Patterns of flow variability: consideration for river regulation and salmon management

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PATTERNS OF FLOW VARIABILITY: CONSIDERATION FOR RIVER REGULATION AND SALMON MANAGEMENT

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ABSTRACT

The natural flow paradigm is based on the assumption that aquatic organisms have adapted to a range of flows. However, flow variability is currently not represented in water resource management in England and Wales. This thesis addresses the need to incorporate seasonal and inter-annual flow variability in managing rivers for migratory salmonids.

This study explores the degree of inter- and intra-annual flow variability at different spatial and temporal scales across the UK, using a novel approach to analysing natural variations in flow regimes. Principle components analysis and cluster analysis, were combined with the Indicators of Hydrologic Alteration approach to analyse 850 years of station flow data from 17 rivers within 3 regions. The analyses focussed on functional flows of know/suspected influence on salmonid populations.

Atlantic salmon (*Salmo salar*) is in decline throughout most of its range, yet as a protected species legally requires measures to improve populations. This thesis assembled multi-decadal datasets in the form of rod catch data, as a proxy to represent salmon populations. However, analyses provided limited meaningful insight into the relationship with flow. It is suggested that the multiple pressures impacting salmon populations, within freshwater, intertidal and marine stages of the lifecycle, made it challenging to isolate the impact of flow.

In light of the uncertainties and with the pressure on water resources set only to increase, it is essential that natural flow variability is understood and incorporated into river management. This will provide protection by increasing heterogeneity and possible refugia from extreme events making the Atlantic salmon populations more resilient and able to adapt to anthropogenic and environmental pressures going forward. This study questions if other management actions, such as juvenile habitat enhancement, could also be influential.

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AUTHOR'S DECLARATION

I declare that all the material contained in this thesis is my own work.

CHAPTER 1: THE 21ST CENTURY RIVER ENVIRONMENT

1.1 Water Management

Water is essential for all life forms; it makes up approximately 60 to 70%, by weight, of all living organisms. It is essential for photosynthesis and is a key driver of biodiversity across the planet. Globally only 3% of water is freshwater and only 1% of this freshwater is readily available in surface waters, such as rivers and lakes (Gleick, 1996). Throughout human history, societies have sought to regulate the temporal variability of river flows to provide water for energy security (e.g. Petts, 1984). These same societies have been responsible for changing the natural flow regime and river basins by developing land for agriculture, industry and/or urban development.

For riverine ecosystems, river flow is viewed as the 'master variable' (Power *et al*., 1995). River flow is the result of the conversion of rainfall into run-off. This conversion is hugely variable across different landscapes (topography, geology, land cover, etc.), climatic (precipitation and temperature) zones and over time, both between different seasons and between years. However, from the perspective of lotic biota, river flow can also be described in hydraulic terms. The interaction of discharge with the shape of a river channel results in variable patterns of hydraulic parameters, such as flow velocity and depth. In-channel features, such as woody debris and submerged vegetation, can also give rise to significant variability in water velocity and depth within a reach of river. This spatial variability can be important for maintaining habitat diversity and biodiversity, including different life stages within individual species, for example fish eggs, fry, juveniles and adults.

For more than 40 years, human water management activities have been recognised as threatening our freshwater systems (Petts, 1984). Human activities, such as the direct removal of water from rivers, canals, lakes, reservoirs and aquifers (abstraction, also called withdrawals in the USA), and impoundment (construction of dams for various purposes), have greatly modified the natural flow regimes of many rivers (Ward and Stanford, 1983, 1995; Poff *et al*., 1997). It is estimated that approximately 60% of the world's rivers have been diverted, and many of the rivers, including the Colorado, Murray and Yellow, now no longer reach the sea throughout the year (Naiman *et al*., 2002). By 1990 there were 400 ‘mega’ projects constructed or planned around the world (which include dams over 150m high, reservoirs over 25 billion m^3 and dam volumes of over 25 million m^3) and over 40,000 dams over 15 m high (Gleick, 1998).

In England and Wales, the latest available statistics for water abstraction indicate that in 2012 an estimated 13.7 billion cubic metres was abstracted from non-tidal surface and ground waters, of which approximately 35% was used in electricity production and 48% in public water supply (Defra, 2013). The remaining amount was utilised by agriculture, fish farming, hydropower, mineral washing and other industries. Although water is usually returned to the river, it is often not in the same place as the discharge point, and the quality of water returned has often decreased, with higher levels of contaminants and/or higher water temperatures.

The recent ‘Water for Life’ document, presented to the UK Parliament in December 2011, acknowledged “*water supplies are already under stress in some parts of country, and because of pollution and over-abstraction only 25% of our rivers and lakes are fully functioning ecosystems. In the coming years, the combined effects of climate change and a growing population are likely to put increasing pressures on our rivers, lakes and aquifers. If we do not act, the security of our water supplies could be comprised*” (Defra, 2011, p. 4). A report by the Environment Agency (EA), issued alongside the Water White Paper, also concluded “*Water resources are already under pressure. Current levels of water abstraction are already harming nature*” (Defra, 2011, p. 4). This raises the question of how much water we can take from our rivers, or how we might be smarter with regard to where and when we abstract water, in order to better protect the environment and its dependent species, while meeting the water demands of an increasing population. This is the challenge to be addressed by this thesis, with the focus on the provision of river flows needed to sustain migratory Atlantic salmon (*Salmo salar*) populations.

Within the UK, the two native migratory fish species are the Atlantic salmon and sea trout (the migratory form of the brown trout, *Salmo trutta*). They are anadromous, meaning they spawn in freshwater and feed and grow at sea, and they have similar life histories; in the UK they typically spawn in autumn/winter, with eggs hatching in the spring. As they are both migratory species, they make use of whole freshwater catchments, estuaries and the sea to complete their life cycles and are considered strong candidates for classification as sentinel species for their environments. Both of these species have similar basic water flow requirements:

- Adequate flows to stimulate adult migrations from the marine into the estuary and upstream into freshwater for spawning.
- Adequate water quantity for access to nursery areas, and to provide holding pools of sufficient depth for sheltering adult fish.
- 'Flushing' flows to maintain clean spawning gravels.

Additionally, for historical, social and economic reasons, these species are comparatively well studied. However, the physiology of what makes some brown trout go to sea and others stay in the river for their whole lifecycle is not understood. This, coupled with the complexity of verifying trout abundances due to stocking pressures, has meant this study focuses solely on how flow affects life histories of Atlantic salmon.

The Atlantic salmon was historically widely distributed in all countries with rivers entering the North Atlantic. However, now its distribution has become restricted by anthropogenic activities (Hendry & Cragg-Hine, 2003). In the UK, the Atlantic salmon has a relatively widespread distribution, apart from in English central and southeast regions, although abundance has been declining since the late 18^{th} century (ICES, 2011).

1.2 Ecological Impacts of Water Abstraction

Hydrological variability within rivers and streams is widely recognised as one of the primary factors influencing the distribution of aquatic flora and fauna (Townsend *et al*., 1997). The biological communities living in flowing water conditions are adapted to natural flow regimes combined with natural channel morphology, for example via their body shape, metabolism and feeding behaviours (Statzner *et al*. 1988). Hence, unnaturally low flows and artificial flow regimes, caused by water abstraction and impoundment, can have damaging impacts on river systems and their associated biota (Wright and Berrie, 1987; Giles *et al*., 1991; Wood and Petts, 1994: McKay and King, 2006).

Human impacts on flows within river basins are complex. River flows can be reduced, increased, or their temporal/spatial regimes modified by different human activities. Flow alteration from abstraction is perhaps the best known and studied. The effects of abstraction on the riverine environment differ depending on the licence condition and the uses, but can be widespread and include changes to temperature, water quality and invertebrate and fish assemblages etc. (Table 1.1).

1.3 CURRENT WATER MANAGEMENT AND POLICY IN ENGLAND AND WALES

In England, the EA and in Wales, Natural Resource Wales (NRW)[1] are responsible for regulating water systems and licenses. Their duties date back to the 1963 Water Resources Act, which required the regulation of water abstraction to balance the needs of water users with those of the environment. Historically, this was undertaken and updated on a piecemeal basis, with many local/regional precedents and "rules of thumb". For example, the use of "hands off flows": when abstraction had to cease or be significantly reduced if specific low flow criteria were reached.

Legislative changes were realised in the 2003 Water Act, which included; time limits for all new, full and transfer abstraction licences, the facility to revoke

[1] In April 2013, the Countryside Council for Wales, Environment Agency Wales and Forestry Commission Wales were merged together to form Natural Resources Wales.
[222] A national assessment of the status of the salmon resource in England and Wales is undertaken annually, using the Pre-fishery Abundance and National Conservation

abstraction licences causing serious environmental damage without compensation, greater flexibility to raise or lower licensing thresholds,

Table 1.1. The impacts of water abstraction on different elements of the riverine environment.

Impact	Justification and reference
Hydrological and hydraulic changes	Velocity is a significant factor affecting the distribution and assemblage of stream invertebrates (Statzner *et al*., 1988); influencing their respiration, feeding biology and behavioural characteristics (Petts, 2008). A reduction in discharge alters the width, depths, velocity patterns and shear stresses within the river channel (Armitage and Petts, 1992), modifying the distribution and availability of in-stream habitat (Wood *et al*., 1999). Altered flow regimes have also been linked to the invasion of non-native species along river corridors, especially with the loss of natural wet and dry cycles (Baltz and Moyle, 1993; Brown and Moyle, 1997: Brown and Ford, 2002: Petts, 2008).
Temperature changes	Artificially low flows may increase water temperatures by increasing the area of air-water interface per unit volume of water (Webb *et al*., 2003), which can affect the river fauna and flora (Richardson *et al*., 1994). Temperatures over 22°C will have serious negative effects on salmonids (Elliott, 1994).
Water quality changes	An artificial decrease in flow reduces effluent dilution (Armitage and Petts, 1992), increasing the concentration of many pollutants, although licences control discharges.
Sediment deposition	Periodic high flows (spates or freshets) are important for maintaining in-stream habitats by flushing fine sediment out of the system thus maintaining the channel carrying capacity and structure (Reiser *et al*., 1989; Old and Acreman 2006). Persistent artificially low flows can result in channel siltation clogging interstitial spaces in the substrate, thus reducing available fish spawning habitat (Carling and McCahon, 1987; Crisp, 1989) and invertebrate refugia (Wood and Armitage, 1999; Milan *et al*., 2000)
Shifts in invertebrate assemblages	Changes in invertebrate composition *(Armitage, 1987),* for example; reduced abundance of filter-feeding invertebrates and a reduction of stoneflies and heptageniid mayflies, which favour clean stones and well-oxygenated water (Extence *et al*., 1999), and an increase in taxa associated with low velocity including chironomids and molluscs (Jowett and Duncan, 1990). Prolonged artificially low flow conditions can lead to invertebrate mortality (Armitage and Petts, 1992).
Reduced growth of aquatic flora	Low flows can inhibit the growth of certain aquatic plants (Franklin *et al.* 2008; Wilby *et al.* 1998*;* Herne and Armitage, 1993), such as *Ranunculus*.
Changes in fish communities and/or reduced fisheries production	Species requiring higher oxygen concentrations (such as salmonids) being replaced by more generalist species. This may jeopardise angling participation, resulting in the loss of social and economic benefits to local communities (Willis and Garrod, 1999) and onward investment in river management and conservation projects.
Disruption to migratory passages	Low flows can impede the migration of salmonids and other migratory fishes and limit access to upper reach spawning areas (Strevens, 1999; Environmental Agency, 2004; Old and Acreman, 2006).
Reduced connectivity with floodplains and riparian margins	Functioning floodplains have a major influence on in-channel processes, for example by providing inputs of nutrients and refugia and breeding habitat, essential to the life cycles of many riverine species (Bunn and Arthington, 2002).

deregulation of small and environmentally insignificant abstractions, and statutory Water Company drought plans and water resource management plans (Defra, 2008).

The Restoring Sustainable Abstraction (RSA) programme was set up by the EA in 1999 to identify rivers/river reaches that may be at risk from abstraction, and to prioritise how to resolve the conflicts in these areas, including sites designated as Sites of Specific Scientific Interest (SSSI). RSA is a successor to the Alleviation of Low Flows (ALF) programme, which during the 1990s targeted 40 rivers believed to be suffering the most because of artificially low flows. An on-going review is still taking place under the RSA programme to identify environmental damage as a result of abstraction, focusing on sites designated under the European Union Habitats and Birds Directives. However, progress has been slow. The EA does already have the power, under existing legalisation, to vary or revoke abstraction licenses causing environmental damage. However, in many circumstances, such as permanent licences, this requires compensation to be paid to the licence holder (Environment Agency, 2005), which has prevented progress to remove damaging abstractions. This was addressed in the new Water Act, which gained Royal Assent in May 2014, which ended the right for water companies to be compensated if an abstraction licence is withdrawn or amended after being deemed to be causing environmental damage. As of April 2004, new legislation also required all new abstraction licenses to be time limited.

In response to the requirements from Defra's 'Taking Water Responsibly' consultation in 1999, Catchment Abstraction Management Strategies (CAMS) were set up to provide a consistent mechanism for managing water use through catchment planning and licensing. The Resource Assessment and Management (RAM) framework within CAMS provides information on water availability at a catchment scale (Dunbar *et al.*, 2004). This assessment is based on the requirements of river ecosystems and other water users. CAMS are a process by which the EA assesses the amount of water available for further abstraction permitting. CAMS also introduce time-limited licenses, so the EA can periodically review the licences to determine whether or not to replace them and, if so, what conditions should apply. The first formal cycle of CAMS commenced in April 2001, and concluded in March 2008.

The latest re-modelling of European water policy led to development of the European Union's Water Framework Directive (WFD; Directive 2000/60/EC) in December 2000. WFD recognises that the needs of the whole water environment must be considered to ensure a healthy river system, including fish, invertebrates and macrophytes. The Directive has therefore moved away from previous chemically dominated monitoring systems, to a new concept with a biological-based monitoring system at its heart (Acreman and Ferguson, 2010). The WFD, which was transposed into UK Law in 2003, requires all member states, including England and Wales, to achieve 'good ecological status' (GES) in all water bodies (rivers, lakes, coastal waters, groundwater and transitional water bodies) by 2015. The Directive also requires no deterioration in water bodies. 'Heavily modified water bodies' are exempt from this, but are required to reach 'good ecological potential' (GEP). With the implementation of the WFD, CAMS will no longer be produced on their own cyclical programme, but will feed into the WFD River Basin Planning process, as will the RSA programme.

Despite the optimism around WFD, environmental NGOs have voiced concerns about the EA's lack of delivery ambition. These concerns have been realised as we approach the end of the first cycle with the EA reporting no statistically significant change in good status from the baseline conditions in 2009 (EA, 2014).

The latest Water White Paper from Government in 2011 made a commitment to reform the current water abstraction regime to produce a 'water abstraction regime resilient to the challenges of climate change and population growth, and which will better protect the environment' (Defra, 2011, pp 20). However, the recent Water Act 2014 did not include any regulation for the reform. Defra did, in the spring of 2014, consult on plans for what a new system may look like and states it plans to introduce the reform legalisation early in the next parliament. However, this indicates there seems to be little political will to prioritise the conservation of aquatic biodiversity and ecosystem health. Instead, within the context of climate change predictions, priority is being given to flooding concerns, energy security issues and agricultural sustainability.

Restoring natural flow regimes is fundamental to improving aquatic habitats and increasing biodiversity. However, restoring flow regimes cannot and should not be seen in isolation, but considered alongside climate change impact and anthropogenic demand in order to improve environmental resilience.

1.4 AIMS OF THE STUDY

Previous research on e-flows for Atlantic salmon in the UK and elsewhere have focused on the 'average' flow regime, for short-term time-scales and the local (reach) scale (Petts, 2008), with an emphasis on eco-hydraulic approaches. This study seeks to demonstrate the temporal and spatial variability in flow regimes across England and Wales over the past 40 – 100 years, and then to elucidate the implications of flow regime dynamics for salmonid populations. Most studies have focussed on flow-biota relationships over short time scales. Here, long-term fish-catch data are assembled as proxy for salmonid population health. Within this context, the objective of this study is to identify key hydrological parameters important to native Atlantic salmon (*Salar salmo*), to help provide guidelines to ensure successful flow management for salmonid species in order to meet the EU objectives.

The study will assume a hierarchical effect in pressures, and will assume flow is the dominant factor determining the physical habitats in rivers, which in turn are a major determinant of the biotic composition. Therefore, it is assumed that flow is the major determinant affecting salmon populations in rivers. The impacts of secondary effects, such as water quality and sediment, will not be investigated within this study, but it is recognised that the water temperature regime in particular is likely to have a significant impact on fish population dynamics. The other important assumption is that Atlantic salmon have evolved their life history strategies primarily in response to natural flow regimes. For this migratory species, the study focuses on the freshwater, catchment phase of their life cycle, but also acknowledges the significance of impacts on the estuarine and marine phases in determining the health of Atlantic salmon populations.

The main research objectives, across a suite of Atlantic salmon rivers throughout the UK, are:

- To characterise inter-annual and intra-annual flow variability at local, regional and national scales.
- To compile long-term Atlantic salmon rod-catch data and to examine patterns of variation at different temporal and spatial scales, and to assess the validity of using long-term rod catch data to improve understanding of Atlantic salmon's relationships with river flow.
- To establish a toolbox of biologically relevant flow parameters for managing Atlantic salmon in rivers.
- To evaluate the evidence for hydrological change as a driver to changing Atlantic salmon populations across the UK.

CHAPTER 2: ENVIRONMENTAL FLOWS AND ATLANTIC SALMON

2.1 Environmental flows

Historically, flow management has been based on water quality and only one aspect of water quantity, the minimum discharge (Dilt *et al*., 1995). This is, however, hugely over-simplified, as lotic fauna and flora depend on dynamic variations of the flow regime. 'Hydroecology', the study of hydrology and biota interactions at the catchment scale, has developed in part from Leopold and Maddock's (1953) pioneering work to quantify the spatial and temporal variations of hydraulic parameters associated with changing discharges, and Hynes (1970) advances in conceptualising the ecological responses to these changes. Research by Gill (1971), assessing the long-term impact of river impoundment on the ecology of the Mackenzie River Delta, and Penaz *et al*. (1968) on the impact of the Vir Valley reservoir on the biota of the Svratka River, also highlighted the need for an interdisciplinary and integrated approach to understanding 'hydro-ecology'.

