**
HOF3: Gauged Month Q97 (m^{3}s^{-1})	23.950	23.950	23.950	23.950	**23.950**
HOF3: Flow to river (m^{3}s^{-1})	23.950	23.950	23.950	23.950	**23.950**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-3.389	-2.522	-2.750	-3.389	**-3.013**
HOF3: Volume to supply (Ml)	10653.12	6537.02	7128.00	43040.16	**16839.58**
HOF3: Difference from HOF1 (Ml)	+8784.29	+6537.02	+7128.00	+8784.29	**+7808.40**
HOF4: Natural Month Q95 (m^{3}s^{-1})	11.100	11.100	11.100	11.100	**11.100**
HOF4: Flow to river (m^{3}s^{-1})	11.100	11.100	11.100	11.100	**11.100**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-16.239	-15.372	-15.600	-16.239	**-15.863**
HOF4: Volume to supply (Ml)	43960.32	39844.22	40435.20	76347.36	**50146.78**
HOF4: Difference from HOF1 (Ml)	+42091.49	+39844.22	+40435.20	+42091.49	**+41115.60**
HOF5: Natural Month Q97 (m^{3}s^{-1})	10.210	10.210	10.210	10.210	**10.210**
HOF5: Flow to river (m^{3}s^{-1})	10.210	10.210	10.210	10.210	**10.210**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-17.129	-16.262	-16.490	-17.129	**-16.7525**
HOF5: Volume to supply (Ml)	46267.20	42151.10	42742.08	78654.24	**52453.66**
HOF5: Difference from HOF1 (Ml)	+44398.37	+42151.10	+42742.08	+44398.37	**+43422.48**

October

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	37.664	42.773	31.213	32.777	**36.107**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^{3}s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	27654.48	41338.43	10376.12	14565.14	**23483.54**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	25.610	25.610	25.610	25.610	**25.610**
HOF2: Flow to river (m^{3}s^{-1})	25.610	25.610	25.610	25.610	**25.610**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-1.729	-1.729	-1.729	-1.729	**-1.729**
HOF2: Volume to supply (Ml)	32285.43	45969.38	15007.08	19196.09	**28114.50**
HOF2: Difference from HOF1 (Ml)	+4630.95	+4630.95	+4630.96	+4630.95	**+4630.95**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	27.730	27.730	27.730	27.730	**27.730**
HOF3: Flow to river (m^{3}s^{-1})	27.730	27.730	27.730	27.730	**27.730**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.391	+0.391	+0.391	+0.391	**+0.391**
HOF3: Volume to supply (Ml)	26607.23	40291.17	9328.87	13517.88	**22436.29**
HOF3: Difference from HOF1 (Ml)	-1047.25	-1047.26	-1047.25	-1047.26	**-1047.26**
HOF4: Natural Month Q95 (m^{3}s^{-1})	15.260	15.260	15.260	15.260	**15.260**
HOF4: Flow to river (m^{3}s^{-1})	15.260	15.260	15.260	15.260	**15.260**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-12.079	-12.079	-12.079	-12.079	**-12.079**
HOF4: Volume to supply (Ml)	60006.87	73690.82	42728.52	46917.53	**55835.94**
HOF4: Difference from HOF1 (Ml)	+32352.39	+32352.39	+32352.40	+32352.39	**+32352.39**
HOF5: Natural Month Q90 (m^{3}s^{-1})	17.110	17.110	17.110	17.110	**17.110**
HOF5: Flow to river (m^{3}s^{-1})	17.110	17.110	17.110	17.110	**17.110**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-10.229	-10.229	-10.229	-10.229	**-10.229**
HOF5: Volume to supply (Ml)	55051.83	68735.78	37773.48	41962.49	**50880.90**
HOF5: Difference from HOF1 (Ml)	+27397.35	+27397.35	+27397.36	+27397.35	**+27397.35**

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	53.314	63.158	34.337	40.011	**47.705**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Flow to river (m^{3}s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	67327.20	92842.85	18138.82	32845.82	**52788.67**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	31.820	31.820	31.820	31.820	**31.820**
HOF2: Flow to river (m^{3}s^{-1})	31.820	31.820	31.820	31.820	**31.820**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+4.481	+4.481	+4.481	+4.481	**+4.481**
HOF2: Volume to supply (Ml)	55712.45	81228.10	6524.06	21231.07	**41173.92**
HOF2: Difference from HOF1 (Ml)	-11614.75	-11614.75	-11614.76	-11614.75	**-11614.75**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	36.460	36.460	36.460	36.460	**36.460**
HOF3: Flow to river (m^{3}s^{-1})	36.460	36.460	34.337	36.460	**35.929**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+9.121	+9.121	+6.998	+9.121	**+8.590**
HOF3: Volume to supply (Ml)	43685.57	69201.22	0.00	9204.19	**30522.75**
HOF3: Difference from HOF1 (Ml)	-23641.63	-23641.63	-18138.82	-23641.63	**-22265.93**
HOF4: Natural Month Q95 (m^{3}s^{-1})	22.590	22.590	22.590	22.590	**22.590**
HOF4: Flow to river (m^{3}s^{-1})	22.590	22.590	22.590	22.590	**22.590**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-4.749	-4.749	-4.749	-4.749	**-4.749**
HOF4: Volume to supply (Ml)	79636.61	105152.26	30448.22	45155.23	**65098.08**
HOF4: Difference from HOF1 (Ml)	+12309.41	+12309.41	+12309.40	+12309.41	**+12309.41**
HOF5: Natural Month Q90 (m^{3}s^{-1})	26.750	26.750	26.750	26.750	**26.750**
HOF5: Flow to river (m^{3}s^{-1})	26.750	26.750	26.750	26.750	**26.750**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-0.589	-0.589	-0.589	-0.589	**-0.589**
HOF5: Volume to supply (Ml)	68853.89	94369.54	19665.50	34372.51	**54315.36**
HOF5: Difference from HOF1 (Ml)	+1526.69	+1526.69	+1526.68	+1526.69	**+1526.69**

Appendix 6.9c: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Tame at Lea Marston Lakes

May

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	9.525	8.550	12.937	15.912	**11.731**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Flow to river (m^{3}s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	5549.64	2938.20	14688.35	22656.59	**11458.20**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	7.630	7.630	7.630	7.630	**7.630**
HOF2: Flow to river (m^{3}s^{-1})	7.630	7.630	7.630	7.630	**7.630**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.177	+0.177	+0.177	+0.177	**+0.177**
HOF2: Volume to supply (Ml)	5075.57	2464.13	14214.27	22182.51	**10984.12**
HOF2: Difference from HOF1 (Ml)	-474.07	-474.07	-474.08	-474.08	**-474.08**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	8.080	8.080	8.080	8.080	**8.080**
HOF3: Flow to river (m^{3}s^{-1})	8.080	8.080	8.080	8.080	**8.080**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.627	+0.627	+0.627	+0.627	**+0.627**
HOF3: Volume to supply (Ml)	3870.29	1258.85	13008.99	20977.23	**9778.84**
HOF3: Difference from HOF1 (Ml)	-1679.35	-1679.35	-1679.36	-1679.36	**-1679.36**
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.666	1.666	1.666	1.666	**1.666**
HOF4: Flow to river (m^{3}s^{-1})	1.666	1.666	1.666	1.666	**1.666**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-5.787	-5.787	-5.787	-5.787	**-5.787**
HOF4: Volume to supply (Ml)	21049.55	18438.11	30188.25	38156.49	**26958.10**
HOF4: Difference from HOF1 (Ml)	+15499.91	+15499.91	+15499.90	+15499.90	**+15499.91**
HOF5: Natural Month Q90 (m^{3}s^{-1})	1.879	1.879	1.879	1.879	**1.879**
HOF5: Flow to river (m^{3}s^{-1})	1.879	1.879	1.879	1.879	**1.879**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-5.574	-5.574	-5.574	-5.574	**-5.574**
HOF5: Volume to supply (Ml)	20479.05	17867.61	29617.75	37585.99	**26387.60**
HOF5: Difference from HOF1 (Ml)	+14929.41	+14929.41	+14929.40	+14929.40	**+14929.41**

June

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	9.456	9.809	10.212	8.855	**9.583**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Flow to river (m^{3}s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	5191.78	6106.75	7151.33	3633.98	**5520.96**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	7.690	7.690	7.690	7.690	**7.690**
HOF2: Flow to river (m^{3}s^{-1})	7.690	7.690	7.690	7.690	**7.690**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.237	+0.237	+0.237	+0.237	**+0.237**
HOF2: Volume to supply (Ml)	4577.47	5492.45	6537.02	3019.68	**4906.66**
HOF2: Difference from HOF1 (Ml)	-614.31	-614.30	-614.31	-614.30	**-614.31**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	8.000	8.000	8.000	8.000	**8.000**
HOF3: Flow to river (m^{3}s^{-1})	8.000	8.000	8.000	8.000	**8.000**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.547	+0.547	+0.547	+0.547	**+0.547**
HOF3: Volume to supply (Ml)	3773.95	4688.93	5733.50	2216.16	**4103.14**
HOF3: Difference from HOF1 (Ml)	-1417.83	-1417.82	-1417.83	-1417.82	**-1417.83**
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.227	1.227	1.227	1.227	**1.227**
HOF4: Flow to river (m^{3}s^{-1})	1.227	1.227	1.227	1.227	**1.227**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-6.226	-6.226	-6.226	-6.226	**-6.226**
HOF4: Volume to supply (Ml)	21329.57	22244.54	23289.12	19771.78	**21658.75**
HOF4: Difference from HOF1 (Ml)	+16137.79	+16137.79	+16137.79	+16137.80	**+16137.79**
HOF5: Natural Month Q90 (m^{3}s^{-1})	1.411	1.411	1.411	1.411	**1.411**
HOF5: Flow to river (m^{3}s^{-1})	1.411	1.411	1.411	1.411	**1.411**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-6.042	-6.042	-6.042	-6.042	**-6.042**
HOF5: Volume to supply (Ml)	20852.64	21767.62	22812.19	19294.85	**21181.83**
HOF5: Difference from HOF1 (Ml)	+15660.86	+15660.87	+15660.86	+15660.87	**+15660.87**

July

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	8.747	8.224	10.523	7.905	**8.850**
HOF1: Gauged Annual Q95 (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Flow to river (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	3465.85	2065.05	8222.69	1210.64	**3741.06**
HOF2: Gauged Month Q95 (m^3s^{-1})	7.230	7.230	7.230	7.230	**7.230**
HOF2: Flow to river (m^3s^{-1})	7.230	7.230	7.230	7.230	**7.230**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.223	-0.223	-0.223	-0.223	**-0.223**
HOF2: Volume to supply (Ml)	4063.13	2662.33	8819.97	1807.92	**4338.34**
HOF2: Difference from HOF1 (Ml)	+597.28	+597.28	+597.28	+597.28	**+597.28**
HOF3: Gauged Month Q97 (m^3s^{-1})	7.080	7.080	7.080	7.080	**7.080**
HOF3: Flow to river (m^3s^{-1})	7.080	7.080	7.080	7.080	**7.080**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.373	-0.373	-0.373	-0.373	**-0.373**
HOF3: Volume to supply (Ml)	4464.89	3064.09	9221.73	2209.68	**4740.098**
HOF3: Difference from HOF1 (Ml)	+999.04	+999.04	+999.04	+999.04	**+999.04**
HOF4: Natural Month Q95 (m^3s^{-1})	0.937	0.937	0.937	0.937	**0.937**
HOF4: Flow to river (m^3s^{-1})	0.937	0.937	0.937	0.937	**0.937**
HOF4: Difference from HOF1 (m^3s^{-1})	-6.516	-6.516	-6.516	-6.516	**-6.516**
HOF4: Volume to supply (Ml)	20918.30	19517.50	25675.14	18663.09	**21193.51**
HOF4: Difference from HOF1 (Ml)	+17452.4	+17452.4	+17452.4	+17452.4	**+17452.4**
HOF5: Natural Month Q97 (m^3s^{-1})	0.851	0.851	0.851	0.851	**0.851**
HOF5: Flow to river (m^3s^{-1})	0.851	0.851	0.851	0.851	**0.851**
HOF5: Difference from HOF1 (m^3s^{-1})	-6.602	-6.602	-6.602	-6.602	**-6.602**
HOF5: Volume to supply (Ml)	21148.65	19747.84	25905.48	18893.43	**21423.85**
HOF5: Difference from HOF1 (Ml)	+17682.80	+17682.79	+17682.79	+17682.79	**+17682.79**

August

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	8.614	8.117	18.134	9.295	**11.040**
HOF1: Gauged Annual Q95 (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Flow to river (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	3109.62	1778.46	28607.99	4933.61	**9607.42**
HOF2: Gauged Month Q95 (m^3s^{-1})	6.980	6.980	6.980	6.980	**6.980**
HOF2: Flow to river (m^3s^{-1})	6.980	6.980	6.980	6.980	**6.980**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.473	-0.473	-0.473	-0.473	**-0.473**
HOF2: Volume to supply (Ml)	4376.51	3045.34	29874.87	6200.50	**10874.31**
HOF2: Difference from HOF1 (Ml)	+1266.89	+1266.88	+1266.88	+1266.89	**+1266.89**
HOF3: Gauged Month Q97 (m^3s^{-1})	6.870	6.870	6.870	6.870	**6.870**
HOF3: Flow to river (m^3s^{-1})	6.870	6.870	6.870	6.870	**6.870**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.583	-0.583	-0.583	-0.583	**-0.583**
HOF3: Volume to supply (Ml)	4671.13	3339.96	30169.50	6495.12	**11168.93**
HOF3: Difference from HOF1 (Ml)	+1561.51	+1561.50	+1561.51	+1561.51	**+1561.51**
HOF4: Natural Month Q95 (m^3s^{-1})	0.743	0.743	0.743	0.743	**0.743**
HOF4: Flow to river (m^3s^{-1})	0.743	0.743	0.743	0.743	**0.743**
HOF4: Difference from HOF1 (m^3s^{-1})	-6.710	-6.710	-6.710	-6.710	**-6.710**
HOF4: Volume to supply (Ml)	21081.69	19750.52	46580.05	22905.68	**27579.49**
HOF4: Difference from HOF1 (Ml)	+17972.07	+17972.06	+17972.06	+17972.07	**+17972.07**
HOF5: Natural Month Q97 (m^3s^{-1})	0.663	0.663	0.663	0.663	**0.663**
HOF5: Flow to river (m^3s^{-1})	0.663	0.663	0.663	0.663	**0.663**
HOF5: Difference from HOF1 (m^3s^{-1})	-6.790	-6.790	-6.790	-6.790	**-6.790**
HOF5: Volume to supply (Ml)	21295.96	19964.79	46794.33	23119.95	**27793.76**
HOF5: Difference from HOF1 (Ml)	+18186.34	+18186.33	+18186.34	+18186.34	**+18186.34**

September

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	7.501	7.856	11.438	11.433	9.557
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	7.453	7.453	7.453	7.453	7.453
HOF1: Flow to river (m^{3}s^{-1})	7.453	7.453	7.453	7.453	7.453
HOF1: Volume to supply (Ml)	124.42	1044.58	10329.12	10316.16	5453.57
HOF2: Gauged Month Q95 (m^{3}s^{-1})	7.070	7.070	7.070	7.070	7.070
HOF2: Flow to river (m^{3}s^{-1})	7.070	7.070	7.070	7.070	7.070
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.383	-0.383	-0.383	-0.383	-0.383
HOF2: Volume to supply (Ml)	1117.15	2037.31	11321.86	11308.90	6446.31
HOF2: Difference from HOF1 (Ml)	+992.73	+992.73	+992.74	+992.74	+992.74
HOF3: Gauged Month Q97 (m^{3}s^{-1})	6.880	6.880	6.880	6.880	6.880
HOF3: Flow to river (m^{3}s^{-1})	6.880	6.880	6.880	6.880	6.880
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.573	-0.573	-0.573	-0.573	-0.573
HOF3: Volume to supply (Ml)	1609.63	2529.79	11814.34	11801.38	6938.79
HOF3: Difference from HOF1 (Ml)	+1485.21	+1485.21	+1485.22	+1485.22	+1485.22
HOF4: Natural Month Q95 (m^{3}s^{-1})	0.914	0.914	0.914	0.914	0.914
HOF4: Flow to river (m^{3}s^{-1})	0.914	0.914	0.914	0.914	0.914
HOF4: Difference from HOF1 (m^{3}s^{-1})	-6.539	-6.539	-6.539	-6.539	-6.539
HOF4: Volume to supply (Ml)	17073.50	17993.66	27278.21	27265.25	22402.66
HOF4: Difference from HOF1 (Ml)	+16949.08	+16949.08	+16949.09	+16949.09	+16949.09
HOF5: Natural Month Q97 (m^{3}s^{-1})	0.808	0.808	0.808	0.808	0.808
HOF5: Flow to river (m^{3}s^{-1})	0.808	0.808	0.808	0.808	0.808
HOF5: Difference from HOF1 (m^{3}s^{-1})	-6.645	-6.645	-6.645	-6.645	-6.645
HOF5: Volume to supply (Ml)	17348.26	18268.42	27552.96	27540.00	22677.41
HOF5: Difference from HOF1 (Ml)	+17223.84	+17223.84	+17223.84	+17223.84	+17223.84

October

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	7.796	10.898	19.667	14.316	13.169
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	7.453	7.453	7.453	7.453	7.453
HOF1: Flow to river (m^{3}s^{-1})	7.453	7.453	7.453	7.453	7.453
HOF1: Volume to supply (Ml)	918.69	9227.09	32713.98	18381.86	15310.41
HOF2: Gauged Month Q95 (m^{3}s^{-1})	7.280	7.280	7.280	7.280	7.280
HOF2: Flow to river (m^{3}s^{-1})	7.280	7.280	7.280	7.280	7.280
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.173	-0.173	-0.173	-0.173	-0.173
HOF2: Volume to supply (Ml)	1382.05	9690.45	33177.34	18845.22	15773.77
HOF2: Difference from HOF1 (Ml)	+463.36	+463.36	+463.36	+463.36	+463.36
HOF3: Gauged Month Q90 (m^{3}s^{-1})	7.560	7.560	7.560	7.560	7.560
HOF3: Flow to river (m^{3}s^{-1})	7.560	7.560	7.560	7.560	7.560
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.107	+0.107	+0.107	+0.107	+0.107
HOF3: Volume to supply (Ml)	632.10	8940.50	32427.39	18095.27	15023.82
HOF3: Difference from HOF1 (Ml)	-286.59	-286.59	-286.59	-286.59	-286.59
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.252	1.252	1.252	1.252	1.252
HOF4: Flow to river (m^{3}s^{-1})	1.252	1.252	1.252	1.252	1.252
HOF4: Difference from HOF1 (m^{3}s^{-1})	-6.201	-6.201	-6.201	-6.201	-6.201
HOF4: Volume to supply (Ml)	17527.45	25835.85	49322.74	34990.62	31919.17
HOF4: Difference from HOF1 (Ml)	+16608.76	+16608.76	+16608.76	+16608.76	+16608.76
HOF5: Natural Month Q90 (m^{3}s^{-1})	1.418	1.418	1.418	1.418	1.418
HOF5: Flow to river (m^{3}s^{-1})	1.418	1.418	1.418	1.418	1.418
HOF5: Difference from HOF1 (m^{3}s^{-1})	-6.035	-6.035	-6.035	-6.035	-6.035
HOF5: Volume to supply (Ml)	17082.84	25391.23	48878.12	34546.00	31474.55
HOF5: Difference from HOF1 (Ml)	+16164.15	+16164.14	+16164.14	+16164.14	+16164.14