One manifestation of this 'hydro-ecology' is 'hydraulic stream ecology', based on the theory that the energy budget of the organism is affected by the speed between the organism and the medium in which it lives (Statzner *et al*., 1988). Different species 'prefer' different 'hydraulic' habitats, as current velocity will affect their feeding biology, metabolism and behavioural traits. The hydraulic conditions affect salmonids through availability of hydraulic habitats described by velocity, turbulence, shear stress, and water depth (Armstrong *et al*., 2003).

Hydrological studies have evolved over the past 30 years to focus on the flow regime and the timing of specific flows in relation to species lifecycles. Research has shown seasonal high flows have a significant impact on both terrestrial and aquatic productivity (Junk *et al*., 1989). Some aquatic species have developed avoidance mechanisms to extreme floods and droughts or life histories synchronized with long-term flow patterns (Lytle and Poff, 2004). Hydraulic studies have focused on floodplain and channel dynamics, and therefore the flows responsible for changing these features, such as bankfull discharge (which often has a recurrence interval of 1.5 years) and high pulse spates (which are more frequent and function as ‘flushing flows’- removing built up organic debris and sediments). These studies overlook the median and low flows, which typically occur 90% of the time and sustain aquatic habitats in most years (Petts, 2008).

It is now recognised that the flow regime is critical for sustaining the health of riverine ecosystems; for the creation and maintenance of in-river morphology, riparian zones and floodplains, and sustaining water quality by flushing nutrients, contaminants and fine sediments from the channel network (Reiser *et al*., 1989; Armitage and Petts, 1992; Old and Acreman, 2006). This stems from understanding that pristine rivers are heterogeneous both temporally and spatially, which allows them to sustain high species richness (Petts, 2008). The key components of a flow regime essential to maintaining biodiversity and ecosystem integrity are: variability, magnitude, timing, frequency and duration of the full spectrum of high and low flow events (Karr, 1991; Poff *et al*., 1997; Richter *et al*., 1997; Rapport *et al*., 1998; Brown and Ford, 2002; Bunn and Arthington 2002). Intra- and inter-annual variations of flows are therefore desirable to sustain and maintain native biodiversity (Richter *et al*., 1996).

The aquatic biota present in a river system are associated with, and shaped by, the natural flow regime (Naiman *et al*., 2002). Lytle and Poff (2004) suggest different components of the flow regime are important for different modes of adaptation; for example, timing is important to life-history adaptations; predictability is important for behavioural adaptations; and magnitude and frequency for morphology adaptations. Variations in flow regimes have also been shown to play a major role in the migration, distribution, phenology of reproduction, spawning behaviour, larval survival and growth patterns of fish (Welcomme, 1985; Junk *et al*., 1989; Copp, 1989, 1990; Sparks, 1995; Poff and Allan, 1995). Alterations to these natural flow regimes can therefore have dramatic repercussions on the entire aquatic ecosystem and its biota (Naiman *et al*., 2002).

The mechanisms of environmental impact are reasonably well known, at least in general terms, and the science of Environmental Flows has developed rapidly over the past three decades (Acreman and Dunbar, 2004). However, the challenge is to understand the dimensions of flow variability in space and over decadal timescales and then to understand the significance of this variability for riverine ecosystems. The incorporation of environmental flows in water resources management requires: 1) short term environmental flow determination to inform local operational rules, 2) ecologically acceptable hydrographs to manage seasonal flows and 3) ecological flow duration curves to assist long term water resources planning (Petts, 1996: Petts, 2008). An ecologically acceptable flow regime (EAFR) must recognise that, naturally, species experience poor, average, and good years, depending on the varying flow conditions.

A range of potentially 'ecologically relevant' hydrological indices have been developed to link river flow with biotic riverine communities (Monk *et al*., 2007; Olden and Poff, 2003), yet still little hydro-ecological analysis has occurred. There are several reasons for this, but particularly important are:

- The lack of long-term paired hydrological, climatic and ecological datasets (Wood *et al*., 2001; Jackson and Füreder, 2006). This is critical for determining acceptable frequencies of hydrographs (e.g. wet and dry year hydrographs) within water resource management. Furthermore, anthropogenic activities, such as species introductions and stocking, can have confounded impacts on hydro-ecological relationships;
- The limited availability of sufficient hydrological data, on historical flows and actual water use (for many abstractions only licensed amounts are available);
- The complexity of the environmental interrelationships and the presence of multiple stressors, such as historical channel modification and water quality impacts. A river ecosystem will respond to an integration of the impacts; hence separating impacts caused by an individual stressor (such as abstraction) alone can be difficult. For Atlantic salmon, these stressors include changes to ocean and estuarine environments, as well as freshwater pressures.

2.2 Flow models

Water resources management requires the regulation of natural flow regimes to mitigate against the risks of extended periods of drought. Environmental flow assessment (EFA) seeks to determine an acceptable level of ecosystem change whilst balancing human water needs (Rapport *et al*., 1998). This means quantifying how much of the original flow is required in order to maintain ecosystem features and functions (Tharme and King, 1998). Since the late 1970s, environmental flow models have been developed in an attempt to ecologically characterise stream flow. These models include hydrological indices, habitat assessment models, biological response models and habitat-inclusive biological models (Table 2.1). The hydrological models statistically describe the flow using historical daily records for actual or naturalised data. Habitat assessment models require the physical mapping of riverine habitat in order to assess the condition of river reaches in terms of available habitats. This assumes that 1) habitats are defined by hydrology, and a range of flows are required to create a diversity of habitats (Dyer and Thoms, 2006) and, 2) biota have evolved to utilise different habitats at different spatial and temporal scales. These methods analyse community structure against available habitat at a local level. Habitat surveys are, however, time consuming and expensive.

The biological response models include the Physical HABitat SIMulation (PHASIM) model, which couples varying hydraulic conditions with discharge and habitat preference for selected species (Bovee, 1978). This method relies on two principles 1) a species shows preferences within the range of habitats it can tolerate and 2) the habitat can be quantified as a function of discharge and channel structure (Petts, 2008). Validation of these biological assumptions has been difficult (Lamouroux *et al*., 1999: Kondolf *et al*., 2000). This method is also expensive and time consuming, and the data produced is only of local significance and species specific. Despite this, PHASIM provides an important voice for the environment in water-resource management and is supported in the legal framework (Tharme, 2003). Habitat-inclusive biological models extend to include the biota's response to temporal habitat variability in order to identify the habitat's carrying capacity (Capra *et al*., 1995). This however requires hydrological, hydraulic (channel morphology) and biological time series data, which are difficult to obtain.

Table 2.1. Summary of environmental flow methods (modified from Petts, 2008).

Method	Examples	References
Hydrological indices	Montana Method Indictor of Hydrological Alteration Regime Classification	Tennant, 1971 Richter *et al*.,1996, 1997 Harris *et al.*, 2000
Habitat assessment	Channel form assessment Meso-habitat assessment	Petts *et al.*, 1995: Stewardson and Gippel, 2003: Jowett, 1998. Newson and Newson, 2000: Dyer and Thoms, 2006.
Biological response models	1D hydraulic models- PHABSIM 2D hydraulic models	Bovee, 1978 Parasiewicz, 2003: Steward *et al.*, 2005
Habitat-inclusive biological models	Model community development	Capra *et al.*, 2003

2.3 A Hydrological Approach

The use of historical daily flow records for hydrological approaches provides a simple and cost effective way to analyse environmental flows, without the need for site visits and fieldwork. This provides the scope for national and regional level analysis, rather than just local site-specific studies. The hydrological approach fundamentally supports the principle that water resource management needs to sustain and mimic natural variability in flows (Petts, 2008). However, in order to do this, analysis requires a minimum of 12 years of flow data for statistical integrity, and decadal timescales in order to incorporate periods of variable weather patterns (e.g. Kelly and Gore, 2007). Approaches extend the raw flow data to a range of hydrologic parameters, which can be used to describe the major components of the flow regime and its inter-annual variability. This, when coupled with biological data, allows ‘ecologically relevant’ hydrological parameters to be established to highlight the significance of specific flow for biota. In order to achieve and enable long-term flow records to be analysed alongside long-term Atlantic salmon catch records, an appropriate hydrological approach is required to describe the flow regime and enable the selection of ‘key flow parameters’. The Index of Hydrological Alteration and Regime Classification are two hydrological approaches that potentially have this wider scale application.

2.3.1 Indicators of Hydrologic Alteration

Indicators of Hydrologic Alteration (IHA), developed by Richter *et al* (1996), analyses existing hydrologic data (from stream gauges) to statistically characterise inter-annual variation by using a range of biologically-relevant hydrological parameters (Olden and Poff, 2003; Monk *et al*., 2007). The model, developed using rivers in the USA, is designed to allow hydrologic perturbations, associated with activities such as river abstraction or dam construction, to be assessed by statistically comparing ‘pre’- and ‘post’- impact series (Richter *et al*., 1996). The model uses 33 parameters in order to compare between these time periods, which are organised into five groups:

1. Magnitude;
2. Timing of occurrence;
3. Frequency of occurrence of specific water conditions;
4. Duration of time over which a specific event exists;
5. Rate of change in water conditions (‘flashiness’).

The method has four main steps (Richer *al et*.,1996):

1. Define the hydrological data series (can be pre and post impact)
2. Calculate values of hydrologic attributes: values of each of the 33 attributes are calculated for each year in the data series.
3. Compute inter-annual statistics: calculate the general tendency and dispersion of the 33 attributes, based on the values of step 2- to produce inter-annual statistics
4. Calculate values of the Indicators of Hydrologic Alteration: compare inter-annual statistics for pre and post impact. This presents each result as a percentage deviation of one time (post-impact) period relative to the other (pre-impact). It can also be used to compare one state of a system (e.g. altered system) to another reference system, or current conditions with projected results in the future.

The IHA data is summarised in a number of different tables:

- Annual Summary Statistics: this displays all the IHA and EFC parameter values for each individual water year that has been included in the time periods selected for analysis. If non-parametric statistics were used, the values in this table are the medians for each water year of the relevant sub-annual data.
- Scorecard Table: this shows a variety of statistics calculated as the averages for the whole dataset using the annual values from the Annual Summary Statistics. The pre and post-impact analysis shows the statistical difference in the parameters.
- Linear Regression Table: this shows complete results from a linear regression on each hydrologic parameter during the period of record for single period analysis only. These statistics are calculated from the annual values in the Annual Summaries Table.
- Percentile Data Table: this table shows the details of the percentile statistics. Results are shown either for the pre-impact and post-impact periods, or for the two Hydro Data files being compared. These statistics are calculated from the annual values in the Annual Summaries Table. For two period analyses, there are 12 columns. The first five columns show the 10th, 25th, 50th, 75th, and 90th percentile values for the pre-impact period. The sixth column has the coefficient of dispersion, calculated as (75th percentile - 25th percentile) / 50th percentile. The last six columns give the analogous values for the post-impact period. For single period analysis, only six columns are shown, showing the analogous values for the entire period.
- Flow Duration Curve Table: this shows for each month the flow duration curve.
- Environmental Flow Components Daily Table: The IHA also calculates parameters for five environmental flow components;
    - **Low flows:** the dominant flow condition in most rivers (the base-flows) when the levels are sustained by groundwater discharge. Low flows are defined as flows less than or equal to the 50th percentile.
    - **Extreme low flows:** typically during drought seasons when rivers drop to levels that can be stressful for aquatic organisms. Extreme

low flows are defined as the lowest 10% of flows during the specified timeframe.

- **High flows:** after events such as rainstorms or brief snow melt, when the river rises above low-flow levels. All flows that exceed 75% of daily flows for the period are classified as high flows.
- **Small floods:** when rivers rise above the main channel, providing access to the floodplain. Small floods are high flow pulses with a recurrence time of at least 2 years (bank full).
- **Large floods:** flood events that typically rearrange the physical and biological structure of the river and its floodplain. Large floods are high flow pulses with a recurrence time of at least 10 years.

A Range of Variability Approach (RVA) table (which uses the pre-development natural variation of IHA parameter values as a reference for defining the extent to which natural flow regimes have been altered, described in Richer *et al*., 1997), and Box and Whisker Tables (contains five values for each hydrologic parameter for the pre-impact and post-impact periods), are also calculated by the IHA model when comparing pre- and post-impact data.

2.3.2 Regime Classification

The natural flow regime describes the long-term average intra-annual variability of flows that reflect the regional climate (Beckinsale, 1969) and is distinctive to each bio-climatic region. However, in the UK, the typical maritime-temperate flow regime masks the different inter-annual regime variations driven by the north Atlantic weather patterns. Regime Classification is the statistical classification of discharge hydrographs into two separate classifications of the discharge time-series which identify differences in:

i) Annual hydrograph ‘shape’

ii) Hydrograph ‘magnitude’ based on bulk flow indices

These shape and magnitude data can be combined to provide a composite classification of hydrographs with similar patterns (Hannah *et al*., 2000). The approach also allows analyses and classifications of hydro-systems according to temperature as well as discharge (Harris *et al*., 2000).

Overall, a combination of the two approaches should enable the development of a toolbox of flow parameters which may be correlated against the biological dataset of rod catch data for Atlantic salmon, and provide the basis for exploring flow guidelines needed to sustain Atlantic salmon populations in UK rivers.

2.4 ATLANTIC SALMON AND FLOW

The Atlantic salmon (*Salmo salar*) is an EC Habitats Directive (92/43/EEC) Annex II protected species. The Habitats Directive was introduced in 1992, following the 1992 Rio Earth Summit, with the primary aim to promote the maintenance of biodiversity, via Special Areas of Conservation (SACs). SACs are locations in which rare, endangered or vulnerable natural habitats or species of plants or animals (other than birds) are protected.

Atlantic salmon are found in the temperate and arctic regions of the Northern Hemisphere. There are three generally recognised groups of Atlantic salmon: North American, European, and Baltic. Atlantic salmon return from sea to spawn in their native rivers. There are sites selected in the UK as SACs to primarily help protect UK Atlantic salmon populations. There are also SACs where Atlantic salmon, as an Annex II species, are a qualifying feature, but not the primary reason for site selection. According to the Joint Nature Conservation Committee (JNCC), SAC site selection in the UK focused on the identification of rivers holding large salmon populations across the geographical range, and sites with a range of ecological and hydrological characteristics to ensure the whole life-cycle was represented, including spawning and nursery requirements (JNCC, 2010). This thesis will investigate flow variability for two SACs classified primarily for Atlantic salmon: the River Teifi and River Tweed, and two SACs with Atlantic salmon as a qualifying feature: Dartmoor- the River Dart and River Camel. Thus, at least one SAC river will be studied in each of the three regions covered in this thesis (Appendix A1).

In the UK, Atlantic salmon spawning generally occurs between November-December. The navigation to and from their native river is not fully understood, but believed to be due to a number of mechanisms, including guidance by the stars, earth's magnetic field (Quinn, 1980) and chemical stimuli (Johnsen and

Hasler, 1980). Spawning time varies between rivers and may be influenced by the water temperature and amount of daylight.

The typical life span of a salmon is between 4 and 10 years. The age of salmon at first spawning can be from 3 years up to 14 years (Niemela *et al*., 2006). Atlantic salmon often survive their first spawning and can go on to spawn two or three times. The survivors, predominantly female, return to sea to feed between spawning. The most common number of eggs laid by Atlantic salmon is variable at between 990-1,500 per kg body weight. They are laid in depressions called "redds" excavated by the female fish in the gravel of the riverbed. After the eggs are deposited, they are immediately fertilised by an accompanying sea-run male, or sometimes by mature (precocious) male parr, before being covered with gravel by the female.

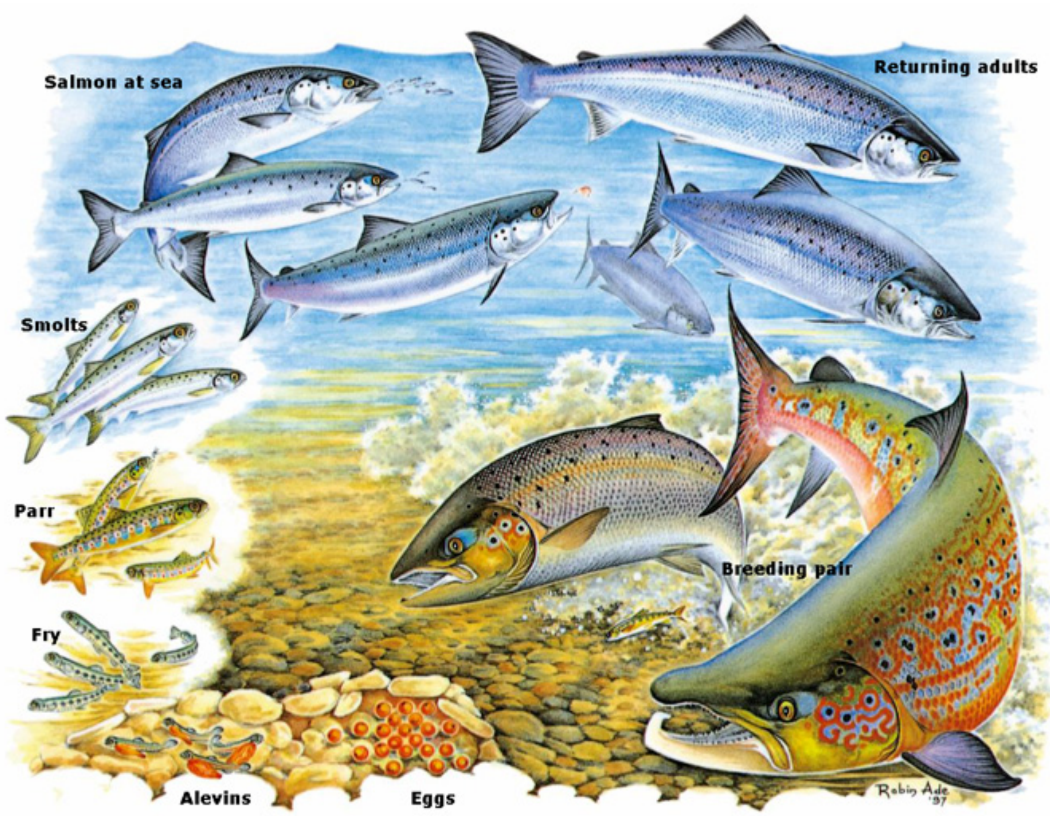

Figure 2.1. The Atlantic salmon life cycle (Illustration from Robin Ade).