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	8.580	10.089	15.214	13.736	**11.905**
HOF1: Gauged Annual Q95 (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Flow to river (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	2921.18	6832.51	20116.51	16285.54	**11538.94**
HOF2: Gauged Month Q95 (m^3s^{-1})	7.880	7.880	7.880	7.880	**7.880**
HOF2: Flow to river (m^3s^{-1})	7.880	7.880	7.880	7.880	**7.880**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.427	+0.427	+0.427	+0.427	**+0.427**
HOF2: Volume to supply (Ml)	1814.40	5725.73	19009.73	15178.75	**10432.15**
HOF2: Difference from HOF1 (Ml)	-1106.78	-1106.78	-1106.78	-1106.79	**-1106.78**
HOF3: Gauged Month Q90 (m^3s^{-1})	8.331	8.331	8.331	8.331	**8.331**
HOF3: Flow to river (m^3s^{-1})	8.331	8.331	8.331	8.331	**8.331**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.878	+0.878	+0.878	+0.878	**+0.878**
HOF3: Volume to supply (Ml)	645.41	4556.74	17840.74	14009.76	**9263.16**
HOF3: Difference from HOF1 (Ml)	-2275.77	-2275.77	-2275.77	-2275.78	**-2275.77**
HOF4: Natural Month Q95 (m^3s^{-1})	1.699	1.699	1.699	1.699	**1.699**
HOF4: Flow to river (m^3s^{-1})	1.699	1.699	1.699	1.699	**1.699**
HOF4: Difference from HOF1 (m^3s^{-1})	-5.754	-5.754	-5.754	-5.754	**-5.754**
HOF4: Volume to supply (Ml)	17835.55	21746.88	35030.88	31199.90	**26453.30**
HOF4: Difference from HOF1 (Ml)	+14914.37	+14914.37	+14914.37	+14914.36	**+14914.37**
HOF5: Natural Month Q90 (m^3s^{-1})	2.080	2.080	2.080	2.080	**2.080**
HOF5: Flow to river (m^3s^{-1})	2.080	2.080	2.080	2.080	**2.080**
HOF5: Difference from HOF1 (m^3s^{-1})	-5.373	-5.373	-5.373	-5.373	**-5.373**
HOF5: Volume to supply (Ml)	16848.00	20759.33	34043.33	30212.35	**25465.75**
HOF5: Difference from HOF1 (Ml)	+13926.82	+13926.82	+13926.82	+13926.81	**+13926.82**

Appendix 6.9d: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Bedford Ouse at Bedford

May

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	3.103	4.347	4.554	5.361	**4.341**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Volume to supply (Ml)	2252.53	5584.46	6138.89	8300.36	**5569.06**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	3.300	3.300	3.300	3.300	**3.300**
HOF2: Flow to river (m^{3}s^{-1})	3.103	3.300	3.300	3.300	**3.251**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.841	+1.038	+1.038	+1.038	**+0.989**
HOF2: Volume to supply (Ml)	0.00	2804.28	3358.71	5520.18	**2920.79**
HOF2: Difference from HOF1 (Ml)	-2252.53	-2780.18	-2780.18	-2780.18	**-2648.27**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	3.600	3.600	3.600	3.600	**3.600**
HOF3: Flow to river (m^{3}s^{-1})	3.103	3.600	3.600	3.600	**3.476**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.841	+1.338	+1.338	+1.338	**+1.214**
HOF3: Volume to supply (Ml)	0.00	2000.76	255.19	4716.66	**1743.15**
HOF3: Difference from HOF1 (Ml)	-2252.53	-3583.70	-5883.70	-3583.70	**-3825.91**
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.597	1.597	1.597	1.597	**1.597**
HOF4: Flow to river (m^{3}s^{-1})	1.597	1.597	1.597	1.597	**1.597**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.665	-0.665	-0.665	-0.665	**-0.665**
HOF4: Volume to supply (Ml)	4033.67	7365.60	7920.03	10081.50	**7350.20**
HOF4: Difference from HOF1 (Ml)	+1781.14	+1781.14	+1781.14	+1781.14	**+1781.14**
HOF5: Natural Month Q90 (m^{3}s^{-1})	1.862	1.862	1.862	1.862	**1.862**
HOF5: Flow to river (m^{3}s^{-1})	1.862	1.862	1.862	1.862	**1.862**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-0.400	-0.400	-0.400	-0.400	**-0.400**
HOF5: Volume to supply (Ml)	+3323.89	+6655.82	+7210.25	+9371.72	**+6640.42**
HOF5: Difference from HOF1 (Ml)	1071.36	1071.36	1071.36	1071.36	**1071.36**

June

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	2.800	4.156	3.110	4.687	**3.688**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Volume to supply (Ml)	1394.50	4909.25	2198.02	6285.60	**3696.84**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	2.560	2.560	2.560	2.560	**2.560**
HOF2: Flow to river (m^{3}s^{-1})	2.560	2.560	2.560	2.560	**2.560**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.298	+0.298	+0.298	+0.298	**+0.298**
HOF2: Volume to supply (Ml)	622.08	4136.83	1425.60	5513.18	**2924.42**
HOF2: Difference from HOF1 (Ml)	-772.42	-772.42	-772.42	-772.42	**-772.42**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	2.900	2.900	2.900	2.900	**2.900**
HOF3: Flow to river (m^{3}s^{-1})	2.800	2.900	2.900	2.900	**2.875**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.538	+0.638	+0.638	+0.638	**+0.613**
HOF3: Volume to supply (Ml)	0.00	3255.55	544.32	4631.90	**2107.94**
HOF3: Difference from HOF1 (Ml)	-1394.50	-1653.70	-1653.70	-1653.70	**-1588.90**
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.297	1.297	1.297	1.297	**1.297**
HOF4: Flow to river (m^{3}s^{-1})	1.297	1.297	1.297	1.297	**1.297**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.965	-0.965	-0.965	-0.965	**-0.965**
HOF4: Volume to supply (Ml)	3895.78	7410.53	4699.30	8786.88	**6198.12**
HOF4: Difference from HOF1 (Ml)	+2501.28	+2501.28	+2501.28	+2501.28	**+2501.28**
HOF5: Natural Month Q90 (m^{3}s^{-1})	1.523	1.523	1.523	1.523	**1.523**
HOF5: Flow to river (m^{3}s^{-1})	1.523	1.523	1.523	1.523	**1.523**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-0.739	-0.739	-0.739	-0.739	**-0.739**
HOF5: Volume to supply (Ml)	3309.98	6824.74	4113.50	8201.09	**5612.33**
HOF5: Difference from HOF1 (Ml)	+1915.48	+1915.49	+1915.48	+1915.49	**+1915.49**

July

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	2.113	2.911	2.684	4.813	**3.130**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^{3}s^{-1})	2.113	2.262	2.262	2.262	**2.225**
HOF1: Volume to supply (Ml)	0.00	1738.28	1130.28	6832.60	**2425.29**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	2.150	2.150	2.150	2.150	**2.150**
HOF2: Flow to river (m^{3}s^{-1})	2.113	2.150	2.150	2.150	**2.141**
HOF2: Difference from HOF1 (m^{3}s^{-1})	0.000	-0.112	-0.112	-0.112	**-0.084**
HOF2: Volume to supply (Ml)	0.00	2038.26	1430.27	7132.58	**2650.28**
HOF2: Difference from HOF1 (Ml)	0.00	+299.98	+299.99	+299.98	**+224.99**
HOF3: Gauged Month Q97 (m^{3}s^{-1})	1.900	1.900	1.900	1.900	**1.900**
HOF3: Flow to river (m^{3}s^{-1})	1.900	1.900	1.900	1.900	**1.900**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.213	-0.362	-0.362	-0.362	**-0.325**
HOF3: Volume to supply (Ml)	570.50	2707.86	2099.87	7802.18	**3295.10**
HOF3: Difference from HOF1 (Ml)	+570.50	+969.58	+969.59	+969.58	**+869.81**
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.003	1.003	1.003	1.003	**1.003**
HOF4: Flow to river (m^{3}s^{-1})	1.003	1.003	1.003	1.003	**1.003**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-1.110	-1.259	-1.259	-1.259	**-1.222**
HOF4: Volume to supply (Ml)	2973.02	5110.39	4502.39	10204.70	**5697.63**
HOF4: Difference from HOF1 (Ml)	+2973.02	+3372.11	+3372.11	+3372.10	**+3272.34**
HOF5: Natural Month Q97 (m^{3}s^{-1})	0.898	0.898	0.898	0.898	**0.898**
HOF5: Flow to river (m^{3}s^{-1})	0.898	0.898	0.898	0.898	**0.898**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-1.215	-1.364	-1.364	-1.364	**-1.327**
HOF5: Volume to supply (Ml)	3254.26	5391.62	4783.62	10485.94	**5978.86**
HOF5: Difference from HOF1 (Ml)	+3254.26	+3653.34	+3653.34	+3653.34	**+3553.57**

August

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	1.571	2.112	1.570	3.129	**2.096**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^{3}s^{-1})	1.571	2.112	1.570	2.262	**1.879**
HOF1: Volume to supply (Ml)	0.00	0.00	0.00	2322.17	**580.54**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	1.480	1.480	1.480	1.480	**1.480**
HOF2: Flow to river (m^{3}s^{-1})	1.480	1.480	1.480	1.480	**1.480**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.091	-0.632	-0.090	-0.782	**-0.399**
HOF2: Volume to supply (Ml)	243.73	1692.75	241.06	4416.68	**1648.56**
HOF2: Difference from HOF1 (Ml)	+243.73	+1692.75	+241.06	+2094.51	**+1068.01**
HOF3: Gauged Month Q97 (m^{3}s^{-1})	1.390	1.390	1.390	1.390	**1.390**
HOF3: Flow to river (m^{3}s^{-1})	1.390	1.390	1.390	1.390	**1.390**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.181	-0.722	-0.180	-0.872	**-0.489**
HOF3: Volume to supply (Ml)	484.79	1933.80	482.11	4657.74	**1889.61**
HOF3: Difference from HOF1 (Ml)	+484.79	+1933.80	+482.11	+2335.57	**+1309.07**
HOF4: Natural Month Q95 (m^{3}s^{-1})	0.881	0.881	0.881	0.881	**0.881**
HOF4: Flow to river (m^{3}s^{-1})	0.881	0.881	0.881	0.881	**0.881**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.690	-1.231	-0.689	-1.381	**-0.998**
HOF4: Volume to supply (Ml)	1848.10	3297.11	1845.42	6021.04	**3252.92**
HOF4: Difference from HOF1 (Ml)	+1848.10	+3297.11	+1845.42	+3698.87	**+2672.38**
HOF5: Natural Month Q97 (m^{3}s^{-1})	0.832	0.832	0.832	0.832	**0.832**
HOF5: Flow to river (m^{3}s^{-1})	0.832	0.832	0.832	0.832	**0.832**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-0.739	-1.280	-0.738	-1.430	**-1.047**
HOF5: Volume to supply (Ml)	1979.34	3428.35	1976.66	6152.28	**3384.16**
HOF5: Difference from HOF1 (Ml)	+1979.34	+3428.35	+1976.66	+3830.11	**+2803.62**