The incubation time depends upon the water temperature. Salmon eggs at 3°C have been shown to have an incubation period of 145 days, while at 10-12°C incubation is only 40 days (Sedgwick, 1982); this can be expressed as 440 degree days. Hatching usually occurs in early spring and the young fish (called ‘alevins’) derive their nourishment from their attached yolk sac for several weeks (Thorpe *et al*., 1999). They emerge when the yolk sac has been absorbed and begin to swim freely for the first time, looking for food. At this point they are about one inch in length and described as ‘fry’. As they grow, the young fish develop prominent markings on their sides and are then known as ‘parr’. Parr feed on the larvae of aquatic insects and other aquatic invertebrates, together with terrestrial insects that fall into the water. The amount of time young Atlantic salmon stay in rivers is dependent upon the water temperature and the availability of food, typically varying from one year in the southern portion of the salmon's range to as many as five plus years in more northern, colder regions. When this period of development is finished, the ‘parr’ turn into ‘smolts’, characterised by a change in the colour of their markings to an overall silver sheen. They acquire the ability to inhabit saline waters by improving their hypo-osmoregulatory performance (Waring and Moore, 2004). This process is essential to their survival. Beyond this, little is known about their life in estuarine waters.

Once smolts have reached marine waters, they are believed to demonstrate schooling whilst heading off to deep-sea feeding areas, the best-known of which are in the Norwegian Sea and the waters off Southwest Greenland. Salmon that remain at sea for more than one winter undertake the longest migrations, whilst grilse, which only spend one winter at sea, tend not to travel beyond the Faroe Islands and the southern Norwegian Sea.

Juvenile Atlantic salmon prey predominately upon invertebrates and terrestrial insects while in freshwater, and amphipods, euphausiids, gammarids and fishes while at sea. Larger adult Atlantic salmon prey mainly on fish such as Atlantic herring, alewife, rainbow smelt, capelin, sand lances, flatfish, blue whiting and small Atlantic mackerel. Growth rates of juvenile salmon are rapid, but depend on a combination of season, habitat quality, age, sex, and population density.

2.4.1 Basic flow requirements

Flow and channel form combine to determine the hydraulic attributes which influence river biota. These hydraulic attributes vary spatially, depending on river location and topographical characteristics (Stewardson and McMahon, 2002). In rivers with generally 'natural' morphology, the mean water depth, mean velocity and channel width all tend to increase with distance downstream (Leopold and Maddock, 1953; Rosenfeld *et al*., 2007; Booker and Dunbar, 2008). At a reach scale, many rivers tend to have alternating habitat types, such as riffle-pool sequences, which is reflected by substrate composition (Leopold *et al*., 1964; Thompson, 1986). These local habitats result in a range of factors related to flow which also influence fish, including temperature, food availability, turbidity, dissolved oxygen and olfactory cues. The complexes with these interrelated factors make it difficult to define general hydrological rules that apply to all river flows (Beecher, 1990; Acreman and Dunbar, 2004). This complexity is increased further due to the historical inheritance of channel modification in many rivers in the UK (Brookes *et al*., 1983; Raven *et al*., 1998).

Nevertheless, the complex freshwater life-cycle of the Atlantic salmon has evolved to utilise the natural variations in water flow (Enders *et al*., 2009), and studies have established general flow requirements for Atlantic salmon, which currently form the basis of river management.

2.4.1.1.Adult sea- estuary migration

The mechanisms governing orientation and attraction of Atlantic salmon into estuaries are not fully understood. Although movements in the estuary are thought to be influenced by tidal state (Potter 1988; Potter *et al*., 1992; Smith *et al*., 1994; Solomon *et al*., 1999), with upstream migration occurring more frequently on the floodtide.

Estuarial movements are strongly affected by the topography of the estuary and the availability of holding habitats (Potter *et al*., 1992). Therefore, in larger estuaries, fish may find holding areas to wait for suitable flow conditions for upstream migration, whereas in smaller rivers salmon might have to return to sea (Potter, 1988) or find refuge in larger estuaries nearby (Clarke *et al*., 1991). The timings of when salmon enter the estuaries are not well understood. Solomon *et al*., (1999) found that, in southern England, salmon that were delayed for ten or more days within the estuary tended not to migrate into the river until the autumn. This may result in significant mortality in the estuaries, particularly in hot dry summers (Solomon and Sambrook, 2004).

2.4.1.2. Adult estuary to river migration

Upstream migration from the estuary depends on the physiological and behavioural preparedness of the fish, as well as the conditions in the river. The up–river migrations of salmon generally comprise of phases of rapid movements (particularly in the initial stages) interspersed with irregular movement (Milner, 1990). The initial upstream migration is believed to stop when the fish experiences unfavourable conditions, such as low flows (NMFS/USFWS, 2004), resulting in a quiescent period. Initiation of the next migratory phase is generally associated with high flow events.

Research suggests during low summer and autumn flows, natural high flow pulses temporarily increase base flow, and provide important stimuli to instigate the adult salmon migration into freshwater (Hendry and Cragg-Hine, 2003). Fish have been recorded frequently moving upstream on the receding phase of a flood spate (Alabaster, 1970). Mills (1991) found that timed flow pulses for attracting adult salmon migration into rivers must also be in conjunction with other cues such as tides, onshore winds, cooler weather or natural freshets.

The trigger level to initiate upstream migration is believed to vary at different times of year and different locations in the river. Solomon *et al*. (1999) found using telemetry studies that the threshold flow required to induce salmon into freshwater in southwest England varied from 101% to 284% of the Q95 (the flow which is exceeded 95% of the time), with the percentage of Q95 being greater in smaller rivers. Fish movement data using counter data in northeast England spate rivers indicated salmon began to migrate upstream when flow reached 0.084 $m^3 s^{-1}$ per metre of channel width, with peak flow at 0.2 $m^3 s^{-1}$ per metre of channel width (Steward, 1973). However, migratory phases tend to be associated with relatively higher flows as salmonids progress upstream, for example on the River Exe, the flow required to initiate salmon movement increased from 97% of Q95 at the estuary to 516% of Q95 49km upstream (Solomon *et al*., 1999).

Potter (1988) found most salmon on the River Fowey entered freshwater at night, on lower flows than the smaller number of fish moving during daylight hours. This is likely to reflect predator avoidance behaviour, with fish gaining protection by moving under hours of darkness or under turbid conditions. The different migratory behaviours are likely to result in different survival rates due to differing interactions with predators.

2.4.1.3. Spawning

Flows in the autumn and early winter affect the spawning location and success of salmon. In low flow years, the distribution of spawning can be dramatically truncated due to reduced upstream and tributary penetration, which can affect consequent parr production (Moir *et al*., 1998; Solomon *et al*., 1999).

The maximum water velocity for salmonid spawning is size dependent, with the upper limit speculated to be approximately two female body lengths per second (Crisp, 1993). Crisp and Carling (1989) found salmonids of all sizes preferred not to spawn in water velocities below 15-20 cm s^{-1} (Table 2.2). Water quantity and velocity directly or indirectly affects many other variables that can affect salmonid migration and distribution, including temperature and substrate size.

Table 2.2. Water velocity and depth requirements of spawning and juvenile Atlantic salmon and brown trout. (Adapted from Armstrong et al., 2003).

Life Stage	Variable	Value		Reference
Spawning requirements	Water velocity	Mean:	40 cm s^{-1}	Heggeberget, (1991)
			53 cm s^{-1}	Moir *et al.,* (1998), Beland *et al*., (1982)
		Range:	35-80 cm s^{-1}	Beland *et al*., (1982)
			30-50 cm s^{-1}	Fleming, (1996)
		Minimum:	>15-20 cm s^{-1}	Crisp and Carling, (1989)
	Water depth	Mean:	50 cm	Heggeberget, (1991)
			<30 cm	Fleming, (1996)
			25 cm	Moir *et al*., (1998),
			38 cm	Beland *et al.,* (1982)
		Range:	17-76 cm	Beland *et al.,* (1982)
Nursery habitat use	Mean column velocity	Range:	20-40 cm s^{-1}	Crisp, (1993, 1996)
			10-30 cm s^{-1}	DeGraaf and Bain, (1986)
		Minimum:	>5-15 cm s^{-1}	Heggenes *et al*., (1999)
		Maximum:	<100 cm s^{-1}	Heggenes *et al*., (1999)
	Water depth	Maximum (fry):	<10 cm	Heggenes *et al*., (1999)
		Range (fry):	20-40 cm	Morantz *et al*., (1987)
		Preference (0+):	<25 cm	Symons and Heland, (1978)

In the autumn, Atlantic salmon deposit eggs in redds within gravel streambeds. Research suggests the average redd water depth is 25-50cm, with velocities typically ranging from 30-80cm s^{-1}. The choice of spawning areas is strongly influenced by the sedimentary characteristics of the riverbed, which are influenced by the hydraulic conditions that sort and distribute gravels (Moir *et al*., 1998, Moir *et al*., 2002). Some evidence suggests fish may avoid spawning during periods of rapidly changing discharge (Moir *et al*., 2006), which may negatively impact spawning success.

2.4.1.4. Incubation

Egg survival is dependent on winter discharge, temperature and clean permeable gravels, which allow aeration of the eggs (MacCrimmon and Gots, 1979: Chadwick, 1982). Winter floods and freshet events that disturb the riverbed are correlated to low egg survival through displacement (Gibson and Myers, 1988). Montgomery *et al*., (1996) suggest salmonids dig their redds in locations and at depths where scour from high flows would be least likely to result in loss of eggs. Low discharge, cold winters have also been correlated with low egg survival rates, particularly when preceded by high discharge events, as the eggs are vulnerable to air exposure (Cunjak and Therrien, 1998: Chadwick, 1982). Intra-gravel survival is dependent upon the availability of dissolved oxygen, which is delivered to the eggs by both groundwater and surface water (Acornley and Sear, 1999).

2.4.1.5 Fry emergence

High spring flows can also scour redds, leading to pre-emergent alevins being washed downstream, and high flows within a week of emergence have been shown to cause fry mortality or displacement to sub-optimal habitats (Jensen and Johnsen, 1999). The timing of fry emergence is believed to be a compromise between the advantages of early establishment in a territory, against the risks early in the season of increased high flow events (Armstrong and Nislow, 2006). Baum (1997) found less than 10% of Atlantic salmon eggs survived to emerge as fry in Maine Rivers in the USA. The reasons for the egg mortality included freezing, sedimentation, predation and extreme flow events leading to riverbed scouring or air exposure (NMFS and USFWS, 2004). Also, in Maine snowmelt rivers, low flows in the thirty days prior to spring runoff were found to increase pre-emergent alevin mortality (Frenette *et al*., 1984).

After emergence, the majority of young fry (approx. 70%) move less than 100m, although downstream distribution has been observed up to 1km (Cowx and Fraser, 2003). They shelter in low velocity nursery grounds (Fausch, 1984), typically near the riverbanks, as during this time the fry, that have limited swimming ability, are very susceptible to being displaced downstream in abrupt high flow events (Heggenes and Traaen, 1988). However, the near shore areas are highly susceptible to fluctuations in river height and discharge, therefore stable appropriate flows are very important in the late spring and early summer to maximise the marginal habitat zone available to fry (McKinney *et a*l., 2001). Territory size increases with fish size, with newly emerged salmon occupying territories of 0.02 to 0.03 m^2, fish on 5 cm length typically occupying 0.2- 0.5 m^2 and 10 cm fish occupying 5- 50 m^2 (Cowx and Fraser, 2003).

2.4.1.6. Juvenile growth

River discharge affects water depth as well as velocity, which are both important to juvenile salmon (Appendix G2). Water velocity near the streambed is also deemed one of the most important factors influencing the selection of microhabitat in juvenile salmon (Morantz *et al*., 1987; De Graf and Bain, 1986). Frenette *et al*. (1984) found parr growth and survival rates during the summer were positively correlated with flow rates, with low flows limiting parr growth and survival. This is believed to be due to the streams becoming shallower, reducing habitat availability and food delivery. The availability of natural sequences of riffles and pools, cover in the form of undercut banks, woody debris and boulders, and the natural sinuosity of the channel, increase the juvenile salmon carrying capacity of the river (Cowx and Fraser, 2003).

2.4.1.7. Juvenile migration into estuaries

Currently there is very limited data available on the flow requirements of migrating juvenile salmonids. Some believe the flow levels that encourage adult upstream migration should be adequate to promote juvenile downstream migration (Hendry and Cragg-Hine, 2003). The downstream migration of smolts is via passive displacement, with smolts actively seeking high velocity areas to assist their journey (Jonsson, 1991). Research has also shown the timing of smolt migrations is associated with increasing day length and water temperatures (Northcote, 1984). It is within the estuaries that smolts undergo smoltification; developing the ability to inhabit saline waters, ready for their migration to the ocean to feed. Despite this being a stressful time for the juvenile salmon, little is known about their habitat/feeding/resting requirements during this time in the lower river and estuary.

2.5 E-flow and Atlantic salmon summary

As exhibited above, the basic flow requirements of different stages of the Atlantic salmon lifecycle are fairly well established, at least compared to other species, but they still remain quite vague in terms of determining management and conservation measures for the species. One particular research gap during the Atlantic salmon lifecycle in the UK is the timing of migration into estuarine water and the use of intertidal habitat.

Overall, specific quantitative data defining flow limits and timings for Atlantic salmon are very limited, which makes setting environmental flows for the species very difficult. Limited information also exists on the impact of between year flow variability's on Atlantic salmon, although the complex lifecycle and varying time periods between different life stages may make this difficult to determine.

The study of environmental flows offers the opportunity to investigate what the ecologically acceptable flow regime for Atlantic salmon is, and what poor, average, and good years for salmon look like in terms of flow variability. However, the challenge remains due to the resolution of the paired hydrological and ecological datasets and the complexity of interrelationships with other stressors on the Atlantic salmon.

CHAPTER 3: RIVER DART- A HYDROLOGICAL CASE STUDY

3.1 APPLICATION OF A HYDROLOGICAL APPROACH

The previous chapter demonstrated the need to link long-term hydrological data with Atlantic salmon data in order to improve the environmental flow science for the species. In order to do this, the initial step was to characterise inter-annual and intra-annual flow variability at local, then regional and national scales in the UK. To achieve this a case study region was chosen: the southwest of England. The southwest was chosen because of the presence of significant salmonid rivers within the region and because it has comparatively less anthropogenic development within the river catchments and fewer modifications to the natural flow regime compared to other regions.

At a river catchment level, the individual rivers were selected to meet the following criteria:

- At least 40 years of flow data, which is comparable to other studies assessing long-term trends (Stahl *et al.*, 2010), and the equivalent for salmonid fish catch statistics;
- Limited flow modifications above the gauging station, in order to make the assumption that 'natural' flow variability was the most dominant factor affecting salmonid populations.

Flow data for individual gauging stations were obtained from the National River Flow Archive (NRFA) centre at the Centre for Ecology and Hydrology (CEH), Wallingford. The UK Hydrometric Register (Marsh & Hannaford, 2008), a periodic publication that catalogues the national hydrometric monitoring networks, was also used to obtain information about catchment characteristics, average runoff/rainfall parameters and anthropogenic modifications associated with each gauging station and its subsequent catchment.

3.2 Case Study- River Dart

The River Dart, a small catchment in the southwest of England (Figure 3.1), with limited anthropogenic influence, was used to assess the viability of using the IHA model to describe flow variability. The River Dart is situated in Devon and raises 550 metres above sea level in the Dartmoor National Park. The river begins as two separate branches, the East Dart and West Dart, which converge at Dartmeet. After leaving the moor, the Dart flows south passed Buckfast Abbey and through the towns of Buckfastleigh, Dartington and Totnes, before flowing into the sea at Dartmouth. The total catchment area covers 475 km^2 and has an estimated population of 31,000 people.

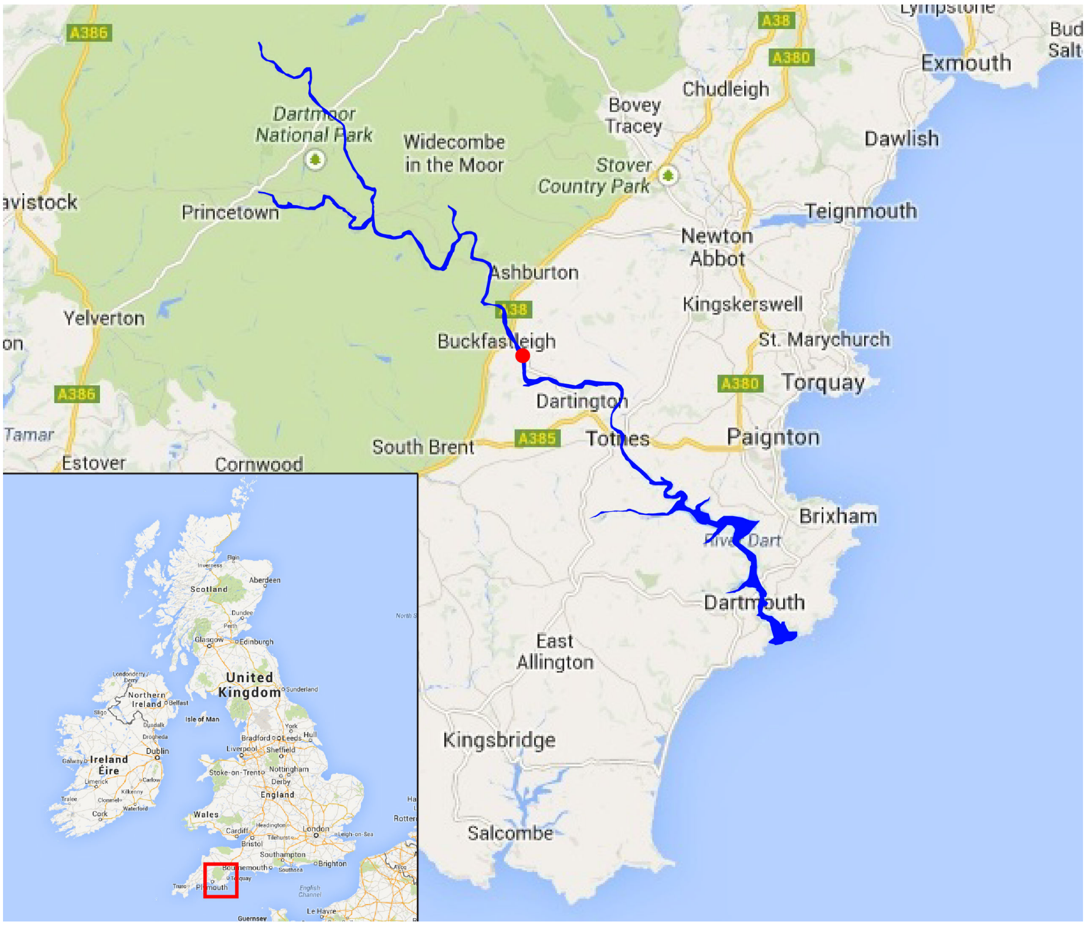

Figure 3.1. Location of the River Dart in the UK.

The River Dart flow at Austin's Bridge gauging station (station number 46003 on the UK Hydrometric Register) has a catchment area of 247.6km^2 and basic flow data is given in Table 4.1. The River Dart Austin's Bridge catchment is classified as quick to respond to precipitation events with the upper two thirds draining moorland, associated with Dartmoor Granite, and the lower third comprising of Carboniferous shales and sandstones. The system has steep relief in the headwaters and at the Granite boundary. The land-use within the catchment comprises approximately 56% grassland, 18% mountain / heath / bogland, 17% woodland and 5% arable land. The mean annual rainfall in the area is 1852mm, with a mean runoff of 1420mm. The Venford Reservoir operation has some affect on low flows on the Dart, as does the export via the Devonport Leat (Marsh & Hannaford, 2008). However, the small catchment has limited other anthropogenic pressures and, therefore, was considered to be a suitable case study to assess the effectiveness of the hydrological approach in differentiating flow regimes.

3.2.1. River Dart year on year variations

Preliminary analysis of median annual flows on the River Dart indicate the presence of 'wet' and 'dry' years, against the averaged annual median flow of the whole data (1959-2008), which was 9.10 $m^3 s^{-1}$ (Figure 3.2). The lowest annual median flows and, therefore, the top three driest years were 1976 with 3.89 $m^3 s^{-1}$, 1992 with 5.90 $m^3 s^{-1}$ and 1989 with 6.13 $m^3 s^{-1}$. The highest annual median flow was in 2000, with 20.55 $m^3 s^{-1}$.

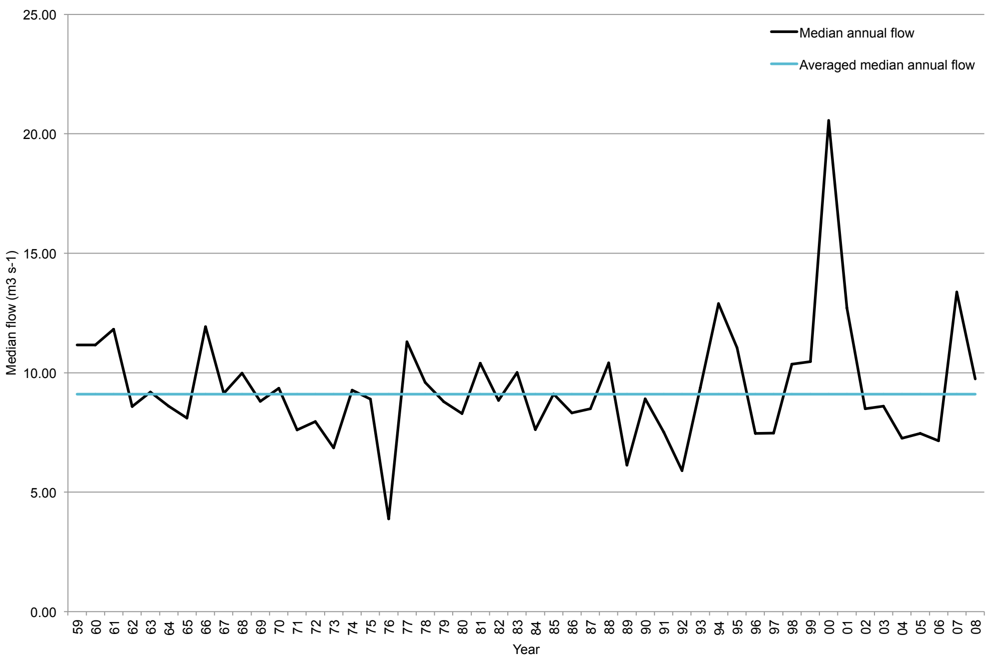

Figure 3.2. Annual median flow averages on the River Dart against the overall average median flow, 1959-2008.

Overall, the annual median average indicates the 1990s and 2000s had the highest proportion of extreme wet and dry years, suggesting the flow regime of the River Dart is becoming more variable over time. To test whether there was a statistically significant difference between the decades, the absolute difference of each score from the overall mean was calculated and entered into a one-way ANOVA (with 5-levels as there were 5 decades). No significant difference between the decades was found (F (4,48)=1.73, p= 0.16).

3.2.2. IHA on whole River Dart dataset

Initially, the IHA was used to analyse 49 years of flow records for the Dart (from 1959 to 2008) in order to examine the ability of the IHA to characterise the flow variability. When using the IHA model to analyse data, the following assumptions were made:

- The water year runs from the 1st September - August 31st.
- All analyses used non-parametric statistics (given that the data does not conform to parametric assumptions), therefore averages were described as medians and percentiles.

The scorecard of annual average data is divided into five groups of parameters (Table 3.1). The first IHA parameter group describes the magnitude of monthly water conditions as a median value for each calendar month for the given watercourse.

The River Dart data shows a flow regime shape typical of the warm temperate maritime hydro-climatic region. This has a single dominant flow peak in December and January (medians 16.16 $m^3 s^{-1}$ and 16.34 $m^3 s^{-1}$), declining in the spring to a minimum median low flow in July of 2.64 $m^3 s^{-1}$ (Figure 3.3 and Table 3.1).

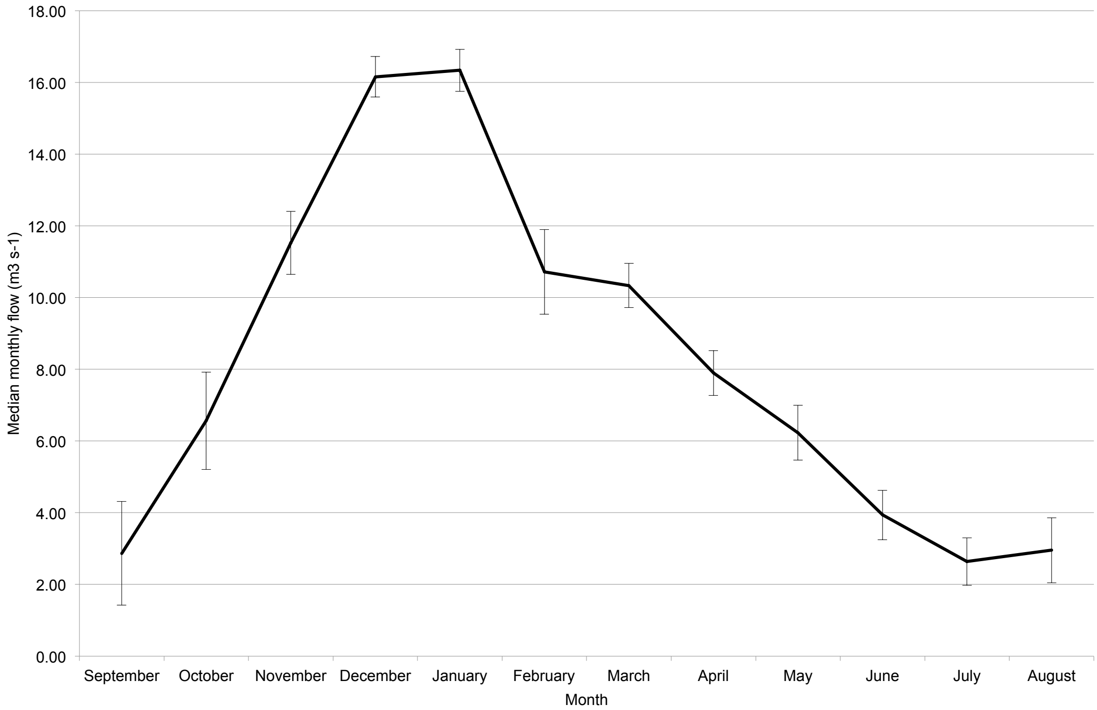

Figure 3.3. Median monthly flows for River Dart, 1959-2008. [Error bars represent ± 1 SE of the median].

However, it is important to understand the natural variability in the flow regime over time. Therefore, the complete River Dart flow record from 1959 to 2008 was divided into six overlapping 15 year time periods; 1959-1974, 1965-1980, 1972-1987, 1979-1994, 1986-2001 and 1993-2008, and analysed using the IHA. This shows that the median monthly flows are relatively similar between the different time periods (Figure 3.4). The time period of 1986-2001 has a higher median flow in November, and 1965-80 has a higher flow in February. The time periods of 1986-2001 and 1993-2008 also have a higher median monthly flow in January, compared with the other time periods. The time periods of 1959-74 and 1965-80 have lower average monthly flows in December. This suggests the most natural variability in median monthly flow occurs in between November and February (see Appendix Table B.1).

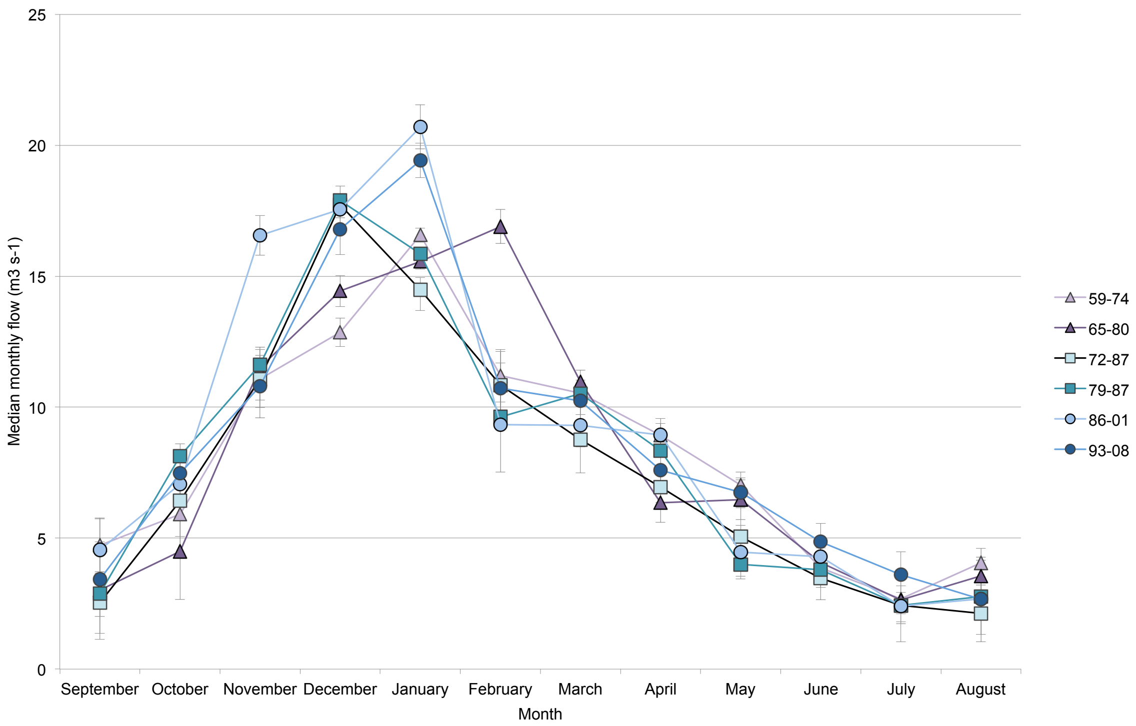

Figure 3.4. Median monthly flow on the River Dart divided into overlapping time series; 59-74, 65-80, 72-87, 79- 94, 86-01 and 93-08.

The parameter group 2 (Table 3.1) depicts the magnitude and duration of mean annual extreme water conditions. The minimum and maximum values are taken from moving averages of the appropriate length calculated for every possible period that is completely within the water year. The median 7-day minimum flow on the River Dart was 1.45 $m^3 s^{-1}$, whereas the 1-day maximum was 91.35 $m^3 s^{-1}$ and 3-day maximum was 63.97 $m^3 s^{-1}$.

Parameter group 3 (Table 3.1) calculates the timing of annual extreme water conditions, using two parameters: the date of each annual 1-day maximum and minimum. The date of the minimum flow on the Dart was in August and the maximum daily flow occurred in January. When the annual data was analysed, the maximum flow days occurred 37% of the time in January and 20% of the time in December.

Parameter group 4 (Table 3.1) describes the flow regime by the frequency and duration of high and low pulses, using four parameters. A pulse in this context is defined as a daily mean flow above or below the annual number of daily mean flows greater than the 75th percentile and the annual number less than the 25th percentile over the period of record. On the River Dart, the annual average between 1959- 2008 was 7 low pulse counts, lasting an average of 6 days each (threshold 3.63 $m^3 s^{-1}$) and 17 high pulses counts averaging 2 days each (threshold 14.53 $m^3 s^{-1}$) per year.

Table 3.1. River Dart environmental flow component parameters, 1959-2008.

	Medians	CoD		Medians	CoD
Parameter Group #1			**EFC Low flows**		
September	2.87	1.45	September Low Flow	2.99	0.93
October	6.56	1.36	October Low Flow	4.69	0.77
November	11.53	0.88	November Low Flow	6.88	0.59
December	16.16	0.56	December Low Flow	8.9	0.36
January	16.34	0.59	January Low Flow	9.45	0.53
February	10.72	1.18	February Low Flow	7.74	0.42
March	10.34	0.62	March Low Flow	6.91	0.43
April	7.9	0.63	April Low Flow	6.15	0.43
May	6.24	0.77	May Low Flow	4.81	0.59
June	3.94	0.69	June Low Flow	3.72	0.54
July	2.64	0.66	July Low Flow	2.56	0.55
August	2.95	0.91	August Low Flow	2.85	0.59
Parameter Group #2			**EFC Parameters**		
1-day minimum	1.36	0.54	Extreme low peak	1.41	0.29
3-day minimum	1.39	0.57	Extreme low duration	6	1.75
7-day minimum	1.45	0.59	Extreme low timing	235	0.16
30-day minimum	1.89	0.63	Extreme low freq.	2	2
90-day minimum	3.8	0.69	High flow peak	17.75	0.23
1-day maximum	91.35	0.5	High flow duration	3	0.33
3-day maximum	63.97	0.52	High flow timing	52.75	0.39
7-day maximum	48.75	0.41	High flow frequency	19	0.33
30-day maximum	31.25	0.31	High flow rise rate	6.35	0.38
90-day maximum	21.39	0.34	High flow fall rate	-3.56	-0.23
Number of zero days	0	0	Small Flood peak	107	0.15
Base flow index	0.13	0.73	Small Flood duration	28	0.98
Parameter Group #3			Small Flood timing	16	0.13
Date of minimum	242.5	0.12	Small Flood freq.	0	0
Date of maximum	18	0.14	Small Flood rise rate	10.87	2.37
Parameter Group #4			Small Flood fall rate	-7.2	-0.5
Low pulse count	7	0.71	Large flood peak	140	0.49
Low pulse duration	6	1.04	Large flood duration	35	0.81
High pulse count	17	0.29	Large flood timing	19	0.14
High pulse duration	2	0.56	Large flood freq.	0	0
Low Pulse Threshold	3.63		Large flood rise rate	6.71	10.78
High Pulse Threshold	14.53		Large flood fall rate	-8.69	-1.13
Parameter Group #5					
Rise rate	1.65	0.76			
Fall rate	-0.6	-0.46			
Number of reversals	128.5	0.15			

The final parameter group 5 (Table 3.1) calculates the rate and frequency of water level changes using three parameters: rise and fall rates and the number of hydrologic reversals. The rates are calculated by dividing the hydrologic record into "rising" and "falling" periods, which relate to periods in which daily changes in flows are either positive or negative, respectively. A rising or falling period is, however, not ended by a pair of days with constant flow, but only by a change of sign in the rate of change. The number of reversals is the number of times that flow switches from one type of period to another during a water year. This is ecologically relevant because of entrapment of organisms on islands, floodplains (rising levels), and desiccation stress on low-mobility organisms (falling levels). On the River Dart, the rise rate was 1.65 and the fall rate was -0.60. The number of hydrologic reversals was 128.50 on average each year.

The annual summary of all years between 1959-2008 on the River Dart show the extreme low flow events typically occurred in August, with a low peak of 1.41 m^3 s^{-1}, and an average duration of 6 days. The high flow timing was typically in February, occurring on average 19 times per year, with an average peak of 17.75 m^3 s^{-1}. The small flood timing was typically in January, with an average peak of 107 m^3 s^{-1}. The large floods also commonly occurred in January with an average peak of 140 m^3 s^{-1}.

To look more specifically at the low and high flow pulses and flood events, the Annual Statistics Table can provide more information. From this table (modified in Table 3.2), it is possible to see that the year with the greatest number of low pulse events was 1997, which had 17 low pulse events. The fewest number of low pulse events was in 1968 and 1983, which both only had 2 low pulse events. The greatest high pulse events occurred in 2008 (24 high pulse events) and fewest number of high pulse events occurred in 1997 (6 high pulse events).

Table 3.2. River Dart environmental flow component low pulse and high pulse parameters, from the Annual Statistic Table (1959-2008).

Year	Low pulse number	Low pulse length	High pulse number	High pulse length	Year	Low pulse number	Low pulse length	High pulse number	High pulse Length
1959	5	13	10	3	1984	5	16	12	2
1960	8	3	10	9	1985	10	4	20	2.5
1961	5	21	16	2.5	1986	6	6.5	19	2
1962	5	2	21	1	1987	11	6	16	2
1963	4	1.5	21	2	1988	9	3	20	1
1964	4	13	17	2	1989	4	1.5	9	3
1965	4	9.5	17	2	1990	11	10	7	6
1966	8	2	15	2	1991	8	9.5	15	1
1967	7	3	19	2	1992	6	9.5	18	1
1968	2	7	21	2	1993	8	6	17	1
1969	3	16	23	2	1994	7	7	18	2
1970	10	5	17	1	1995	6	7.5	12	3
1971	11	8	14	2.5	1996	11	5	18	2
1972	6	12	19	1	1997	17	3	6	8.5
1973	13	5	18	1.5	1998	5	12	17	2
1974	11	7	16	1	1999	8	4.5	15	1
1975	6	13	23	2	2000	0		9	2
1976	11	6	8	1.5	2001	7	9	9	1
1977	6	5.5	17	3	2002	7	6	15	2
1978	13	5	13	2	2003	5	22	14	3
1979	7	5	18	2	2004	10	2	23	1
1980	13	5	17	1	2005	9	3	17	2
1981	7	3	23	2	2006	8	5.5	15	2
1982	9	11	19	3	2007	5	13	22	1.5
1983	2	45.5	19	1	2008	6	5	24	2

In order to determine the timing of the high pulses the environmental flow components daily table must be consulted manually, as the output shows how each day has been classified in terms of environmental flow components, therefore it is possible to determine when each high pulse event has occurred. For the River Dart, this indicates that 16.96% (n=567) of the high pulse events recorded were in December (Table 3.3). A secondary peak of 13.04% (n=436) in occurred in March. The percentage distribution shows an expected distribution pattern throughout the year, with the lowest number of high pulse events occurring in June and July. There was a steep increase in high pulse events between September and October. This may suggest that, on the River Dart, the upward migration of salmonids is likely to coincide with this.