September

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	1.550	2.312	3.910	3.277	**2.762**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^{3}s^{-1})	1.550	2.262	2.262	2.262	**2.084**
HOF1: Volume to supply (Ml)	0.00	129.60	4271.62	2630.88	**1758.03**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	1.700	1.700	1.700	1.700	**1.700**
HOF2: Flow to river (m^{3}s^{-1})	1.550	1.700	1.700	1.700	**1.663**
HOF2: Difference from HOF1 (m^{3}s^{-1})	0.000	-0.562	-0.562	-0.562	**-0.422**
HOF2: Volume to supply (Ml)	0.00	1586.30	5728.32	4087.58	**2850.55**
HOF2: Difference from HOF1 (Ml)	0.00	+1456.70	+1456.70	+1456.70	**+1092.53**
HOF3: Gauged Month Q97 (m^{3}s^{-1})	1.400	1.400	1.400	1.400	**1.400**
HOF3: Flow to river (m^{3}s^{-1})	1.400	1.400	1.400	1.400	**1.400**
HOF3: Difference from HOF1 (m^{3}s^{-1})	-0.150	-0.862	-0.862	-0.862	**-0.684**
HOF3: Volume to supply (Ml)	388.80	2363.90	6505.92	4865.18	**3530.95**
HOF3: Difference from HOF1 (Ml)	+388.80	+2234.30	+2234.30	+2234.30	**+1772.93**
HOF4: Natural Month Q95 (m^{3}s^{-1})	0.890	0.890	0.890	0.890	**0.890**
HOF4: Flow to river (m^{3}s^{-1})	0.890	0.890	0.890	0.890	**0.890**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.660	-1.372	-1.372	-1.372	**-1.194**
HOF4: Volume to supply (Ml)	1710.72	3685.82	7827.84	6187.10	**4852.87**
HOF4: Difference from HOF1 (Ml)	+1710.72	+3556.22	+3556.22	+3556.22	**+3094.85**
HOF5: Natural Month Q97 (m^{3}s^{-1})	0.843	0.843	0.843	0.843	**0.843**
HOF5: Flow to river (m^{3}s^{-1})	0.843	0.843	0.843	0.843	**0.843**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-0.707	-1.419	-1.419	-1.419	**-1.241**
HOF5: Volume to supply (Ml)	1832.54	3807.65	7949.66	6308.93	**4974.70**
HOF5: Difference from HOF1 (Ml)	+1832.54	+3678.05	+3678.04	+3678.05	**+3216.67**

October

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^{3}s^{-1})	2.858	3.487	2.760	3.294	**3.100**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Volume to supply (Ml)	1596.33	3281.04	1333.84	2764.11	**2243.83**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	2.200	2.200	2.200	2.200	**2.200**
HOF2: Flow to river (m^{3}s^{-1})	2.200	2.200	2.200	2.200	**2.200**
HOF2: Difference from HOF1 (m^{3}s^{-1})	-0.062	-0.062	-0.062	-0.062	**-0.062**
HOF2: Volume to supply (Ml)	1762.39	3447.10	1499.90	2930.17	**2409.89**
HOF2: Difference from HOF1 (Ml)	+166.06	+166.06	+166.06	+166.06	**+166.06**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	2.350	2.350	2.350	2.350	**2.350**
HOF3: Flow to river (m^{3}s^{-1})	2.350	2.350	2.350	2.350	**2.350**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.088	+0.088	+0.088	+0.088	**+0.088**
HOF3: Volume to supply (Ml)	1360.63	3045.34	1098.14	2528.41	**2008.13**
HOF3: Difference from HOF1 (Ml)	-235.70	-235.70	-235.70	-235.70	**-235.70**
HOF4: Natural Month Q95 (m^{3}s^{-1})	1.015	1.015	1.015	1.015	**1.015**
HOF4: Flow to river (m^{3}s^{-1})	1.015	1.015	1.015	1.015	**1.015**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-1.247	-1.247	-1.247	-1.247	**-1.247**
HOF4: Volume to supply (Ml)	4936.29	6621.00	4673.81	6104.07	**5583.79**
HOF4: Difference from HOF1 (Ml)	+3339.96	+3339.96	+3339.97	+3339.96	**+3339.96**
HOF5: Natural Month Q90 (m^{3}s^{-1})	1.133	1.133	1.133	1.133	**1.133**
HOF5: Flow to river (m^{3}s^{-1})	1.133	1.133	1.133	1.133	**1.133**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-1.129	-1.129	-1.129	-1.129	**-1.129**
HOF5: Volume to supply (Ml)	4620.24	6304.95	4357.76	5788.02	**5267.74**
HOF5: Difference from HOF1 (Ml)	+3023.91	+3023.91	+3023.92	+3023.91	**+3023.91**

November

Dry Year Rank	**1**	**2**	**3**	**4**	**Average**
Monthly daily mean flow (m^3s^{-1})	2.757	6.700	4.871	9.677	**6.001**
HOF1: Gauged Annual Q95 (m^3s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Flow to river (m^3s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Volume to supply (Ml)	1283.04	11503.30	6762.53	19219.68	**9692.14**
HOF2: Gauged Month Q95 (m^3s^{-1})	2.650	2.650	2.650	2.650	**2.650**
HOF2: Flow to river (m^3s^{-1})	2.650	2.650	2.650	2.650	**2.650**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.388	+0.388	+0.388	+0.388	**+0.388**
HOF2: Volume to supply (Ml)	277.34	10497.60	5756.83	18213.98	**8686.44**
HOF2: Difference from HOF1 (Ml)	-1005.70	-1005.70	-1005.70	-1005.70	**-1005.70**
HOF3: Gauged Month Q90 (m^3s^{-1})	3.300	3.300	3.300	3.300	**3.300**
HOF3: Flow to river (m^3s^{-1})	2.757	3.300	3.300	3.300	**3.164**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.495	+1.038	+1.038	+1.038	**+0.902**
HOF3: Volume to supply (Ml)	0.00	8812.80	4072.03	16529.18	**7353.50**
HOF3: Difference from HOF1 (Ml)	-1283.04	-2690.50	-2690.50	-2690.50	**-2338.64**
HOF4: Natural Month Q95 (m^3s^{-1})	1.245	1.245	1.245	1.245	**1.245**
HOF4: Flow to river (m^3s^{-1})	1.245	1.245	1.245	1.245	**1.245**
HOF4: Difference from HOF1 (m^3s^{-1})	-1.017	-1.017	-1.017	-1.017	**-1.017**
HOF4: Volume to supply (Ml)	3919.10	14139.36	9398.59	21855.74	**12328.20**
HOF4: Difference from HOF1 (Ml)	+2636.06	+2636.06	+2636.06	+2636.06	**+2636.06**
HOF5: Natural Month Q90 (m^3s^{-1})	1.435	1.435	1.435	1.435	**1.435**
HOF5: Flow to river (m^3s^{-1})	1.435	1.435	1.435	1.435	**1.435**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.827	-0.827	-0.827	-0.827	**-0.827**
HOF5: Volume to supply (Ml)	3426.62	13646.88	8906.11	21363.26	**11835.72**
HOF5: Difference from HOF1 (Ml)	+2143.58	+2143.58	+2143.58	+2143.58	**+2143.58**

Appendix 6.9e: Application of alternative flow management scenarios during the four driest years in the 25-year record: River Derwent at Yorkshire Bridge

May

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.958	0.601	0.682	0.468	**0.677**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Volume to supply (Ml)	1315.09	358.91	575.86	2.68	**563.14**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.437	0.437	0.437	0.437	**0.437**
HOF2: Flow to river (m^3s^{-1})	0.437	0.437	0.437	0.437	**0.437**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.030	-0.030	-0.030	-0.030	**-0.030**
HOF2: Volume to supply (Ml)	1395.45	439.26	656.21	83.03	**643.49**
HOF2: Difference from HOF1 (Ml)	+80.36	+80.35	+80.35	+80.35	**+80.35**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.474	0.474	0.474	0.474	**0.474**
HOF3: Flow to river (m^3s^{-1})	0.474	0.474	0.474	0.468	**0.473**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.007	+0.007	+0.007	+0.001	**+0.005**
HOF3: Volume to supply (Ml)	1296.35	340.16	557.11	0.00	**548.41**
HOF3: Difference from HOF1 (Ml)	-18.74	-18.75	-18.75	-2.68	**-14.73**
HOF4: Natural Month Q95 (m^3s^{-1})	0.446	0.446	0.446	0.446	**0.446**
HOF4: Flow to river (m^3s^{-1})	0.446	0.446	0.446	0.446	**0.446**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.021	-0.021	-0.021	-0.021	**-0.021**
HOF4: Volume to supply (Ml)	1371.34	415.15	632.10	58.92	**619.38**
HOF4: Difference from HOF1 (Ml)	+56.25	+56.24	+56.24	+56.24	**+56.24**
HOF5: Natural Month Q90 (m^3s^{-1})	0.586	0.586	0.586	0.586	**0.586**
HOF5: Flow to river (m^3s^{-1})	0.586	0.586	0.586	0.468	**0.557**
HOF5: Difference from HOF1 (m^3s^{-1})	+0.119	+0.119	+0.119	+0.001	**+0.090**
HOF5: Volume to supply (Ml)	996.36	40.18	257.13	0.00	**323.42**
HOF5: Difference from HOF1 (Ml)	-318.73	-318.73	-318.73	-2.68	**-239.72**

June

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.750	0.448	0.679	0.418	**0.574**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^3s^{-1})	0.467	0.448	0.467	0.418	**0.450**
HOF1: Volume to supply (Ml)	733.54	0.00	549.50	0.00	**320.76**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.419	0.419	0.419	0.419	**0.419**
HOF2: Flow to river (m^3s^{-1})	0.419	0.419	0.419	0.418	**0.419**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.048	-0.029	-0.048	0.000	**-0.031**
HOF2: Volume to supply (Ml)	857.95	75.17	673.92	0.00	**401.76**
HOF2: Difference from HOF1 (Ml)	+124.41	+75.17	+124.42	+0.00	**+81.00**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.448	0.448	0.448	0.448	**0.448**
HOF3: Flow to river (m^3s^{-1})	0.448	0.448	0.448	0.418	**0.441**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.019	0.000	-0.019	0.000	**-0.010**
HOF3: Volume to supply (Ml)	782.78	0.00	598.75	0.00	**345.38**
HOF3: Difference from HOF1 (Ml)	+49.24	0.00	+49.25	0.00	**+24.62**
HOF4: Natural Month Q95 (m^3s^{-1})	0.363	0.363	0.363	0.363	**0.363**
HOF4: Flow to river (m^3s^{-1})	0.363	0.363	0.363	0.363	**0.363**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.104	-0.085	-0.104	-0.055	**-0.087**
HOF4: Volume to supply (Ml)	1003.10	220.32	819.07	142.56	**546.26**
HOF4: Difference from HOF1 (Ml)	+269.56	+220.32	+269.57	+142.56	**+225.50**
HOF5: Natural Month Q90 (m^3s^{-1})	0.438	0.438	0.438	0.438	**0.438**
HOF5: Flow to river (m^3s^{-1})	0.438	0.438	0.438	0.418	**0.433**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.029	-0.010	-0.029	0.000	**-0.017**
HOF5: Volume to supply (Ml)	808.70	25.92	624.67	0.00	**364.82**
HOF5: Difference from HOF1 (Ml)	+75.16	+25.92	+75.17	+0.00	**+44.06**

July

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.401	0.451	0.694	0.640	**0.547**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^3s^{-1})	0.401	0.451	0.467	0.467	**0.447**
HOF1: Volume to supply (Ml)	0.00	0.00	608.00	463.36	**267.84**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.415	0.415	0.415	0.415	**0.415**
HOF2: Flow to river (m^3s^{-1})	0.401	0.415	0.415	0.415	**0.412**
HOF2: Difference from HOF1 (m^3s^{-1})	0.000	-0.036	-0.052	-0.052	**-0.035**
HOF2: Volume to supply (Ml)	0.00	96.42	747.27	602.64	**361.58**
HOF2: Difference from HOF1 (Ml)	0.00	+96.42	+139.27	+139.28	**+93.74**
HOF3: Gauged Month Q97 (m^3s^{-1})	0.412	0.412	0.412	0.412	**0.412**
HOF3: Flow to river (m^3s^{-1})	0.401	0.412	0.412	0.412	**0.409**
HOF3: Difference from HOF1 (m^3s^{-1})	0.000	-0.039	-0.055	-0.055	**-0.037**
HOF3: Volume to supply (Ml)	0.00	104.46	755.31	610.68	**367.613**
HOF3: Difference from HOF1 (Ml)	0.00	+104.46	+147.31	+147.32	**+99.77**
HOF4: Natural Month Q95 (m^3s^{-1})	0.271	0.271	0.271	0.271	**0.271**
HOF4: Flow to river (m^3s^{-1})	0.271	0.271	0.271	0.271	**0.271**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.130	-0.180	-0.196	-0.196	**-0.176**
HOF4: Volume to supply (Ml)	348.19	482.11	1132.96	988.33	**737.90**
HOF4: Difference from HOF1 (Ml)	+348.19	+482.11	+524.96	+524.97	**+470.06**
HOF5: Natural Month Q97 (m^3s^{-1})	0.235	0.235	0.235	0.235	**0.235**
HOF5: Flow to river (m^3s^{-1})	0.235	0.235	0.235	0.235	**0.235**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.166	-0.216	-0.232	-0.232	**-0.2115**
HOF5: Volume to supply (Ml)	444.61	578.53	1229.39	1084.75	**834.32**
HOF5: Difference from HOF1 (Ml)	+444.61	+578.53	+621.39	+621.39	**+566.48**

August

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	0.535	0.620	0.699	0.822	**0.669**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Volume to supply (Ml)	182.13	409.80	621.39	950.83	**541.04**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.453	0.453	0.453	0.453	**0.453**
HOF2: Flow to river (m^3s^{-1})	0.453	0.453	0.453	0.453	**0.453**
HOF2: Difference from HOF1 (m^3s^{-1})	-0.014	-0.014	-0.014	-0.014	**-0.014**
HOF2: Volume to supply (Ml)	219.63	447.29	658.89	988.33	**578.54**
HOF2: Difference from HOF1 (Ml)	+37.50	+37.49	+37.50	+37.50	**+37.50**
HOF3: Gauged Month Q97 (m^3s^{-1})	0.430	0.430	0.430	0.430	**0.430**
HOF3: Flow to river (m^3s^{-1})	0.430	0.430	0.430	0.430	**0.430**
HOF3: Difference from HOF1 (m^3s^{-1})	-0.037	-0.037	-0.037	-0.037	**-0.037**
HOF3: Volume to supply (Ml)	281.23	508.90	720.49	1049.93	**640.14**
HOF3: Difference from HOF1 (Ml)	+99.10	+99.10	+99.10	+99.10	**+99.10**
HOF4: Natural Month Q95 (m^3s^{-1})	0.299	0.299	0.299	0.299	**0.299**
HOF4: Flow to river (m^3s^{-1})	0.299	0.299	0.299	0.299	**0.299**
HOF4: Difference from HOF1 (m^3s^{-1})	-0.168	-0.168	-0.168	-0.168	**-0.168**
HOF4: Volume to supply (Ml)	632.10	859.77	1071.36	1400.80	**991.01**
HOF4: Difference from HOF1 (Ml)	+449.97	+449.97	+449.97	+449.97	**+449.97**
HOF5: Natural Month Q97 (m^3s^{-1})	0.259	0.259	0.259	0.259	**0.259**
HOF5: Flow to river (m^3s^{-1})	0.259	0.259	0.259	0.259	**0.259**
HOF5: Difference from HOF1 (m^3s^{-1})	-0.208	-0.208	-0.208	-0.208	**-0.208**
HOF5: Volume to supply (Ml)	739.24	966.90	1178.50	1507.94	**1098.15**
HOF5: Difference from HOF1 (Ml)	+557.11	+557.10	+557.11	+557.11	**+557.11**

September

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	1.700	0.642	0.690	0.876	**0.977**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^{3}s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Volume to supply (Ml)	3195.94	453.60	578.02	1060.13	**1321.92**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	0.640	0.640	0.640	0.640	**0.640**
HOF2: Flow to river (m^{3}s^{-1})	0.640	0.640	0.640	0.640	**0.640**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.173	+0.173	+0.173	+0.173	**+0.173**
HOF2: Volume to supply (Ml)	2747.52	5.18	129.60	611.71	**873.50**
HOF2: Difference from HOF1 (Ml)	-448.42	-448.42	-448.42	-448.42	**-448.42**
HOF3: Gauged Month Q97 (m^{3}s^{-1})	0.632	0.632	0.632	0.632	**0.632**
HOF3: Flow to river (m^{3}s^{-1})	0.632	0.632	0.632	0.632	**0.632**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.165	+0.165	+0.165	+0.165	**+0.165**
HOF3: Volume to supply (Ml)	2768.26	25.92	150.34	632.45	**894.24**
HOF3: Difference from HOF1 (Ml)	-427.68	-427.68	-427.68	-427.68	**-427.68**
HOF4: Natural Month Q95 (m^{3}s^{-1})	0.345	0.345	0.345	0.345	**0.345**
HOF4: Flow to river (m^{3}s^{-1})	0.345	0.345	0.345	0.345	**0.345**
HOF4: Difference from HOF1 (m^{3}s^{-1})	-0.122	-0.122	-0.122	-0.122	**-0.122**
HOF4: Volume to supply (Ml)	3512.16	769.82	894.24	1376.35	**1638.14**
HOF4: Difference from HOF1 (Ml)	+316.22	+316.22	+316.22	+316.22	**+316.22**
HOF5: Natural Month Q97 (m^{3}s^{-1})	0.309	0.309	0.309	0.309	**0.309**
HOF5: Flow to river (m^{3}s^{-1})	0.309	0.309	0.309	0.309	**0.309**
HOF5: Difference from HOF1 (m^{3}s^{-1})	-0.158	-0.158	-0.158	-0.158	**-0.158**
HOF5: Volume to supply (Ml)	3605.47	863.14	987.55	1469.66	**1731.46**
HOF5: Difference from HOF1 (Ml)	+409.53	+409.54	+409.53	+409.53	**+409.53**