Table 3.3. Number of high pulse events, which occurred in each month for River Dart between 1959-2008.

Month	Number of high pulse events	Average per year (to nearest whole number)
January	530	11
February	394	8
March	436	9
April	235	5
May	137	3
June	54	1
July	42	1
August	76	2
September	99	2
October	313	6
November	460	9
December	567	12

The annual statistics table indicates that between 1959 and 2008, the River Dart had 30 small floods (see Appendix B.2) and 5 large floods events. Further analysis of the environmental flow components daily table (Appendix B.3) shows the large floods were mainly concentrated in the 1990s and the peak flow for the large floods remained relatively constant, apart from 1980. The timing and details of the large flood events on the River Dart were:

- Water year 1961: 28/01/61- 13/02/61 – duration 18 days, peak 140.3 m^3 s^{-1}
- Water year 1980: 26/12/79- 07/01/80 – duration 13 days, peak 268 m^3 s^{-1}
- Water year 1990: 19/01/90- 05/03/90 – duration 46 days, peak 143.3 m^3 s^{-1}
- Water year 1993: 16/11/92-12/12/92 – duration 27 days, peak 135 m^3 s^{-1}
- Water year 1999: 18/12/98- 29/01/99 – duration 43 days, peak 140.6 m^3 s^{-1}

In contrast, the small floods appeared to increase in frequency through time, with the greatest quantity of the small floods occurring in the 2000s; four of which occurred in just two years (2007 and 2008). The small floods occurred in (where * = indicates two small floods in the same year):

- 1960’s: 4 small floods (61, 62 and 66*)
- 1970’s: 5 small floods (71, 73, 74, 75 and 78)
- 1980’s: 7 small floods (81*, 83, 84, 85, 87 and 88)

- 1990’s: 6 small floods (93*, 94, 95* and 99)
- 2000’s: 8 small floods (02, 06, 07* and 08*)

3.3. TRIALLING NEW ANALYSIS METHOD

The IHA descriptive summary of the average flow regime has limited functional use in helping to determine between year variability in the flow regime, because the variability is grouped annually to illustrate a typical annual flow regime. In order to assess between year variability, it is proposed the IHA is combined with regime classification. This should enable subtle differences between years to be identified, which may influence ecological responses.

In order to assess intra-annual flow regime variation, principle components analysis (PCA) and cluster analysis (CA) were applied to the daily flow records. PCA in combination with CA is a frequently used approach to classify hydrological similarities (Yarnal, 1993; Hannah *et al*., 2000). A varimax rotation was used on the PCA to reduce the dimensionality of the large multivariate flow data set, the outcome of which is a number of principle components (PCs) that describe the main modes of covariation between the original flow variables. Subsequently, an agglomerative hierarchical CA was applied to the matrix of PC scores in order to identify groups of years with similar hydrologic characteristics. As the CA groups are based on similar (or related) parameters within the group, the distinct clustering comes from greater similarity within the group and greater differences between the groups. Years that did not group with any other year were classified as outliers. Finally, the IHA is applied to the resultant CA output, in order to better describe the flow parameters found in each of the output groups. The PCA and CA analyses were conducted in SPSS, PASW Statistics 12 (See method protocol Appendix B.4).

The results from the River Dart, using the method above, (from 1959-2008, where 1968 and 2008 were removed as outliers) indicated four distinct regime types (Appendix B.5):

- Regime 1: the largest cluster occurred 53.2% of the time (25 years in total) and had a single, high magnitude peak in median average flow in January/February.

- Regime 2: occurred 25.5% of the time (12 years in total) and had a single high magnitude peak in December.
- Regime 3: occurred 12.8% of the time (6 years in total) and had an early high magnitude peak in December, followed by a higher magnitude peak in March.
- Regime 4: occurred 8.5% of the time (4 years in total) and had two peaks, the first in November, followed by a second, higher magnitude peak in January.

3.3.1 Suitable measure of variability around the median

The IHA is hard-wired to calculate the inner quartile range, or coefficient of dispersion, as: (75th percentile - 25th percentile) / 50th percentile. This non-parametric statistic is comparable to the coefficient of variation (standard deviation / mean), and considered an important measure of the spread of data about the median value. It allows meaningful comparisons to be made from comparative data sets.

Analyses of each of the regimes (defined above) was conducted using the basic assumption that the regimes would be grouped together if the coefficients of dispersion range overlap (Figure 3.5), where for the purpose of this analysis i) ‘clustered’ is defined as three of the four regimes having overlapping coefficients of variation, ii) ‘overlap’ is defined as two of the four regimes having overlapping coefficients of variation, and iii) ‘grouped’ is defined as all the four regimes having overlapping coefficients of variation.

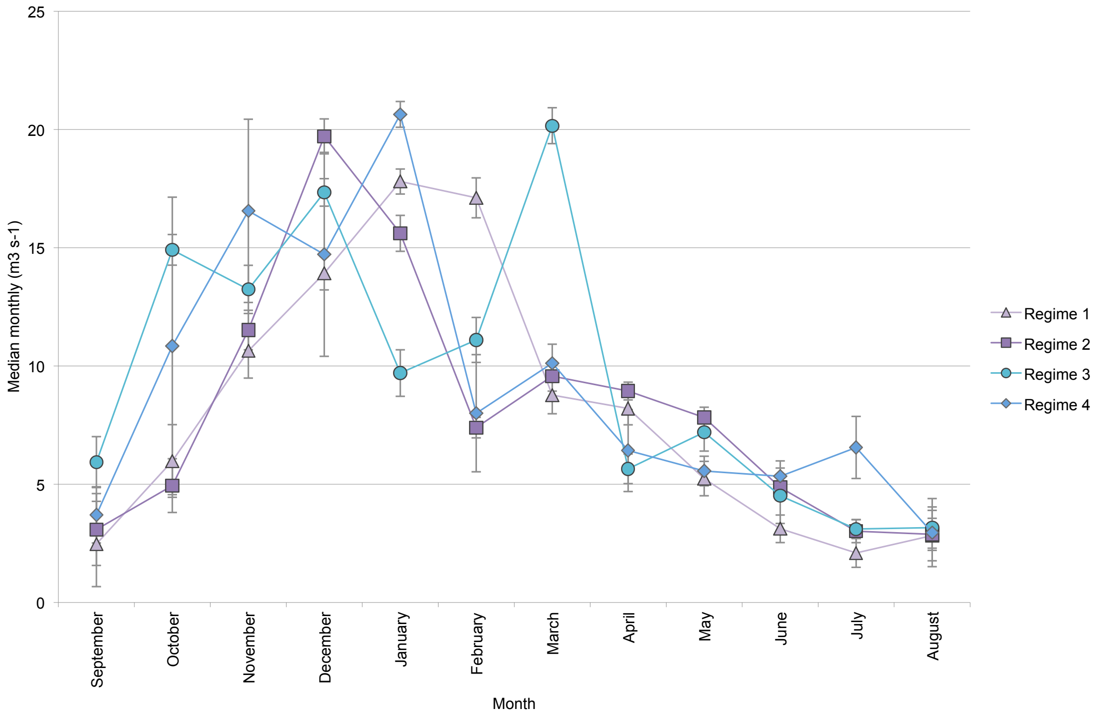

Figure 3.5. Median monthly flows for the four regime shapes from the River Dart, 1959-2008 (1968 and 2008 were removed as outliers).

This indicated that:

- October: All regime flows overlap, apart from regime 1 and 3, and 2 and 3.
- November: Separately regimes 1 and 2, and 3 and 4 overlap. Regimes 2 and 3 also overlap.
- December: Regime 4 independently overlaps with each of the other regimes.
- January: All regimes have distinct non-overlapping median flows.
- February: Regimes 2, 3 and 4 are clustered together, with regime 1 being an outlier, with higher median flow; however regimes 2 and 3 do not directly overlap.
- March: Regimes 1, 2 and 4 are clustered together, with regime 3 being an outlier, with higher median flow.
- April: two distinct overlaps are apparent, with regimes 1 and 2 with a higher median flow than the second overlap, regimes 3 and 4; however regimes 1 and 4 also overlap.
- May: two distinct overlaps are apparent with regimes 2 and 3 with a higher median flow than the second overlap, regimes 1 and 4.

- June: Regimes 2, 3 and 4 are clustered together, whereas regime 1 only overlaps with regime 3.
- July: Regimes 1, 2 and 3 are clustered together, with regime 4 being an outlier, with higher median flow; however regimes 1 and 3 do not directly overlap.
- August: All regimes grouped together.
- September: All regimes grouped together.

The most variation and unpredictability in median flows between years was found in January, shown by no overlap in the coefficient of variation for any of the four regimes. In January, regime 4 had the highest median monthly flow, with 20.64 $m^3 s^{-1}$, and regime 3 had the lowest median flow with 9.70$m^3 s^{-1}$. In October, the median monthly flows varied from 4.94$m^3 s^{-1}$ in regime 2 to 14.91$m^3 s^{-1}$ in regime 3. This variability reduced substantially in November, with median monthly flows varying from 10.64 $m^3 s^{-1}$ (regime 1) to 16.56 $m^3 s^{-1}$ (regime 4). In December, the median monthly flows ranged between 13.92$m^3 s^{-1}$ (regime 1) to 19.71$m^3 s^{-1}$ (regime 2). The range of regime 4 overlapped with each of the other regimes; however, the coefficient of dispersion for regime 4 was very large (4.31 $m^3 s^{-1}$).

In both February and March, three out of the four regimes tended to have similar median flows, with one outlier. In February, regime 1 was the outlier, with substantially higher median monthly flows (averaging 17.11 $m^3 s^{-1}$) compared to the other regimes. However, as regime 1 was the largest cluster (i.e. represented the most years), and was, therefore, the most commonly occurring regime, it means these higher flow events in February typically occurred 1 in 1.8 years. The median monthly flow for the remaining clustered regimes (2, 3 and 4) ranged between 7.40- 11.11 $m^3 s^{-1}$. In March, regime 3 was the outlier with a higher average monthly flow of 20.16 $m^3 s^{-1}$, compared with a range between 8.77- 10.12 $m^3 s^{-1}$ for regime 1, 2 and 3. As regime 3 was less common, these higher flows in March would typically only occur 1 in 7.8 years.

The variability in median monthly flow reduced between April and September. In April and May the regimes split into two distinct groupings. In April, regimes 1 and 2 overlapped, with ranges between 8.20 to 8.94 $m^3 s^{-1}$, and regimes 3 and 4 overlapped, with a range of between 5.65 to 6.43 $m^3 s^{-1}$. However, in this month, regime 1 and 4 also overlapped, predominately due to larger variability in median flows in regime 4, demonstrated by a coefficient of dispersion of 1.64 $m^3 s^{-1}$. In May there was no overlap between these two groupings. In the previous month, regimes 2 and 3 overlapped, with a range of between 7.20 to 7.82 $m^3 s^{-1}$, and regime 1 and 4 overlapped, with a range of between 5.24 to 5.34 $m^3 s^{-1}$ This change in groupings is likely be due to the median monthly flow of regime 3 increasing between April and May, whereas in all the other regimes flow decreased between these months.

In June, the variability between regimes reduced and most of the regimes were clustered together. During this month, regime 1 had the lowest median monthly flows of 3.12 $m^3 s^{-1}$ and regime 2 had the highest median monthly flows of 4.86 $m^3 s^{-1}$. In July, regime 4 was the outlier with substantially higher median flows (6.56 $m^3 s^{-1}$) compared to the other regimes, which ranged between 2.10 (regime 1) to 3.11 $m^3 s^{-1}$ (regime 3). This augmentation in flows during regime 4 could be the result of summer storm events or possibly due to human alterations in the flow regime, such as an alteration in the operation of the Venford Reservoir.

In August, all four regimes were grouped together with a median monthly flow range of between 2.83 $m^3 s^{-1}$ (regime 1) - 3.17 $m^3 s^{-1}$ (regime 3). The same pattern was found in September, with a range of between 2.24 $m^3 s^{-1}$ (regime 1) – 4.57 $m^3 s^{-1}$ (regime 3).

Flow over the year in regime 1 was the typical temperate hydrograph, with high winter flow, followed by spring recession and summer base flows. Regime 2 had an earlier high magnitude peak in December, followed also by a typical spring recession. Regime 3, however, had high early autumn flows, followed by a dry early winter and high late winter peak. To investigate whether the high autumn flows were an artificial phenomenon due to the forced year start in September, the August flows prior to the 6 years (1963, 1967, 1981, 1982, 1989 and 1997) in regime 3 were analysed. The results show no indication of a wet

August prior to these years. Regime 4 also had a high flow autumn, followed by a typical spring recession, but larger than average base flows in July.

The median low (base) flows show a similar pattern to the median monthly average flows, with the most variation and unpredictability occurring in January; with regime 4 having the largest average base flows of 11.35 $m^3 s^{-1}$ and regime 3 with the lowest average base flows of 6.61 $m^3 s^{-1}$ (Figure 3.6).

In October, November, February, March, April, May and June three out of the four regimes tended to have similar median base flows, with one outlier:

- October: regime 3 had the highest base flows with 8.77 $m^3 s^{-1}$, compared with a range of 4.49-5.70 $m^3 s^{-1}$ between the remaining regimes.
- November: regime 4 had higher base flows, with 10.49 $m^3 s^{-1}$, compared with a range of 7.02-7.83 $m^3 s^{-1}$ between the remaining regimes.
- February: regime 1 had higher than average base flows, with 9.07 $m^3 s^{-1}$, compared with a range of 6.21-6.59 $m^3 s^{-1}$ between the remaining regimes.
- March: regime 3 had higher than average base flows with 9.13 $m^3 s^{-1}$, compared with a range of 6.28-8.02 $m^3 s^{-1}$ between the remaining regimes.
- April: regime 2 had higher base flows with 8.18 $m^3 s^{-1}$, compared with a range of 4.83-5.92 $m^3 s^{-1}$ between the remaining regimes
- May: regime 2 had higher base flows with 6.76 $m^3 s^{-1}$, compared with a range of 4.61-5.53 $m^3 s^{-1}$ between the remaining regimes
- June: regime 1 had lower base flows with 3.12 $m^3 s^{-1}$, compared with a range of 4.24-5.19 $m^3 s^{-1}$ between the remaining regimes

The least variability in base flow during the autumn/winter months was found in December, where all the regimes' medians were within the range of 8.14-9.29 $m^3 s^{-1}$. In the spring/summer months, the lowest variability between regimes base flows was found in August, with a range of 2.74 - 3.38 $m^3 s^{-1}$. In July, regime 4 had higher median flows of 6.50 $m^3 s^{-1}$ compared to the other regimes, while regime 1 had a lower base flow of 2.13 $m^3 s^{-1}$, compared with regime 2 and 3, which ranged between 3.16-3.31 $m^3 s^{-1}$.

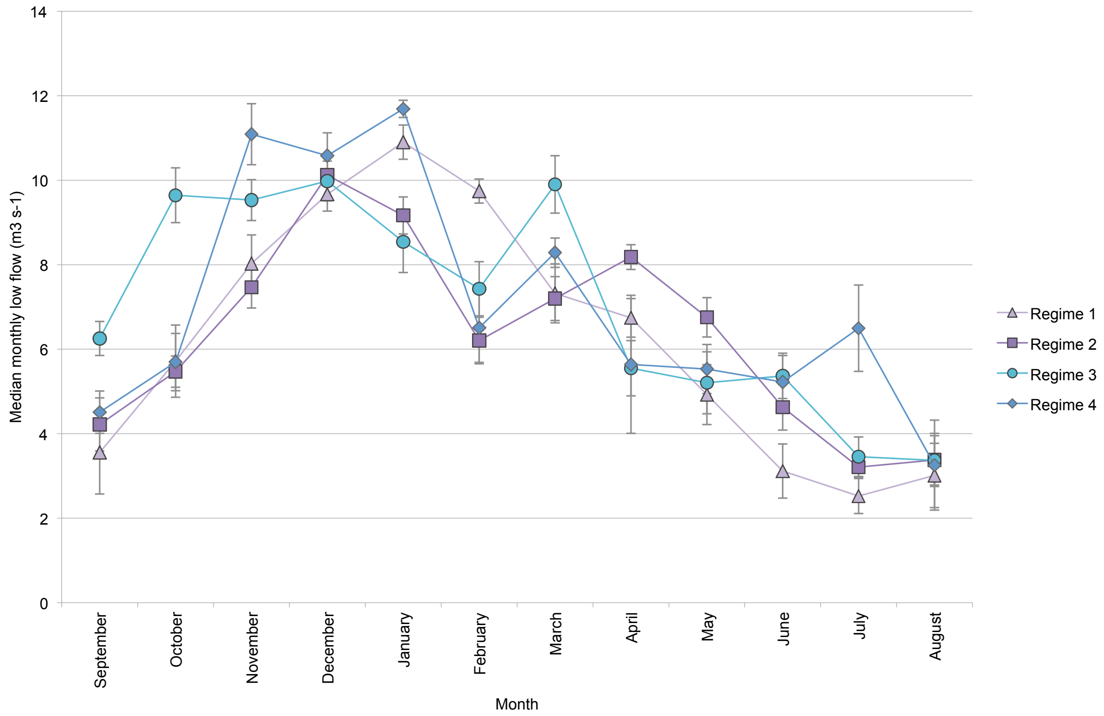

Figure 3.6. Median monthly low flows of four regime types from the River Dart, 1959-2008 (1968 and 2008 were removed as outliers).

3.3.2. Other IHA output parameter analysis

The additional IHA parameter output on the River Dart showed (see Appendix B5):

- Regime 1: the lowest median flows typically occurred in July. The typical extreme low flow event occurred in July, the high flow timing, small flood and large flood timing all typically occurring in January.
- Regime 2: the lowest median lows typically occurred in July. The average extreme low flow event occurred in August, the high flow timing typically in March, small flood in December and large flood timing in January.
- Regime 3: the lowest flows typically occurred in August. The average extreme low flow event occurred in August, and the high flow timing typically in November, small flood in December and large flood timing in March.
- Regime 4: the lowest flows typically occurred in August. The average extreme low flow event occurred in August, the high flow timing typically in February, small flood in November and large flood timing in March.