October

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^{3}s^{-1})	2.387	0.657	0.682	0.683	**1.102**
HOF1: Gauged Annual Q95 (m^{3}s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^{3}s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Volume to supply (Ml)	5142.53	508.90	575.86	578.53	**1701.46**
HOF2: Gauged Month Q95 (m^{3}s^{-1})	0.627	0.627	0.627	0.627	**0.627**
HOF2: Flow to river (m^{3}s^{-1})	0.627	0.627	0.627	0.627	**0.627**
HOF2: Difference from HOF1 (m^{3}s^{-1})	+0.160	+0.160	+0.160	+0.160	**+0.160**
HOF2: Volume to supply (Ml)	4713.98	80.35	147.31	149.99	**1272.91**
HOF2: Difference from HOF1 (Ml)	-428.55	-428.55	-428.55	-428.54	**-428.55**
HOF3: Gauged Month Q90 (m^{3}s^{-1})	0.665	0.665	0.665	0.665	**0.665**
HOF3: Flow to river (m^{3}s^{-1})	0.665	0.657	0.665	0.665	**0.663**
HOF3: Difference from HOF1 (m^{3}s^{-1})	+0.198	+0.190	+0.198	+0.198	**+0.196**
HOF3: Volume to supply (Ml)	4612.20	0.00	45.53	48.21	**1176.49**
HOF3: Difference from HOF1 (Ml)	-530.33	-508.90	-530.33	-530.32	**-524.97**
HOF4: Natural Month Q95 (m^{3}s^{-1})	0.516	0.516	0.516	0.516	**0.516**
HOF4: Flow to river (m^{3}s^{-1})	0.516	0.516	0.516	0.516	**0.516**
HOF4: Difference from HOF1 (m^{3}s^{-1})	+0.049	+0.049	+0.049	+0.049	**+0.049**
HOF4: Volume to supply (Ml)	5011.29	377.65	444.61	447.29	**1570.21**
HOF4: Difference from HOF1 (Ml)	-131.24	-131.25	-131.25	-131.24	**-131.25**
HOF5: Natural Month Q90 (m^{3}s^{-1})	0.704	0.704	0.704	0.704	**0.704**
HOF5: Flow to river (m^{3}s^{-1})	0.704	0.657	0.682	0.683	**0.682**
HOF5: Difference from HOF1 (m^{3}s^{-1})	+0.237	+0.190	+0.215	+0.216	**+0.215**
HOF5: Volume to supply (Ml)	4507.75	0.00	0.00	0.00	**1126.94**
HOF5: Difference from HOF1 (Ml)	-634.78	-508.90	-575.86	-578.53	**-574.52**

November

Dry Year Rank	1	2	3	4	Average
Monthly daily mean flow (m^3s^{-1})	2.688	3.489	0.694	0.522	**1.848**
HOF1: Gauged Annual Q95 (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Flow to river (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Volume to supply (Ml)	5756.83	7833.02	588.38	142.56	**3580.20**
HOF2: Gauged Month Q95 (m^3s^{-1})	0.570	0.570	0.570	0.570	**0.570**
HOF2: Flow to river (m^3s^{-1})	0.570	0.570	0.570	0.522	**0.558**
HOF2: Difference from HOF1 (m^3s^{-1})	+0.103	+0.103	+0.103	+0.055	**+0.091**
HOF2: Volume to supply (Ml)	5489.86	7566.05	321.41	0.00	**3344.33**
HOF2: Difference from HOF1 (Ml)	-266.97	-266.97	-266.97	-142.56	**-235.87**
HOF3: Gauged Month Q90 (m^3s^{-1})	0.622	0.622	0.622	0.622	**0.622**
HOF3: Flow to river (m^3s^{-1})	0.622	0.622	0.622	0.522	**0.597**
HOF3: Difference from HOF1 (m^3s^{-1})	+0.155	+0.155	+0.155	+0.055	**+0.130**
HOF3: Volume to supply (Ml)	5355.07	7431.26	186.62	0.00	**3243.24**
HOF3: Difference from HOF1 (Ml)	-401.76	-401.76	-401.76	-142.56	**-336.96**
HOF4: Natural Month Q95 (m^3s^{-1})	0.985	0.985	0.985	0.985	**0.985**
HOF4: Flow to river (m^3s^{-1})	0.985	0.985	0.694	0.522	**0.7965**
HOF4: Difference from HOF1 (m^3s^{-1})	+0.518	+0.518	+0.227	+0.055	**+0.3295**
HOF4: Volume to supply (Ml)	4414.18	6490.37	0.00	0.00	**2726.14**
HOF4: Difference from HOF1 (Ml)	-1342.65	-1342.65	-588.38	-142.56	**-854.06**
HOF5: Natural Month Q90 (m^3s^{-1})	1.335	1.335	1.335	1.335	**1.335**
HOF5: Flow to river (m^3s^{-1})	1.335	1.335	0.694	0.522	**0.972**
HOF5: Difference from HOF1 (m^3s^{-1})	+0.868	+0.868	+0.227	+0.055	**+0.505**
HOF5: Volume to supply (Ml)	3506.98	5583.17	0.00	0.00	**2272.54**
HOF5: Difference from HOF1 (Ml)	-2249.85	-2249.85	-588.38	-142.56	**-1307.66**

Appendix 6.10a: Change in water allocation during the four driest years – River Hiz at Arlesey (totals aggregated by season)

May and June

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.326	0.328	0.328	0.328	**0.327**
HOF1: Volume to supply (Ml)	119.23	350.26	651.29	805.77	**481.64**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.330	0.343	0.344	0.344	**0.340**
HOF2 % change from HOF1	1.2	4.6	4.7	4.7	**3.8**
HOF2: Volume to supply (Ml)	98.5	270.5	568.9	723.4	**415.35**
HOF2 % change from HOF1	-17.4	-22.8	-12.6	-10.2	**-13.8**
HOF3: Gauged Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.349	0.370	0.393	0.393	**0.376**
HOF3 % change from HOF1	7.1	12.8	19.8	19.8	**14.9**
HOF3: Volume to supply (Ml)	0.00	125.88	307.67	462.15	**223.93**
HOF3 % change from HOF1	-100.0	-64.1	-52.8	-42.6	**-53.5**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.237	0.237	0.237	0.237	**0.237**
HOF4 % change from HOF1	-27.2	-27.7	-27.7	-27.7	**-27.6**
HOF4: Volume to supply (Ml)	584.23	828.66	1129.68	1284.16	**956.68**
HOF4 % change from HOF1	390.0	136.6	73.5	59.4	**98.6**
HOF5: Natural Month Q90 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	0.281	0.281	0.281	0.281	**0.281**
HOF5 % change from HOF1	-13.8	-14.5	-14.5	-14.5	**-14.3**
HOF5: Volume to supply (Ml)	355.88	600.31	901.33	1055.81	**728.33**
HOF5 % change from HOF1	198.5	71.4	38.4	31.0	**51.2**

July to September

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.294	0.313	0.328	0.328	**0.316**
HOF1: Volume to supply (Ml)	0.00	26.53	495.34	306.38	**207.06**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.288	0.290	0.297	0.297	**0.293**
HOF2 % change from HOF1	-2.0	-7.6	-9.5	-9.5	**-7.3**
HOF2: Volume to supply (Ml)	48.21	213.06	740.79	551.84	**388.48**
HOF2 % change from HOF1		703.1	49.6	80.1	**87.6**
HOF3: Gauged Month Q97 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.271	0.272	0.272	0.272	**0.271**
HOF3 % change from HOF1	-7.9	-13.3	-17.2	-17.2	**-14.1**
HOF3: Volume to supply (Ml)	187.49	355.88	942.53	753.58	**559.87**
HOF3 % change from HOF1		1241.4	90.3	146.0	**170.4**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.217	0.217	0.217	0.217	**0.217**
HOF4 % change from HOF1	-26.3	-30.9	-33.9	-33.9	**-31.4**
HOF4: Volume to supply (Ml)	617.41	793.59	1380.24	1191.28	**995.63**
HOF4 % change from HOF1		2891.3	178.6	288.8	**380.8**
HOF5: Natural Month Q97 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	0.196	0.196	0.196	0.196	**0.196**
HOF5 % change from HOF1	-33.4	-37.6	-40.3	-40.3	**-38.0**
HOF5: Volume to supply (Ml)	784.26	960.42	1547.07	1358.12	**1162.47**
HOF5 % change from HOF1		3520.1	212.3	343.3	**461.4**

October and November

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.311	0.328	0.303	0.328	**0.317**
HOF1: Volume to supply (Ml)	0.00	554.09	0.00	2262.22	**704.08**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.296	0.296	0.296	0.296	**0.296**
HOF2 % change from HOF1	-5.0	-9.9	-2.3	-9.9	**-6.9**
HOF2: Volume to supply (Ml)	81.62	762.36	36.29	2434.49	**828.69**
HOF2 % change from HOF1		37.6		7.6	**17.7**
HOF3: Gauged Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.311	0.341	0.303	0.341	**0.324**
HOF3 % change from HOF1	0.0	4.0	0.0	4.0	**2.0**
HOF3: Volume to supply (Ml)	0.00	485.83	0.00	2193.95	**669.95**
HOF3 % change from HOF1		-12.3		-3.0	**-4.8**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.249	0.249	0.249	0.249	**0.249**
HOF4 % change from HOF1	-19.9	-24.1	-17.7	-24.1	**-21.5**
HOF4: Volume to supply (Ml)	326.25	970.79	280.72	2678.92	**1064.17**
HOF4 % change from HOF1		75.2		18.4	**51.1**
HOF5: Natural Month Q90 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	0.261	0.261	0.261	0.261	**0.261**
HOF5 % change from HOF1	-16.1	-20.4	-13.7	-20.4	**-17.8**
HOF5: Volume to supply (Ml)	263.18	907.72	217.64	2615.85	**1001.10**
HOF5 % change from HOF1		63.8		15.6	**42.2**

Appendix 6.10b: Change in water allocation during the four driest years – River Trent at North Muskham (totals aggregated by season)

May and June

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	101992.9	39377.8	31667.2	71442.0	**61120.0**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	30.305	30.305	30.305	30.305	**30.305**
HOF2 % change from HOF1	10.8	10.8	10.8	10.8	**10.8**
HOF2: Volume to supply (Ml)	86188.6	23573.5	15862.9	55637.6	**45315.64**
HOF2 % change from HOF1	-15.5	-40.1	-49.9	-22.1	**-25.9**
HOF3: Gauged Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	32.160	31.956	31.929	32.160	**32.051**
HOF3 % change from HOF1	17.6	16.9	16.8	17.6	**17.2**
HOF3: Volume to supply (Ml)	76397.73	14878.08	7309.44	45846.78	**36108.01**
HOF3 % change from HOF1	-25.1	-62.2	-76.9	-35.8	**-40.9**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	16.71	16.71	16.71	16.71	**16.710**
HOF4 % change from HOF1	-38.9	-38.9	-38.9	-38.9	**-38.9**
HOF4: Volume to supply (Ml)	157821.95	95206.84	87496.24	127271.00	**116949.01**
HOF4 % change from HOF1	54.7	141.8	176.3	78.1	**91.3**
HOF5: Natural Month Q90 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	18.810	18.810	18.810	18.810	**18.810**
HOF5 % change from HOF1	-31.2	-31.2	-31.2	-31.2	**-31.2**
HOF5: Volume to supply (Ml)	146729.92	84114.81	76404.21	116178.97	**105856.98**
HOF5 % change from HOF1	43.9	113.6	141.3	62.6	**73.2**

July to September

HOF1: Gauged Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	27.339	26.974	27.126	27.339	**27.195**
HOF1: Volume to supply (Ml)	24332.57	10544.86	10729.67	66702.01	**28077.28**
HOF2: Gauged Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	24.623	24.623	24.623	24.623	**24.623**
HOF2 % change from HOF1	-9.9	-8.7	-9.2	-9.9	**-9.5**
HOF2: Volume to supply (Ml)	45922.03	29279.05	30662.84	88291.46	**48538.85**
HOF2 % change from HOF1	88.7	177.7	185.8	32.4	**72.9**
HOF3: Gauged Month Q97 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	23.847	23.847	23.847	23.847	**23.847**
HOF3 % change from HOF1	-12.8	-11.6	-12.1	-12.8	**-12.3**
HOF3: Volume to supply (Ml)	52101.36	35458.38	36842.17	94470.80	**54718.18**
HOF3 % change from HOF1	114.1	236.3	243.4	41.6	**94.9**
HOF4: Natural Month Q95 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	10.592	10.592	10.592	10.592	**10.592**
HOF4 % change from HOF1	-61.3	-60.7	-61.0	-61.3	**-61.1**
HOF4: Volume to supply (Ml)	157495.01	140852.04	142235.83	199864.45	**160111.83**
HOF4 % change from HOF1	547.3	1235.7	1225.6	199.6	**470.3**
HOF5: Natural Month Q97 (m^{3}s^{-1})					
HOF5: Flow to river (m^{3}s^{-1})	9.473	9.473	9.473	9.473	**9.473**
HOF5 % change from HOF1	-65.3	-64.9	-65.1	-65.3	**-65.2**
HOF5: Volume to supply (Ml)	166406.83	149763.86	151147.64	208776.27	**169023.65**
HOF5 % change from HOF1	583.9	1320.3	1308.7	213.0	**502.0**

October and November

HOF1: Gauged Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	27.339	27.339	27.339	27.339	**27.339**
HOF1: Volume to supply (Ml)	94981.68	134181.28	28514.94	47410.96	**76272.22**
HOF2: Gauged Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	28.715	28.715	28.715	28.715	**28.715**
HOF2 % change from HOF1	5.0	5.0	5.0	5.0	**5.0**
HOF2: Volume to supply (Ml)	87997.88	127197.48	21531.14	40427.16	**69288.42**
HOF2 % change from HOF1	-7.4	-5.2	-24.5	-14.7	**-9.2**
HOF3: Gauged Month Q90 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	32.095	32.095	31.034	32.095	**31.830**
HOF3 % change from HOF1	17.4	17.4	13.5	17.4	**16.4**
HOF3: Volume to supply (Ml)	70292.80	109492.39	9328.87	22722.07	**52959.03**
HOF3 % change from HOF1	-26.0	-18.4	-67.3	-52.1	**-30.6**
HOF4: Natural Month Q95 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	18.925	18.925	18.925	18.925	**18.925**
HOF4 % change from HOF1	-30.8	-30.8	-30.8	-30.8	**-30.8**
HOF4: Volume to supply (Ml)	139643.48	178843.08	73176.74	92072.76	**120934.02**
HOF4 % change from HOF1	47.0	33.3	156.6	94.2	**58.6**
HOF5: Natural Month Q90 (m^{3}s^{-1})					
HOF5: Flow to river (m^{3}s^{-1})	21.93	21.93	21.93	21.93	**21.930**
HOF5 % change from HOF1	-19.8	-19.8	-19.8	-19.8	**-19.8**
HOF5: Volume to supply (Ml)	123905.72	163105.32	57438.98	76335.00	**105196.26**
HOF5 % change from HOF1	30.5	21.6	101.4	61.0	**37.9**

Appendix 6.10c: Change in water allocation during the four driest years – River Tame at Lea Marston Lakes (totals aggregated by season)

May and June

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	10741.42	9044.95	21839.68	26290.57	**16979.16**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	7.660	7.660	7.660	7.660	**7.660**
HOF2 % change from HOF1	2.8	2.8	2.8	2.8	**2.8**
HOF2: Volume to supply (Ml)	9653.0	7956.6	20751.3	25202.2	**15890.78**
HOF2 % change from HOF1	-10.1	-12.0	-5.0	-4.1	**-6.4**
HOF3: Gauged Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	8.040	8.040	8.040	8.040	**8.040**
HOF3 % change from HOF1	7.9	7.9	7.9	7.9	**7.9**
HOF3: Volume to supply (Ml)	7644.24	5947.78	18742.49	23193.39	**13881.98**
HOF3 % change from HOF1	-28.8	-34.2	-14.2	-11.8	**-18.2**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	1.4465	1.4465	1.4465	1.4465	**1.447**
HOF4 % change from HOF1	-80.6	-80.6	-80.6	-80.6	**-80.6**
HOF4: Volume to supply (Ml)	42379.12	40682.65	53477.37	57928.27	**48616.85**
HOF4 % change from HOF1	294.5	349.8	144.9	120.3	**186.3**
HOF5: Natural Month Q90 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	1.645	1.645	1.645	1.645	**1.645**
HOF5 % change from HOF1	-77.9	-77.9	-77.9	-77.9	**-77.9**
HOF5: Volume to supply (Ml)	41331.69	39635.23	52429.94	56880.84	**47569.43**
HOF5 % change from HOF1	284.8	338.2	140.1	116.4	**180.2**

July to September

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	6699.89	4888.09	47159.80	16460.41	**18802.05**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	7.093	7.093	7.093	7.093	**7.093**
HOF2 % change from HOF1	-4.8	-4.8	-4.8	-4.8	**-4.8**
HOF2: Volume to supply (Ml)	9556.79	7744.98	50016.70	19317.32	**21658.95**
HOF2 % change from HOF1	42.6	58.4	6.1	17.4	**15.2**
HOF3: Gauged Month Q97 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	6.943	6.943	6.943	6.943	**6.943**
HOF3 % change from HOF1	-6.8	-6.8	-6.8	-6.8	**-6.8**
HOF3: Volume to supply (Ml)	10745.65	8933.84	51205.57	20506.18	**22847.81**
HOF3 % change from HOF1	60.4	82.8	8.6	24.6	**21.5**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.865	0.865	0.865	0.865	**0.865**
HOF4 % change from HOF1	-88.4	-88.4	-88.4	-88.4	**-88.4**
HOF4: Volume to supply (Ml)	59073.49	57261.68	99533.40	68834.02	**71175.65**
HOF4 % change from HOF1	781.7	1071.5	111.1	318.2	**278.6**
HOF5: Natural Month Q97 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	0.774	0.774	0.774	0.774	**0.774**
HOF5 % change from HOF1	-89.6	-89.6	-89.6	-89.6	**-89.6**
HOF5: Volume to supply (Ml)	59792.87	57981.05	100252.77	69553.38	**71895.02**
HOF5 % change from HOF1	792.4	1086.2	112.6	322.5	**282.4**

October and November

HOF1: Gauged Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	7.453	7.453	7.453	7.453	**7.453**
HOF1: Volume to supply (Ml)	3839.87	16059.60	52830.49	34667.40	**26849.34**
HOF2: Gauged Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	7.580	7.580	7.580	7.580	**7.580**
HOF2 % change from HOF1	1.7	1.7	1.7	1.7	**1.7**
HOF2: Volume to supply (Ml)	3196.45	15416.18	52187.07	34023.97	**26205.92**
HOF2 % change from HOF1	-16.8	-4.0	-1.2	-1.9	**-2.4**
HOF3: Gauged Month Q90 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	7.946	7.946	7.946	7.946	**7.946**
HOF3 % change from HOF1	6.6	6.6	6.6	6.6	**6.6**
HOF3: Volume to supply (Ml)	1277.51	13497.24	50268.13	32105.03	**24286.98**
HOF3 % change from HOF1	-66.7	-16.0	-4.9	-7.4	**-9.5**
HOF4: Natural Month Q95 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	1.476	1.476	1.476	1.476	**1.476**
HOF4 % change from HOF1	-80.2	-80.2	-80.2	-80.2	**-80.2**
HOF4: Volume to supply (Ml)	35363.00	47582.73	84353.62	66190.52	**58372.47**
HOF4 % change from HOF1	820.9	196.3	59.7	90.9	**117.4**
HOF5: Natural Month Q90 (m^{3}s^{-1})					
HOF5: Flow to river (m^{3}s^{-1})	1.749	1.749	1.749	1.749	**1.749**
HOF5 % change from HOF1	-76.5	-76.5	-76.5	-76.5	**-76.5**
HOF5: Volume to supply (Ml)	33930.84	46150.56	82921.45	64758.35	**56940.30**
HOF5 % change from HOF1	783.6	187.4	57.0	86.8	**112.1**

Appendix 6.10d: Change in water allocation during the four driest years – River Bedford Ouse at Bedford (totals aggregated by season)

May and June

HOF1: Gauged Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Volume to supply (Ml)	3647.03	10493.71	8336.91	14585.96	**9265.90**
HOF2: Gauged Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	2.832	2.930	2.930	2.930	**2.905**
HOF2 % change from HOF1	25.2	29.5	29.5	29.5	**28.4**
HOF2: Volume to supply (Ml)	622.1	6941.1	4784.3	11033.4	**5845.22**
HOF2 % change from HOF1	-82.9	-33.9	-42.6	-24.4	**-36.9**
HOF3: Gauged Month Q90 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	2.952	3.250	3.250	3.250	**3.175**
HOF3 % change from HOF1	30.5	43.7	43.7	43.7	**40.4**
HOF3: Volume to supply (Ml)	0.00	5256.31	799.51	9348.56	**3851.10**
HOF3 % change from HOF1	-100.0	-49.9	-90.4	-35.9	**-58.4**
HOF4: Natural Month Q95 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	1.447	1.447	1.447	1.447	**1.447**
HOF4 % change from HOF1	-36.0	-36.0	-36.0	-36.0	**-36.0**
HOF4: Volume to supply (Ml)	7929.45	14776.13	12619.33	18868.38	**13548.32**
HOF4 % change from HOF1	117.4	40.8	51.4	29.4	**46.2**
HOF5: Natural Month Q90 (m^{3}s^{-1})					
HOF5: Flow to river (m^{3}s^{-1})	1.693	1.693	1.693	1.693	**1.693**
HOF5 % change from HOF1	-25.2	-25.2	-25.2	-25.2	**-25.2**
HOF5: Volume to supply (Ml)	6633.87	13480.56	11323.75	17572.81	**12252.75**
HOF5 % change from HOF1	81.9	28.5	35.8	20.5	**32.2**