The largest magnitude (peak) of small flood was found in regime 2 (121.50 m^3 s^{-1}), compared to the lowest in regime 3 (91.95 m^3 s^{-1}). The duration of small floods varied from 25.5 days in regime 2 to 17 days in regime 2. The largest magnitude of large flood was found in regime 1 (205.60 m^3 s^{-1}), compared the lowest in regime 4 (97.20 m^3 s^{-1}). The duration of large floods varied from 30 days in regime 1 and 2, to 9 days in regime 3. Based on the flood data, regime 3 appeared to contain the least flashy years and, therefore, years with the least heavy rainfall events.

The lowest 7- day minimum flows of 1.22 m^3 s^{-1} occurred in regime 3, and the highest in regime 3, with 1.83 m^3 s^{-1}. For the 30-day and 90-day minimum flow, regime 1 had notably prolonged lower flows than the other regimes. The highest 1-day maximum flow was found in regime 2 (109.30 m^3 s^{-1}), and the highest 30 and 60-day maximums were found regime 4 (35.88 m^3 s^{-1} and 25.8 m^3 s^{-1}). The lowest 1-day maximum flows were in regime 3, with 89.58 m^3 s^{-1}.

The dates of minimum flows were all very similar, with regime 1, 2 and 4 all occurring in August, and regime 3 on average, occurring on the first day of September. The date of the maximum flow was December for regimes 2 and 3, January for regime 1 and February for regimes 4.

Environmental flow components analyses on the occurrence of high pulse events for different months for each regime showed the largest variability in the number of high pulse events occurred in January (Figure 3.7), where regime 4 (24.76%) had the highest occurrence of high pulse and regime 3 (6.21%) had the lowest occurrence of high pulses. The number of high pulses increased for all regime between September and October. Regime 3 was the only regime to have a higher occurrence of high pulses in February than in January.

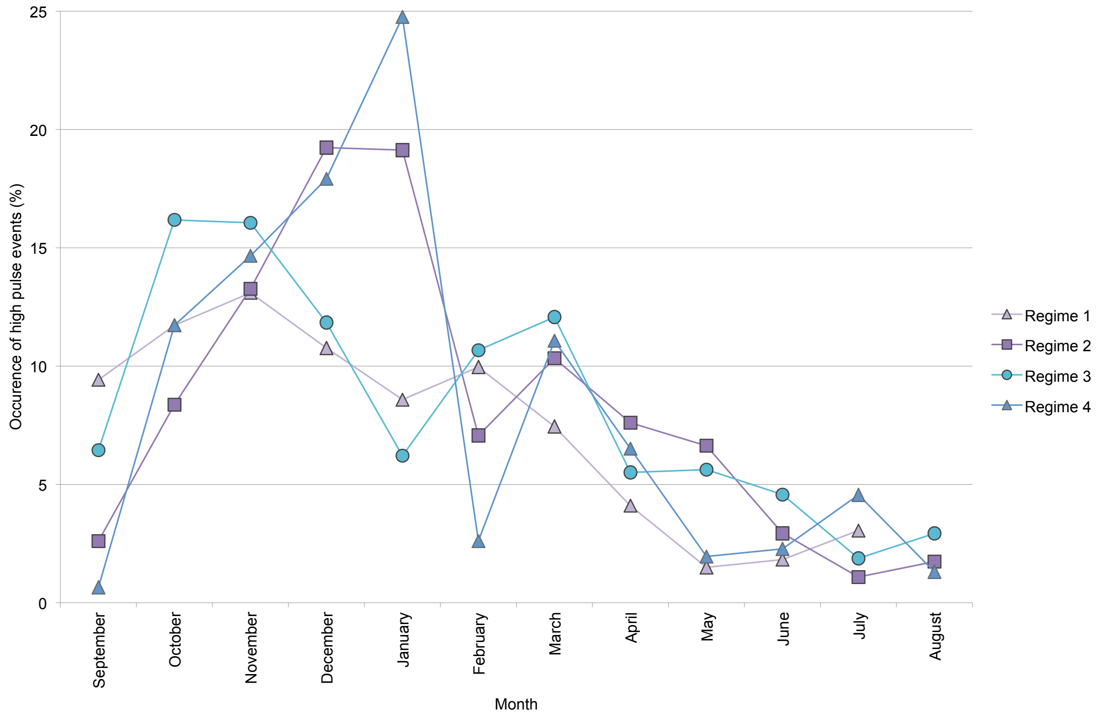

Figure 3.7. High pulse occurrence (%) in each month for the four regimes on the River Dart, 1959-2008 (1968 and 2008 were removed as outliers).

3.4. REDUNDANT IHA PARAMETERS

Olden and Poff (2003) assessed the statistical variation (using PCA) of 171 published hydrological variables, using long term flow records in 420 locations across the USA. They found that the IHA parameters adequately represented the majority of flow information, which could be derived by current indices available to scientists. However, there is concern that some of the IHA's 33 individual metrics and 33 associated measures of variation are inter-correlated and, therefore, over complicating the environment flow assessment (Arthington *et al*., 2006).

In order to assess which parameters should make up the toolbox for comparisons with fisheries data within this study, a Spearman's (non-parametric) correlation was conducted between all IHA parameters using the southwest regional database (a database containing flow daily data for the six southwest rivers used in this study). This assessed whether there was a significant relationship between each of the parameters used, and therefore if any of the IHA parameters were not required because they did not provide significantly different data from other parameters.

The results showed (Appendix B.6):

- The median monthly flows between January and August are correlated with the month before, e.g. January was positively correlated with February, February was positively correlated with March, March was positively correlated with April etc. This relationship breaks down between August and November (which reflects the end/start of the hydrological year). However, November was also positively correlated with December. This means is it possible to use every other month in the analysis. This also indicates that the beginning of the hydrologic year in the southwest of England is September, because the months up until this month correlate with the preceding month.
- The 1, 3, 7, 30 and 90-day minimum flows are all positively correlated with July flows, therefore July flows are representative of the summer flows in the southwest.
- The 1, 3, 7, 30 and 90-day maximum flows are all positively correlated with January flows, therefore January flows are representative of the winter flows in the southwest.
- All the small flood parameters (flood peak, duration, time and frequency) are positively correlated with 1, 3, 7, 30 and 90-day maximum flows, therefore 1-day maximum will be used to represent these parameters.
- All the large flood parameters (large flood peak, duration, time and frequency) are all positively correlated with each other. These are important for the morphology of the river, although the timing and peak could be the most important large flood parameters for fish.

High flow parameters are recognised as important for upstream salmonid migration in the autumn, therefore all high flow parameters were selected. Therefore, the final toolbox of IHA parameters chosen to reduce overlap and represent flow parameters deemed to be the most important for Atlantic salmon are: January, March, May, June, July, September, October and November median flows, 1-day maximum flow, 1-day minimum flow, high flow peak, time and frequency, and large flood time and peak.

3.5. VARIATION IN REGIMES OVER TIME

The classification of each flow year into a regime type allows investigation into how the regime types vary through time. On the River Dart the occurrence of the different regimes indicates that the 1960s were quite varied (Appendix B.7), with regime shape 1 only occurring 40% of the time. The 1970s were dominated by regime shape 1, with 80% occurrence and no occurrence of regime 3 or 4. The 1980s were also dominated by regime 1, with 50% occurrence. Regime 4 did not occur in the 60s, 70s or 80s. The 1990s were varied: regime 1 had 40% occurrence, regime 2 had 30% occurrence, and regime 4 occurred 20% of the time. The 2000s were dominated by regime 1 with 57% occurrence, and regime 4 was the second most common with 29% occurrence. A comparison of regime alteration in other southwest rivers would need to be conducted to determine if this is a regional/ climatic pattern, or due to local changes in land-use and flow modification on the River Dart.

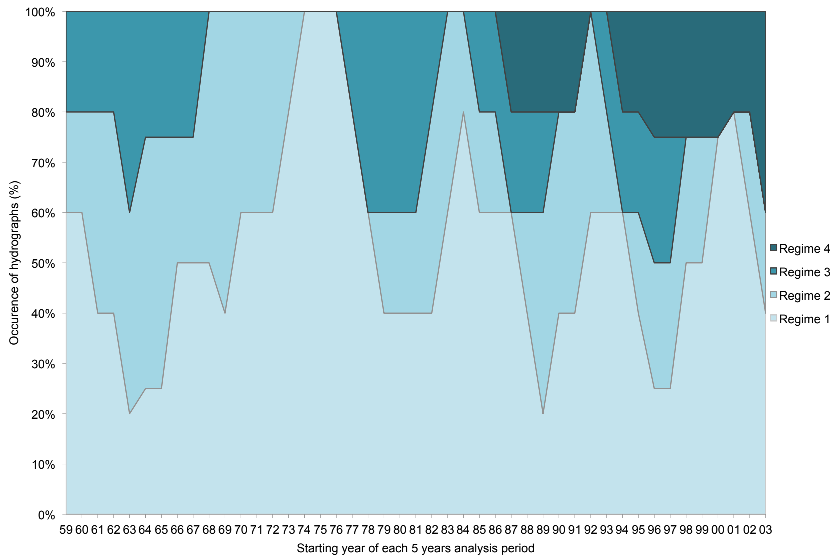

Figure 3.8 Moving averages for 5-year regime distribution on the River Dart (where each x-axis year represents the proportion of each regime type for a 5 year time period).

In order to display the occurrence data, overlapping moving average graphs were used to emphasise the trends and smooth out the 'noise' in the data. Displaying the occurrence of regimes through time in this way indicated the finer scale 5-year moving average (Figure 3.8) was less useful at highlighting generic patterns in regime distribution than the coarser 20 year moving average (Figure 3.9), which was more appropriate to investigate long-term trends.

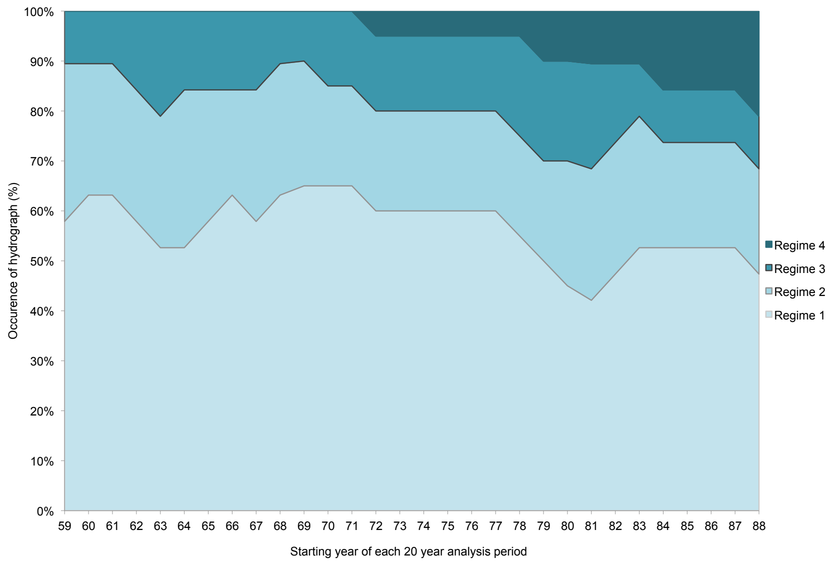

Figure 3.9 Moving averages for 20-year regime distribution on the River Dart (where each x-axis year represents the proportion of each regime type for a 20 year time period).

3.6. River Dart case study summary

The River Dart case study indicates that overall the PCA/CA combined with IHA model could provide a useful toolbox of flow parameters to correlate with Atlantic salmon rod catch data. This analysis method would allow between year variations in flow regimes to be investigated, in particular:

i. The **magnitude** of the flow within a river system. Flow magnitude is important as it affects the habitat and food availability for aquatic organisms, including salmon, and influences abiotic factors, such as water temperature and oxygen levels, which are vital to salmon populations. Biologically, the variations in flow are extremely important for the evolution of life history strategies and behavioural mechanisms, such as spawning cues for migratory fish, and access to preferential habitats. High flow magnitude, timing, and duration can also impact the ecosystem by shaping river channel morphology and the physical habitats for organisms, and affecting the volume of nutrient exchanges between rivers and floodplains.

ii. The **timing** of high flows is also particularly significant for salmonid species in initiating migrations. Flow pulses affect the availability of floodplain habitats and the water quality, by influencing the nutrient and organic matter exchanges between river and floodplain. It also influences bedload transport, and duration of substrate disturbance in high pulses. A weakness, however, of the IHA model is in the characterisation of pulse and flood events as annual averages. This means there is no way (other than referring back to the raw data) to determine which season the events have occurred in. The lack of seasonal resolution in this approach is a limitation. However, the possibility of its wide scale application at local, regional and national levels could make this approach beneficial.

The next two chapters (4 & 5) will use the approach trialled in this chapter, PCA with CA and IHA model, to investigate UK national, regional and local flow variability.

CHAPTER 4: FLOW VARIABILITY ACROSS ENGLAND AND WALES

4.1. UNDERSTANDING VARIABILITY

In the UK there are almost 1500 discrete river basins draining to the sea through over 100 estuaries, comprising of over 200,000 km of watercourses (Acreman, 2000). By global standards, these watercourses are short, shallow and largely modified, yet they act as major components of the landscape and in turn are influenced by the catchments within which they flow. The catchment forms a landscape element, at various scales, that integrates all aspects of the hydrologic cycle within a defined area (Wagener *et al.*, 2004). The geological and climatic characteristics of a catchment determine how variations in rainfall from year to year impact upon river flow variability, therefore the flow regime is often used as a basis for regionalisation; the determination of hydrologically similar areas (Bower and Hannah, 2002). However, today the geological influence on river regimes is highly modified by 'human factors': dams and reservoirs, urban development, and rural land-use change, especially land drainage (Petts & Wood, 1998).

Research on UK river flow regimes has, to date, been quite limited. An omission to this was work by Ward (1968), which considered regimes to be fixed entities. Research, from Scandinavia (Krasovskaia & Gottschalk, 1992) and Western Europe (Krasovskaia, 1995), has challenged this by highlighting the importance of recognising regime variability. Bower & Hannah (2002) investigated the spatial distribution and temporal stability of annual flow regimes in the UK and suggested the regime 'shape' (the form of annual regime, regardless of absolute runoff magnitude) was controlled by the timing and nature of hydro-climatic conditions, as well as geology. However, the regime 'magnitude' decreased from west to east, along a precipitation gradient, and therefore changes in inter-annual 'magnitude' variations could be linked to atmospheric circulation patterns.

Understanding how flows vary in magnitude and time, between different seasons and years, is necessary to interpret how this variation could impact Atlantic salmon populations. This type of analysis can also provide an important basis for the development of water resource management strategies by helping to improve understanding of inter-regional variation in river discharge (Hannah *et al*., 2005). This chapter will start to investigate these dimensions of flow variability at a national and regional level.

4.1.1. Region and river selection

In order to evaluate flow variability, a range of rivers was selected within different regions of the UK. The three regions selected for analyses each had known salmonid rivers and available flow and salmon rod catch data. These regions were: the southwest of England, northern England, and Wales. Individual rivers within each of these regions were selected on the basis of the following criteria:

- First, all rivers selected were classified as salmon rivers according to the Environment Agency/Cefas Annual Assessment of Salmon Stocks and Fisheries in the England and Wales[2].
- Secondly, the qualifying rivers were assessed according to the length of their flow record, where the rivers with longest flow records were used where possible. Flow records were used up to and including 2009 for consistency across the different regions.
- Thirdly, rivers with limited anthropogenic modifications to the flow regime and catchment were preferred, to ensure as close to 'natural' flow regime as possible. However, it is recognised that within the UK, a highly populated and heavily managed island, true natural flow regimes no

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[222] *A national assessment of the status of the salmon resource in England and Wales is undertaken annually, using the Pre-fishery Abundance and National Conservation Limit Models originally developed by Cefas (Potter et al., 2004), and reported to the International Council for the Exploration of the Sea (ICES). The status of individual river stocks in England and Wales are also evaluated annually against the stock Conservation Limits (CLs) and Management Targets (MTs) in line with the requirements of ICES and NASCO. Details of these assessments are provided in an annual report prepared by Cefas and the Environment Agency.*

longer exist, as all catchments have been modified to some degree over centuries of human impact. Therefore, regulated rivers were considered when the corresponding gauging station data described the regime as 'naturally responsive to within 10% at the 95-percentile flow'.

Based on these criteria (Appendix C1):

- In the southwest of England six rivers were deemed suitable: the rivers Dart, Frome, Lynher, Tamar, Axe and Camel.
- In the north of England five rivers were selected as suitable, the rivers Ribble, Tyne, Lune, Kent and Coquet. Of these rivers three were located in the northwest of England (the Ribble, Lune and Kent) and two in the northeast (the Coquet and Tyne[3]). It was therefore decided to extend the search for representative rivers to the southeast of Scotland (Figure 3.1). Here, salmon rivers in Scotland are monitored and reported in the Rivers and Fisheries Trust of Scotland (RAFTS) Annual Report, which is responsible for rod catch data in Scotland. This resulted in one additional river being selected: the River Tweed.
- In Wales, only five rivers were deemed suitable: the Conwy, Western Cleddau, Teifi, Dyfi and Dysynni.

These criteria produced a range of rivers with different catchment sizes and catchment characteristics. The River Frome was the only chalk stream selected and as it is groundwater fed, it had the highest base flow index (0.86) of all the rivers (Table 4.1). The smallest catchment was the River Dysynni in Wales (at 75.1 km^2), and the largest was the River Tweed in Scotland (at approx. 1500 km^2). The least variation throughout the flow records between Q_{95} and Q_{10} was found on the River Tyne (a difference of 5.399 $m^3 s^{-1}$), one of the middle size catchments in the analysis (307 km^2), but most regulated of the selected rivers. The highest variation between these parameters was found on the River Tweed (a difference of 73.901 $m^3 s^{-1}$), the largest catchment in the study.

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[3] *The River Tyne was selected despite being a regulated river because the Morwick gauging station data describes the regime as naturally responsive to within 10% at the 95 percentile flow.*

Table 4.1. Summary of selected rivers catchment area and average flow parameters.

	River	Gauging station	Catchment area (km^2)	Mean flow (m^3 s^{-1})	Base flow Index	Q95 (m^3 s^{-1})	Q10 (m^3 s^{-1})
South West	**Dart**	Austins Bridge (46003)	247.6	11.296	0.52	1.6	25.5
	Frome	East Stoke (44001)	414.4	6.592	0.86	2.484	12.47
	Lynher	Pillaton Mill (47004)	135.5	4.391	0.58	0.635	10.5
	Tamar	Gunnislake (47001)	916.9	22.346	0.46	2.198	55.06
	Axe	Whitford (45004)	288.5	5.324	0.48	1.245	11.17
	Camel	Denby (49001)	208.8	5.971	0.62	0.938	13.2
North	**Ribble**	Samlesbury (71001)	1145	33.417	0.33	4.613	81.77
	Lune	Killington New Bridge (72005)	219	10.053	0.33	0.895	24.8
	Kent	Sedgwick (73005)	209	9.286	0.41	1.17	21.7
	Coquet	Morwick (22001)	569.8	8.604	0.44	1.211	18.86
	Tweed	Boleside (21006)	1500	37.289	0.51	7.049	80.95
	Tyne	East Linton (20001)	307	2.981	0.53	0.582	5.981
Wales	**Conwy**	Cwmlanerch (66011)	344.5	19.034	0.28	1.38	46
	Western Cleddau	Prendergast Mill (61001)	197.6	5.609	0.63	0.799	12.4
	Teifi	Glan Teifi (62001)	893.6	29.232	0.54	3.226	66.93
	Dyfi	Dyfi Bridge (64001)	471.3	23.552	0.39	2.323	54.68
	Dysynni	Pont-y-Garth (64002)	75.1	4.533	0.47	0.635	10

4.2 NATIONAL TRENDS IN FLOW

To assess the national trend in flow variability, the river flow data for all 17 rivers across the three regions was amalgamated into one database. In order to compare hydrological properties from rivers with different catchment sizes, the flow data was standardised by dividing each daily flow by the long-term mean flow (using available records from 1970-2009) for the corresponding gauge (Yevyevich, 1972, Poff and Ward, 1989).

To assess the 'big' picture, all-available years with flow data between 1970 and 2009 were used in the analysis. Due to incomplete flow records, this resulted in the following individual years being removed from the analysis: 1970 on the Teifi, 1971 and 1976 on the Coquet, 1971-1975 on the Dyfi, 1980 on the Lune, 1992 on the Frome and Coquet, 1997 on the Tyne and Dysynni, 2000 on the Frome, 2001 on the Lune, 2003 on the Tyne and 2006 on the Frome and Tyne (a total of 18 years was removed).

This indicated for the whole national dataset, in rank order, the wettest (highest 25th percentile) years were 2000, 2008, 1998, 1994, 2002, 1986, 1981, 2009, 1999 and 1974, and the driest (lowest 25th percentile) years were 1973, 2003, 1971, 1975, 1976, 1989, 1996, 1997, 1995 and 2005 (Figure 4.1 & Table 4.5).

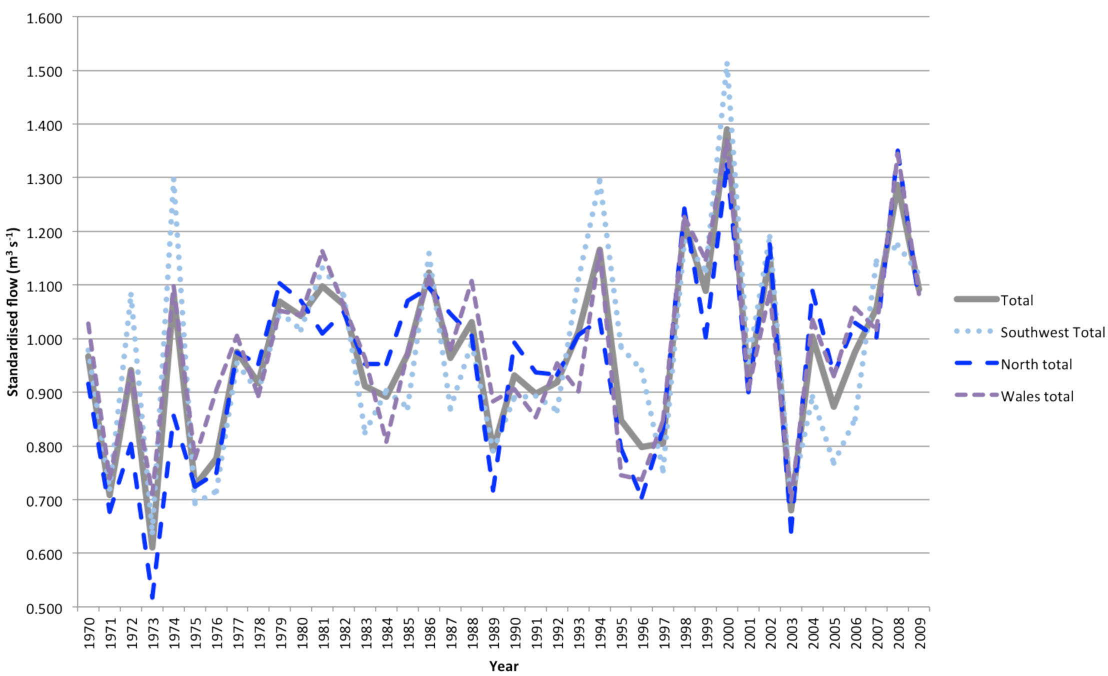

Figure 4.1.Standardised annual flows for all 17 rivers used in this study (total) and individual regions: southwest, welsh and north rivers

The southwest and Welsh regions had 90% overlap with the national wettest 25th percentile of years, whereas the northern region only had 60% overlap (Table 4.2), as the result of lower flows in 1974, 1981, 1994 and 1999. The northern region, however, had the highest overlap in the driest years with the national driest 25th percentile of years, with 90% overlap. The southwest and Welsh regions both had 80% overlap with the national driest years.

Table 4.2. Standardised (using the grand mean flow) national annual flow and regional annual flows (with missing years for individual rivers stated above).

Date	Total	Southwest Total	North Total	Wales Total
1970	0.967	0.978	0.916	1.028
1971	0.708	0.719	0.677	0.74
1972	0.942	1.082	0.804	0.939
1973	0.611	0.638	0.517	0.71
1974	1.082	1.296	0.856	1.098
1975	0.726	0.693	0.725	0.777
1976	0.776	0.716	0.75	0.905
1977	0.976	0.954	0.974	1.005
1978	0.917	0.901	0.952	0.893
1979	1.069	1.049	1.103	1.052
1980	1.042	1.016	1.071	1.043
1981	1.098	1.131	1.01	1.162
1982	1.064	1.08	1.049	1.062
1983	0.911	0.825	0.952	0.964
1984	0.892	0.902	0.953	0.807
1985	0.972	0.871	1.07	0.973
1986	1.123	1.158	1.095	1.116
1987	0.964	0.869	1.046	0.979
1988	1.031	0.992	1.006	1.107
1989	0.792	0.791	0.716	0.883
1990	0.931	0.89	0.993	0.906
1991	0.897	0.892	0.936	0.854
1992	0.918	0.866	0.932	0.954
1993	1.012	1.11	1.007	0.901
1994	1.165	1.295	1.036	1.165
1995	0.847	0.984	0.795	0.745
1996	0.798	0.942	0.705	0.737
1997	0.805	0.754	0.832	0.848
1998	1.216	1.181	1.242	1.226
1999	1.089	1.127	1.003	1.148
2000	1.389	1.512	1.325	1.368
2001	0.922	0.957	0.9	0.906
2002	1.154	1.19	1.176	1.085
2003	0.68	0.7	0.64	0.698
2004	1.003	0.892	1.089	1.035
2005	0.874	0.768	0.933	0.93
2006	0.976	0.85	1.03	1.058
2007	1.056	1.144	1.002	1.016
2008	1.286	1.174	1.351	1.345
2009	1.092	1.12	1.07	1.084

Where:	
	Lowest 25th percentile
	Highest 25th percentile

These most extreme wet and dry flow years were most similar between the southwest and Welsh regions, which due to their close proximity geographically is not surprising.

Overall, this indicated that although the flows did show a degree of similarity on the occurrence of the extreme wet and dry years across the country, there were differences between the regions. This suggests, even during the most extreme 25th percentile of wet and dry flow year's, refugia for a species from extreme flow conditions may exist between regions. However, the ability to exploit this would depend on the species.

4.2.1 National trend in the 'shape' of flow regimes

A PCA and CA were conducted on the national amalgamated database of 442 station years to see how the regime types were distributed. The database comprised of 17 river stations from 1977-2009 (where 1980, 1992, 1997, 2000, 2002, 2003 and 2006 were removed due to lack of data). The CA of the PC loadings fit into seven flow regime groups with four regimes dominating and accounting for 88.9%[4] of the flow years (Figure 4.2):

- Regime 1: the largest cluster, which occurred 38.7% of the time (171 years in total), had a single high magnitude peak in median flow in January and had the lowest median monthly flows in October.
- Regime 2: occurred 22.6% of the time (100 years in total) and had a high magnitude peak in median flow between November and January.
- Regime 3: occurred 15.4% of the time (68 years in total) and had a late peak in median flow in March. Regime 3 had the lowest median monthly flows of all the different regimes between July and September.
- Regime 4: occurred 12.2% of the time (54 years in total) and had two high magnitude peaks, the first in October, followed by a higher

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[4] *All percentages refer to the percentages of years used in the analysis, e.g. percentage of time between to 1977-2009 (excluding 1980, 1992, 1997, 2000, 2002, 2003 and 2006)*

magnitude peak in January. Regime 4 had the lowest median monthly flows of all the different regimes in June.

The high flow timing typically occurred in January for regimes 1, 3 and 4, and December for regime 2. The 1-day minimum was lowest for regime 3 (0.89 $m^3 s^{-1}$) and the typical timings of large flood events for regimes 1 and 2 typically occurred in December, and regime 3 and 4 in January (Table 4.3). The sustained rise in autumn flows were earliest for regimes 2 and 3 (October) but were delayed to December in regime 1 and late December in regime 4. Spring flows were similar in regimes 1, 2 and 3 but higher in regime 4.

The three rare regimes, which equivalent to one station-year (N=17) or less were:

- Regime 5: occurred 3.8% of the time (17 years in total). This regime had no clear peaks, but was characterised by winter drought, with low median monthly flows between December and February. This regime exclusively comprised of flow records from 1987, apart from on the River Coquet- where this was replaced with 1988 and also 1993, and the River Frome, which was not present because 1987 was classified as regime type 2.
- Regime 6: occurred 3.6% of the time (16 years in total) and had multiple high magnitude peaks in December, April, August and September. Regime 6 had the lowest median monthly flows of all the different regimes in November. Regime 6 contained flow records only from 1985, apart from the River Frome (where 1985 was classified as regime type 1) and apart from on the River Coquet, where 1985 this was replaced with 1986.
- Regime 7: occurred 3.6% of the time (16 years in total) and had multiple high magnitude peaks in October, January and August. This comprised flow records for one year (2008) on all rivers except the River Frome.

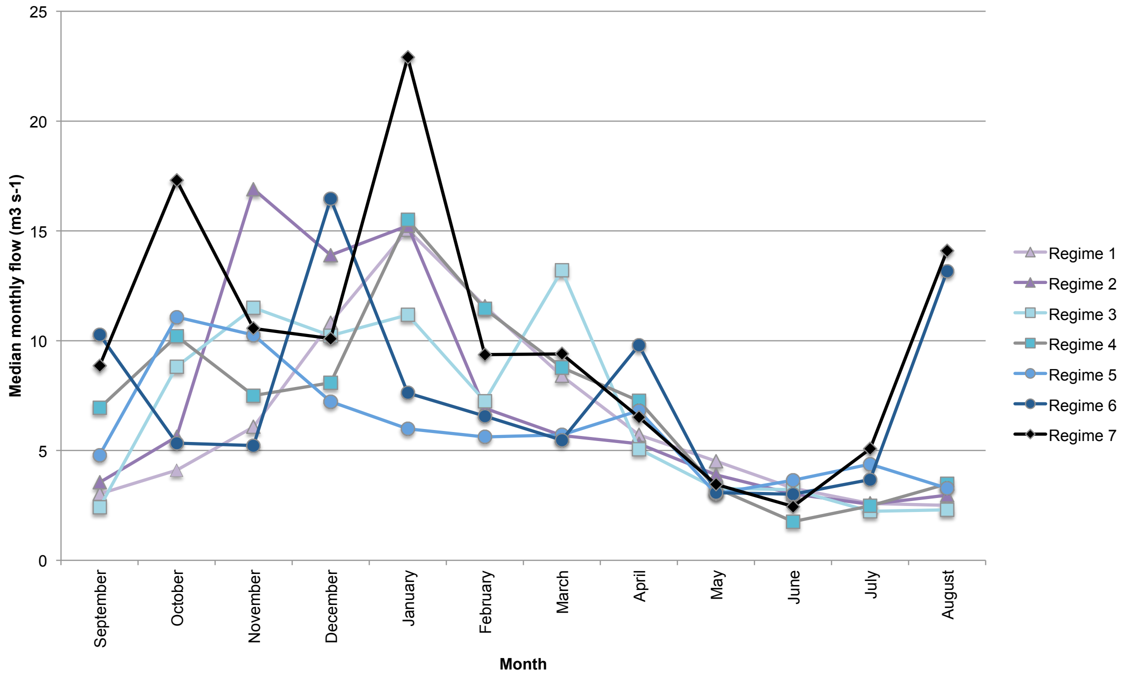

Figure 4.2.Median monthly flows of the seven flow regimes from the National river database of 17 rivers 1977-2009 (excluding 1980, 1992, 1997, 2000, 2002, 2003 and 2006).

Removing years with incomplete data from this national scale analysis allowed a true representation of flow variability across the country during the same time period. Overall, this showed a degree of homogeneity at the national scale in the general shape of the flow regime (Appendix C2), with the notable exception of two rivers, Frome and Coquet. The River Frome behaved most differently from the others, consisting predominately of regime type 1. As this is the only chalk stream in the analyses, this suggests the river is less responsive to rainfall as it is buffered by the groundwater discharge. On the River Coquet, the rare regime types 6 and 7 occurred a year later than on other rivers. The River Coquet catchment is classified as low permeability and predominately grassland (Marsh & Hannaford, 2008) and it is unlikely that this is due to the responsiveness of the catchment. However, the fact that the catchment is the most eastward of all the catchments in this study may be of importance.

This method, of excluding years with incomplete data, does mean proportions of between year flow variability are lost, potentially at the most variable times (as incomplete records could be, for example, the result of extreme high flow wash-outs). The coarse nature of this national-level clustering could mean more subtle regional and/or individual river differences in the shape of the flow regime are lost, which could have important ecological impacts. This raises the question; which scale is most suitable to truly understand, but also manage, flow variability.

Table 4.3. Selected IHA parameters output data for the seven flow regimes resulting from the national database of 17 rivers, (1977- 2009, excluding 1980, 1992, 2000, 2002, 2003 and 2006).

	Regime 1		**Regime 2**		**Regime 3**		**Regime 4**		**Regime 5**		**Regime 6**		**Regime 7**	
	Medians	CoD	Medians	CoD	Medians	CoD	Medians	CoD	Medians	CoD	Medians	CoD	Medians	CoD
September	3.02	1.26	3.54	1.54	2.41	1.23	6.94	1.30	4.80	3.36	10.28	1.05	8.85	1.72
October	4.10	1.84	5.63	2.08	8.82	1.39	10.20	2.15	11.08	2.55	5.34	1.44	17.30	2.37
November	6.08	1.71	16.90	2.03	11.50	1.69	7.51	2.07	10.26	2.05	5.23	2.00	10.56	2.26
December	10.82	2.20	13.90	1.42	10.23	1.32	8.08	2.22	7.23	2.13	16.46	2.18	10.10	2.44
January	15.05	1.85	15.23	1.45	11.17	1.25	15.50	1.60	5.99	1.57	7.62	1.04	22.90	1.41
February	11.57	1.39	6.92	1.49	7.25	1.82	11.45	1.68	5.62	1.95	6.57	1.38	9.37	1.13
March	8.40	1.32	5.68	1.80	13.20	2.05	8.78	1.46	5.71	2.81	5.47	1.20	9.40	2.15
April	5.71	1.32	5.30	1.73	5.07	1.33	7.26	1.40	6.82	1.87	9.80	2.08	6.52	1.64
May	4.52	1.17	3.89	1.75	3.28	1.50	3.30	1.39	3.04	1.13	3.08	1.24	3.46	1.67
June	3.29	1.13	3.02	1.28	3.22	1.81	1.77	1.55	3.65	2.17	3.01	1.87	2.45	2.00
July	2.59	1.09	2.55	1.84	2.23	1.51	2.48	1.99	4.38	1.00	3.68	2.40	5.08	1.84
August	2.50	1.23	2.97	2.04	2.30	1.06	3.48	2.49	3.28	1.64	13.17	2.12	14.10	1.47
1-day minimum	1.07	1.35	1.00	1.03	0.89	0.70	1.01	1.18	1.16	0.49	1.27	0.34	1.58	0.91
1-day maximum	111.80	1.38	126.90	1.36	128.30	1.44	141.00	1.13	189.60	0.49	156.20	0.87	195.00	0.48
High flow peak	22.29	0.41	27.40	0.40	22.60	0.44	31.41	0.39	28.61	0.53			38.04	0.32
High flow timing	26.00	0.25	336.00	0.39	31.00	0.39	27.00	0.23	33.00	0.47			324.00	0.35
High flow frequency	9.00	1.00	11.00	0.91	10.00	0.75	10.00	0.90	12.00	0.79			13.50	1.07
Large flood peak	341.00	0.26	382.50	0.19	360.20	0.29	354.50	0.43	373.60				423.00	
Large flood timing	363.00	0.16	348.50	0.17	3.00	0.18	2.00	0.24	292.00				21.00	

4.3. VARIATIONS IN 'MAGNITUDE' OF FLOW BETWEEN REGIONS

The analysis so far has concentrated on the seasonal pattern of flow between years at the national scale. However, this raises the question as to whether the pattern of flow variations affect rivers from the same region in the same way, and therefore, do all rivers in a region show the same level of sensitivity to high and low flow events? To what extent do catchment orientation and drainage network structure, as well as human modifications to catchments, create hydrological diversity within regions?

To investigate how individual rivers within a region react to extremes in flow events, two 'drought' and two 'flood' parameters were selected from the IHA parameter set. The 1-day maximum and high flow frequency were chosen as the 'flood' parameters. The 1-day maximum was selected because it had a lower coefficient of dispersion than the 2,7 or 30-day maximum averages and was therefore less variable. The high flow frequency was chosen to give a measure of the temporal variability of high flow events across the region. The ‘drought’ parameters selected were the 1-day minimum and Q95. Again, the 1-day minimum was the least variable, with a lower coefficient of dispersion than the other 2,7 or 30-day minima. There was, however, concern that gauging station errors could play a greater role in the extreme low flow readings, therefore the Q95 value was also used. The Q95 parameter was not an output of the IHA model so, therefore, was calculated for each year and each river manually.

For each river within each region, the top 10 flow events for each of the four parameters outlined above, were ranked (e.g. the top 10 years with the lowest 1-day minimum flow, the top 10 years with the highest number of days equal or below Q95, the top 10 years with the highest 1-day maximum flow and the top ten years with the highest number of high flow events) to assess the overlap between rivers on a temporal scale and find out when these flow events had occurred.