July to September

HOF1: Gauged Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	1.745	2.212	2.031	2.262	**2.063**
HOF1: Volume to supply (Ml)	0.00	1867.88	5401.90	11785.65	**4763.86**
HOF2: Gauged Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	1.714	1.777	1.777	1.777	**1.761**
HOF2 % change from HOF1	-1.7	-19.7	-12.5	-21.5	**-14.6**
HOF2: Volume to supply (Ml)	243.73	5317.31	7399.65	15636.84	**7149.38**
HOF2 % change from HOF1		184.7	37.0	32.7	**50.1**
HOF3: Gauged Month Q97 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	1.563	1.563	1.563	1.563	**1.563**
HOF3 % change from HOF1	-10.4	-29.3	-23.0	-30.9	**-24.2**
HOF3: Volume to supply (Ml)	1444.09	7005.56	9087.90	17325.10	**8715.66**
HOF3 % change from HOF1		275.1	68.2	47.0	**83.0**
HOF4: Natural Month Q95 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	0.925	0.925	0.925	0.925	**0.925**
HOF4 % change from HOF1	-47.0	-58.2	-54.5	-59.1	**-55.2**
HOF4: Volume to supply (Ml)	6531.84	12093.32	14175.65	22412.84	**13803.41**
HOF4 % change from HOF1		547.4	162.4	90.2	**189.8**
HOF5: Natural Month Q97 (m^{3}s^{-1})					
HOF5: Flow to river (m^{3}s^{-1})	0.858	0.858	0.858	0.858	**0.858**
HOF5 % change from HOF1	-50.8	-61.2	-57.8	-62.1	**-58.4**
HOF5: Volume to supply (Ml)	7066.14	12627.62	14709.94	22947.15	**14337.71**
HOF5 % change from HOF1		576.0	172.3	94.7	**201.0**

October and November

HOF1: Gauged Annual Q95 (m^{3}s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^{3}s^{-1})	2.262	2.262	2.262	2.262	**2.262**
HOF1: Volume to supply (Ml)	2879.37	14784.34	8096.37	21983.79	**11935.97**
HOF2: Gauged Month Q95 (m^{3}s^{-1})					
HOF2: Flow to river (m^{3}s^{-1})	2.425	2.425	2.425	2.425	**2.425**
HOF2 % change from HOF1	7.2	7.2	7.2	7.2	**7.2**
HOF2: Volume to supply (Ml)	2039.73	13944.70	7256.73	21144.15	**11096.33**
HOF2 % change from HOF1	-29.2	-5.7	-10.4	-3.8	**-7.0**
HOF3: Gauged Month Q90 (m^{3}s^{-1})					
HOF3: Flow to river (m^{3}s^{-1})	2.554	2.825	2.825	2.825	**2.757**
HOF3 % change from HOF1	12.9	24.9	24.9	24.9	**21.9**
HOF3: Volume to supply (Ml)	1360.63	11858.14	5170.17	19057.59	**9361.63**
HOF3 % change from HOF1	-52.7	-19.8	-36.1	-13.3	**-21.6**
HOF4: Natural Month Q95 (m^{3}s^{-1})					
HOF4: Flow to river (m^{3}s^{-1})	1.130	1.130	1.130	1.130	**1.130**
HOF4 % change from HOF1	-50.0	-50.0	-50.0	-50.0	**-50.0**
HOF4: Volume to supply (Ml)	8855.39	20760.36	14072.40	27959.81	**17911.99**
HOF4 % change from HOF1	207.5	40.4	73.8	27.2	**50.1**
HOF5: Natural Month Q90 (m^{3}s^{-1})					
HOF5: Flow to river (m^{3}s^{-1})	1.284	1.284	1.284	1.284	**1.284**
HOF5 % change from HOF1	-43.2	-43.2	-43.2	-43.2	**-43.2**
HOF5: Volume to supply (Ml)	8046.86	19951.83	13263.87	27151.28	**17103.46**
HOF5 % change from HOF1	179.5	35.0	63.8	23.5	**43.3**

Appendix 6.10e: Change in water allocation during the four driest years – River Derwent at Yorkshire Bridge (totals aggregated by season)

May and June

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.467	0.458	0.467	0.443	**0.459**
HOF1: Volume to supply (Ml)	2048.63	358.91	1125.36	2.68	**883.90**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.428	0.428	0.428	0.428	**0.428**
HOF2 % change from HOF1	-8.4	-6.4	-8.4	-3.4	**-6.7**
HOF2: Volume to supply (Ml)	2253.4	514.4	1330.1	83.0	**1045.25**
HOF2 % change from HOF1	10.0	43.3	18.2	2998.1	**18.3**
HOF3: Gauged Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.461	0.461	0.461	0.443	**0.457**
HOF3 % change from HOF1	-1.3	0.8	-1.3	0.1	**-0.4**
HOF3: Volume to supply (Ml)	2079.13	340.16	1155.86	0.00	**893.79**
HOF3 % change from HOF1	1.5	-5.2	2.7	-100.0	**1.1**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.4045	0.4045	0.4045	0.4045	**0.405**
HOF4 % change from HOF1	-13.4	-11.6	-13.4	-8.6	**-11.8**
HOF4: Volume to supply (Ml)	2374.44	635.47	1451.17	201.48	**1165.64**
HOF4 % change from HOF1	15.9	77.1	29.0	7417.9	**31.9**
HOF5: Natural Month Q90 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	0.512	0.512	0.512	0.443	**0.495**
HOF5 % change from HOF1	9.6	11.9	9.6	0.1	**7.9**
HOF5: Volume to supply (Ml)	1805.06	66.10	881.80	0.00	**688.24**
HOF5 % change from HOF1	-11.9	-81.6	-21.6	-100.0	**-22.1**

July to September

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.445	0.462	0.467	0.467	**0.460**
HOF1: Volume to supply (Ml)	3378.07	863.40	1807.41	2474.32	**2130.80**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.498	0.503	0.503	0.503	**0.502**
HOF2 % change from HOF1	11.9	8.9	7.6	7.6	**9.0**
HOF2: Volume to supply (Ml)	2967.15	548.89	1535.76	2202.68	**1813.62**
HOF2 % change from HOF1	-12.2	-36.4	-15.0	-11.0	**-14.9**
HOF3: Gauged Month Q97 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.488	0.491	0.491	0.491	**0.490**
HOF3 % change from HOF1	9.6	6.4	5.2	5.2	**6.6**
HOF3: Volume to supply (Ml)	3049.49	639.28	1626.14	2293.06	**1901.99**
HOF3 % change from HOF1	-9.7	-26.0	-10.0	-7.3	**-10.7**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.305	0.305	0.305	0.305	**0.305**
HOF4 % change from HOF1	-31.5	-33.9	-34.7	-34.7	**-33.7**
HOF4: Volume to supply (Ml)	4492.45	2111.70	3098.56	3765.48	**3367.05**
HOF4 % change from HOF1	33.0	144.6	71.4	52.2	**58.0**
HOF5: Natural Month Q97 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	0.268	0.268	0.268	0.268	**0.268**
HOF5 % change from HOF1	-39.9	-42.0	-42.7	-42.7	**-41.8**
HOF5: Volume to supply (Ml)	4789.32	2408.57	3395.44	4062.35	**3663.92**
HOF5 % change from HOF1	41.8	179.0	87.9	64.2	**72.0**

October and November

HOF1: Gauged Annual Q95 (m^3s^{-1})	**1**	**2**	**3**	**4**	**Average**
HOF1: Flow to river (m^3s^{-1})	0.467	0.467	0.467	0.467	**0.467**
HOF1: Volume to supply (Ml)	10899.36	8341.92	1164.24	721.09	**5281.65**
HOF2: Gauged Month Q95 (m^3s^{-1})					
HOF2: Flow to river (m^3s^{-1})	0.599	0.599	0.599	0.575	**0.593**
HOF2 % change from HOF1	28.2	28.2	28.2	23.0	**26.9**
HOF2: Volume to supply (Ml)	10203.84	7646.40	468.72	149.99	**4617.24**
HOF2 % change from HOF1	-6.4	-8.3	-59.7	-79.2	**-12.6**
HOF3: Gauged Month Q90 (m^3s^{-1})					
HOF3: Flow to river (m^3s^{-1})	0.644	0.640	0.644	0.594	**0.630**
HOF3 % change from HOF1	37.8	36.9	37.8	27.1	**34.9**
HOF3: Volume to supply (Ml)	9967.27	7431.26	232.15	48.21	**4419.72**
HOF3 % change from HOF1	-8.6	-10.9	-80.1	-93.3	**-16.3**
HOF4: Natural Month Q95 (m^3s^{-1})					
HOF4: Flow to river (m^3s^{-1})	0.751	0.751	0.605	0.519	**0.656**
HOF4 % change from HOF1	60.7	60.7	29.6	11.1	**40.5**
HOF4: Volume to supply (Ml)	9425.47	6868.02	444.61	447.29	**4296.35**
HOF4 % change from HOF1	-13.5	-17.7	-61.8	-38.0	**-18.7**
HOF5: Natural Month Q90 (m^3s^{-1})					
HOF5: Flow to river (m^3s^{-1})	1.0195	0.996	0.688	0.6025	**0.827**
HOF5 % change from HOF1	118.3	113.3	47.3	29.0	**77.0**
HOF5: Volume to supply (Ml)	8014.73	5583.17	0.00	0.00	**3399.48**
HOF5 % change from HOF1	-26.5	-33.1	-100.0	-100.0	**-35.6**