In order to determine which years were more similar with regard to the most extreme flow events, a similarly index (SI) was created using a simple weighting system. Each time a year occurred in the top two years of the extreme flow metric, it received 5 points and every time a year occurred in the top ten years of the extreme flow metric, it received 2 points. For the southwest and northern regions each year was scored out of a maximum of 42, where the higher the number and closer to 42, the more overlap between the rivers within that region during the extreme flow parameter. For the Welsh region, which had one less river, the maximum score was 35 and therefore the higher the number and closer to 35, the more overlap between the rivers within that region.

To test this approach, in the southwest region analyses were conducted for 10, 15 and 20-year periods to ensure that imposing an artificial cut-off time did not influence the results (Appendix C3 and C4). As all the timeframes demonstrated similar patterns, the 10-year magnitude was used.

4.3.1. Southwest magnitude analysis

In the southwest, each river was assessed from 1965-2009 (excluding[5] 2000). The similarity indices showed on average a higher level of similarity for the low flow parameters than for the high flow parameters (Appendix C5). The low flow years of 1976, 1977 and 1990 were common to all 6 rivers (Table 4.4). Only 1980 overlapped in all rivers for 1-day maximum and no year had complete overlap between all the rivers for high flow frequency.

Table 4.4. Southwest England regional flow similarity, recording the number of years (year) of overlap between rivers for 1-day maximum, 1-day minimum, Q95 and high flow frequency metrics based on the top 10 years for each parameter.

Flow metric	6 river overlap	5 river overlap	4 river overlap	3 river overlap	2 river overlap	No river overlap
1 day Maximum	**1** (80)	**2** (90,95)	**4** (66,87,93, 99)	**3** (69,81,03)	**4** (74,82,86, 96)	**11** (68,75,78,83,88, 94,97,98,02,08, 09)
High flow frequency	**0**	**3** (68,81,04)	**3** (69,72,88)	**5** (71,86,05, 08,09)	**4** (74,75,91, 98)	**10** (66,67,73,79,80, 82,85,92,96,02)
1 day Minimum	**3** (76,77,90)	**2** (84,89)	**3** (79,95,96)	**1** (85)	**4** (74,75,83, 97)	**9** (65,73,71,72,91, 92,02,03, 04)
Q95	**2** (76,89)	**4** (84,78,90, 95)	**0**	**4** (01,75,77, 96)	**2** (83,82)	**12** (70,71,72,73,74, 75,87,91,92,97,99, 03)

The similarity index was highest for 1-day minimum flows in 1977, with a maximum score of 42, meaning it was one of the two lowest flow years throughout the flow record for every river. The second highest similarity index, both with index scores of 37, were Q95 in 1977 and 1-day minimum in 1978. The next highest similarity index was the 1-day maximum in 1980 (SI = 32), followed by high flow frequency (SI = 30) in 1966 and Q95 (SI = 30) in 1985. Surprisingly, the index scores for Q95 and 1-day minimum varied between the parameters for some of the years, in particular 1978 where Q95 had a SI= 6

[5] *Excluded years are years where full flow records do not exist for all rivers in the region.*

and the 1-day minimum had a SI= 37, and in 1985 where the Q95 had a SI= 30 and the 1-day minimum had a SI= 10.

Despite the moderate levels of overlap there was still a high level of variability between the six rivers, shown by the lack of river overlap in a number of cases, resulting in many (47%) of the similarity indices having a score of zero (no-overlap).

4.3.2 Northern region analysis

In the northern region, each river was assessed from 1970-2009 (excluding 1975, 1979, 1980, 1981, 2002, 2003, 2005 and 2006). The indices again showed on average a higher level of similarity for the low flow parameters than for the high flow parameters (Appendix C6). The low flow years of 1984, 1995 and 1996 were common to all 6 rivers (Table 4.5). Only 1982 overlapped in all rivers for 1-day maximum and no year had complete overlap between all the rivers for high flow frequency.

The similarity index was highest for 1-day minimum flows in 1976 and Q95 in 1984, both with a maximum score of 25. The next highest score was 1-day minimum flows in 1984 with a similarity index score of 22, followed 1-day minimum flows in 1970, Q95 in 1972 and 1989 and 1-day maximum flows in 1995, which all had an SI= 20.

In 1972, 1984 and 1989 overlap occurred in the top ten years for Q95 for all five rivers apart from the Kent, and 1976 all rivers apart from the Coquet. For the 1-day minimum flow overlap occurred of all five rivers in 1976 and 1977 apart from the Coquet, and in 1983 and 1989 on all rivers but the Tweed, 1995 on all rivers but the Ribble and 1970 on all rivers but the Kent. This indicates there was no pattern between east and west regions, and that they were not functioning distinctly.

The lower similarity indexes for the north indicate there was not as strong an overlap in the flow parameters as in the southwest, particularly for the high flow parameters. However, the years with no overlap at all in the top ten years was lower than the southwest, with only 35.5% of years scoring zero for each of the four parameters.

Table 4.5. Northern England/southern Scotland regional flow similarity, recording the number of years (year) of overlap between rivers for 1-day maximum, 1-day minimum, Q95 and high flow frequency metrics based on the top 10 years for each parameter.

Flow metric	6 river overlap	5 river overlap	4 river overlap	3 river overlap	2 river overlap	No river overlap
1 day Maximum	**1** 1982	**1** 1986	**3** 1991, 1995, 2000	**7** 1992, 1993, 1990, 1999, 2001, 2004, 2009	**6** 1978, 1985, 1989, 2007, 2008	**5** 1971, 1974, 1983, 1987, 1988, 1994
High flow frequency		**2** 1986, 1999	**5** 1972, 1983, 1988, 2007, 2009	**6** 1977, 1985, 1987, 1993, 1998, 2001	**5** 1971, 1978, 1989, 2000, 2008	**2** 1992, 1970
1 day Minimum	**1** 1984	**6** 1970, 1976, 1977, 1983, 1989, 1995	**2** 1974, 1996	**1** 1973	**3** 1978, 1985, 1990	**7** 1971, 1982, 1991, 1992, 1994, 2001, 2004
Q95	**2** 1995, 1996	**4** 1972, 1976, 1984, 1989	**3** 1974, 1978, 1991	**2** 1973,1983	**1** 1971	**8** 1970, 1975, 1977, 1980, 1982, 1988, 1990, 2005

4.3.3 Welsh magnitude analysis

In the Welsh region each river was assessed from 1975-2009 (excluding 1988 and 1997). The similarity indices were similar to the northern and southwest regions, which showed on average there was a higher level of similarity for the low flow parameters than for the high flow parameters (Appendix C7). The low flow years of 1984 and 1989 were common to all 5 rivers, as were the high flow years of 1981 and 1985 (Table 4.6).

There were seven years that overlapped for four of the five rivers for the low flow parameters. These included: Q95, which occurred on all rivers apart from the River Dyfi in 1975 and the River Conwy in 1990, and 1-day minimum flow, which occurred on all rivers apart from the River Western Cleddau in 1983 and River Dysynni in 1996. There were also five years that overlapped in four of the five rivers for the high flow parameters. These were; 1-day maximum flows which occurred on all rivers apart from the River Dysynni in 2008 and River Western Cleddau in 1995 and 2004, and the high flow frequencies that occurred on all rivers apart from the River Conwy in 2008 and River Dysynni in 2000.

Table 4.6. Welsh regional flow similarity, recording the number of years (year) of overlap between rivers for 1-day maximum, 1-day minimum, Q95 and high flow frequency metrics based on the top 10 years for each parameter.

Flow metric	5 river overlap	4 river overlap	3 river overlap	2 river overlap	No river overlap
1 day Maximum	**1** 1981	**3** 1995, 2004, 2008	**2** 1979, 2002	**11** 1980, 1982, 1987, 1989, 1990, 1993, 1998, 2001, 2003, 2005, 2006	**6** 1981, 1983, 1984, 1986, 1999, 2007
High flow frequency	**1** 1985	**2** 2000, 2008	**2** 2007, 2009	**12** 1975, 1979, 1980, 1982, 1986, 1989, 1992, 1994, 1998, 1999, 2003, 2006	**7** 1977, 1978, 1982, 1983, 1993, 2001, 2004
1 day Minimum	**1** 1984	**4** 1976, 1977, 1983, 1996	**5** 1980, 1989, 1990, 1995, 2006	**4** 1975, 1982, 1985, 1991	**6** 1978, 1979, 1998, 2003, 2004, 2008
Q95	**2** 1984, 1989	**3** 1975, 1976, 1990	**6** 1980, 1983, 1995, 1996, 2003, 2006	**3** 1981, 1982, 1995	**4** 1977, 1979, 1987, 2006

The similarity index was highest for Q95 in 1984, with a score of 35. The second highest similarity index, with an index score of 25, was high flow frequency in 1985, followed by Q95 in 1980 with a similarity score of 23 and 1-day maximum flows in 1981 with score of 20.

Overall, the similarity index for the Welsh rivers indicated there was a similar level of overlap to the northern region, because although the highest score was greater in Wales, there were fewer years with scores above 20. The percentage of years with no overlap in the top ten years was similar to the northern region but less than the southwest, with only 38.6% of years scoring zero for each of the four parameters using the similarity index.

4.3.4 Regional magnitude summary

Across the three regions there was a greater degree of overlap and similarity in the low flow parameters, than high flow parameters. This was not unexpected, as extreme high flow events tend to be more localised storm/rain events and more greatly influenced by catchment characteristics. Flood regimes are difficult to characterise due to the diversity of generating mechanisms, catchment types and human impacts on runoff. However, catchment geology and relief provide important controls; for example, spate flows are more common in mountainous, impermeable catchments than subdued permeable catchments. However, during extreme flood events when the catchment is saturated, this tends to counter catchment characteristics due to the quality of water.

Whereas the extreme low flow events had relatively greater regional and national overlap in the analysis because they tend to be more regional/national scale events. According to the National River Hydrologic Records the 1975/76 drought was at the time considered to be the most severe experienced across the UK due to its extreme intensity and broad spatial extent. Overall, in this analysis these years resulted in the greatest overlap between rivers and regions, although the 1975/76 drought appeared to be most extreme in the southwest. The years 1989 and 1990 were also classified as drought years, and also resulted in high overlap across all regions in this analysis. Other notable drought episodes according to the Hydrologic Records were 1984, 1991/92, 1995-97, 2003 and 2004-06. The 1984 drought episode also resulted in high overlap across the regions. It was in the top ten years for both low flow parameters in 5 of out the 6 rivers, the exception was the River Frome, whose groundwater recharge may have buffered the impacts. The other drought years resulted in less prominent overlaps between the rivers and regions.

In a similar way to the ‘high-level’ national magnitude analysis, this suggests that even during the most extreme high and low flow conditions, within a geographical region, individual rivers still function/respond differently. This intra-regional variability maybe significance for ecological resilience, providing opportunities for a regional population of a species, such as Atlantic salmon, to adapt to short-term flow disturbances.

4.4 Flow variability across England and Wales summary

Overall, in the UK river flows tend to be highest in the winter months, when evaporation is low and groundwater/soil moisture storage is high, and lowest in the summer when the opposite is true of evaporation and storage. However, across the regions the river flow shape did vary at the national scale between years, in response to varying precipitation events. The most commonly occurring regime, characterised by a single high magnitude peak in median monthly flow in January, occurred approximately 1 in every 2.5 years. Regime 2, characterised by a single high magnitude peak in median monthly flow between November-January, occurred approximately 1 in every 4.5 years. Regime 3, with a late peak in median flow in March, occurred approximately 1 in every 6.5 years, and regime 4, characterised by two high magnitude peaks, the first in October followed by a higher magnitude peak in January, occurred approximately 1 in every 8 years. The IHA parameters highlight that the timing, peak and frequency of high flow and flood events also varied between the different regime types, as did the minimum flows. These four regimes account for 88.9 % of the years.

From a hydrological perspective, once the groundwater and surface water storages are full, typically from around February, monthly flows are auto-correlated because the stores are draining through until the summer. But from September through to around January, flows are more related to the pattern of weather conditions, i.e. to primary precipitation, therefore this results in the more variable flows in September, October and November, as seen in this analysis (Graph 4.3). This high autumn variability from an ecological perceptive could be very influential, as it's the key time for Atlantic salmon migration upstream. It is possible delays in the high autumn flows may result in Atlantic salmon being trapped in estuaries waiting for sufficient flows to move upstream to spawn.

Despite similarities, the flow regime also varied in the magnitude of extreme flow events between the different regions and nationally. This means, in most years, species responses within different regions and rivers may vary, as some regions/rivers will be less impacted by flow events, such as delayed autumn high flows and/or low spring flows, than others. The variability in flow during these key ecological timeframes may lead to species-level behavioural adaptations over short timeframes, but could also lead to changes in life strategies in respond to varying flow parameters over evolutionary timescales.

Although not designed to, this analysis did not suggest the variability in high and low flow parameters was scale dependent. However, the 1-day minimum flow outliers did include the River Dysynni and River Western Cleddau, which were two of the smallest catchments. Previous research by Sanford *et al*., (2007) found limited flow variability under wet conditions in natural forested catchments. However, flow variability under drier conditions was scale-dependent, with smaller basins (<600 ha) showing a large range in variability and less variability in basins over this area.

This analysis suggests that patterns of flow variations do not affect rivers from the same region in the same way, and even rivers within a region do not show the same level of sensitivity to high and low flow events. Catchments are 'organising systems' whose form, drainage network, soils, vegetation, channel hydraulics etc. are all the result of adaptive ecological and geomorphic processes (Sivapalan, 2005) and therefore patterns and similarities will exist. However, internal variability and connectivity within a catchment make seeing these patterns difficult (Buttle, 2006), as shown by Poff *et al*. (2006), who highlighted that we currently have limited knowledge about extrapolating hydrologic characteristics even just up- or downstream of a gauging station. Added to this, it has long been recognised that anthropogenic alternations, including land-use changes, increasing impermeable areas and artificial channels, also affect hydrological processes within catchment (Graf, 1977). This typically results in increases in peak discharges (Zheng and Baetz, 1999), by reducing infiltration and accelerating the catchment response. Beven (2000) suggested all these reasons (the topography, soil, geology, vegetation and human modifications) even within each catchment limit our ability to generalise or regionalise hydrological diversity.

This inter-annual and regional variability, demonstrated by the PCA/CA and IHA model approach, is currently not represented in river flow management. This means significant proportions of flow variability, in timing as well as magnitude, are being lost on regulated rivers, which in turn could impact on the ecology. This method of analysing the flow regime year clusters based on their similarities, by its very nature removes ‘extreme’ variability’ or outliers. This approach, therefore, could be important in developing a practical management tool that can be used and applied on the ground to help maintain flow variability, but in a manageable way. However, the scale of which analysis should be conducted is questionable. The next chapter will investigate within intra-regional variability and individual river flow variability.

CHAPTER 5: REGIONAL AND LOCAL FLOW VARIABILITY

5.1 Regional Analysis

The national level flow analyses showed there was inter-annual variability in flow regimes across the country, which impacted regions differently. This raises the question as to whether river flow variability between years could be set and managed at the national/regional scale, or if this would exclude important local variations in flow regimes. To assess this, intra-regional analyses were conducted separately for each of the three study regions (the southwest, Wales and north England/south east Scotland) and further local analyses were conducted on each individual river within each region. This was done by using the method described in chapter 3 (a PCA and CA on daily flow data to produce regime types, which are when described by the IHA model) to describe the 'shape' and 'timing' of the flow events through the time record for each river and region.

5.2 Southwest

The first region was the southwest of England, which forms a peninsula between the English Channel and Bristol Channel and has the longest coastline of all England's regions, totalling over a thousand kilometres (Figure 5.1). It is also one of the least populated regions of England. The EA southwest River Basin District plan identified the main pressures on the water environment in the region were (EA, 2009c); sediment (rivers and lakes), physical modification of water bodies, nitrate and phosphorus pollution, invasive non-native species, abstraction and other artificial flow pressures, mines and minewaters, pesticides, organic pollution and other pollutants and urban and transport pressures.

Figure 5.1. Map of 6 rivers in the southwest region (where the red dot indicates the location of the gauging station).

To assess the regional trend in flow regimes, the CA/PCA method was used on a database of the combined six southwest rivers (from 1966-2009, where 1992, 2000 and 2006 were removed due to lack of data). This analysis indicated six flow regime types (Figure 5.2):

- Regime 1: the largest cluster, which occurred 60.8% of the time (149 years in total), had a single high magnitude peak in median flow in January/February.
- Regime 2: occurred 20.4% of the time (50 years in total) and had two peaks, the first in December/January followed by a lower magnitude peak in March, which has resulted from a dry February.
- Regime 3: occurred 7.3% of the time (18 years in total). This regime had no clear peaks, and was characterised by low median monthly flows throughout most of the year, particularly in the winter.

- Regime 4: occurred 5.3% of the time (13 years in total) and had two peaks, the first a marked peak in November followed by a lower magnitude peak in February.
- Regime 5: occurred 4.1% of the time (10 years in total) and had two peaks, the first in October followed by a higher magnitude peak in February, but overall as a relatively dry winter compared to other regimes.
- Regime 6: occurred 2.0% of the time (5 years in total) and had two peaks, the first in January followed by a higher magnitude peak in August, but overall relatively low winter flows. As defined in the broader 'national' analysis, this regime only comprised of the year 2008 for all rivers, apart from the River Frome, which was missing from regime 6. The start of the hydrological year for regime 6 (2008) started in July, with higher flows in July and August compared to the other regimes types.

Analysis of IHA toolbox parameters showed: the high flow timing typically occurred in January for regime 1 and 2, December for regime 3, November for regime 4 and 5 and October for regime 6. The 1-day minimum was lowest for regime 3 (0.61 $m^3 s^{-1}$) and the greatest 1-day maximum flow was from regime 6 (80.90 $m^3 s^{-1}$). The highest large flood peak also occurred during regime 2 (254.2 $m^3 s^{-1}$). The typical timings of large flood events varied for the regimes, regime 1 and 2 typically occurred in December, regime 3 and 4 in November and regime 6 in October (Appendix D1).

There was little difference in the timing of the sustained rise in autumn flows (which were above $5m^3 s^{-1}$) in the southwest region as a whole between years. The earliest was during regimes 2, 3 and 5, which occurred between September and October (excluding regime 6, which was a rare variant and occurred from July) and shortly after in November for regime 1. Spring flows were similar in all regimes, with slightly higher early spring flows (in March) for regimes 1 and 2. The winter months were the most variable across the region.

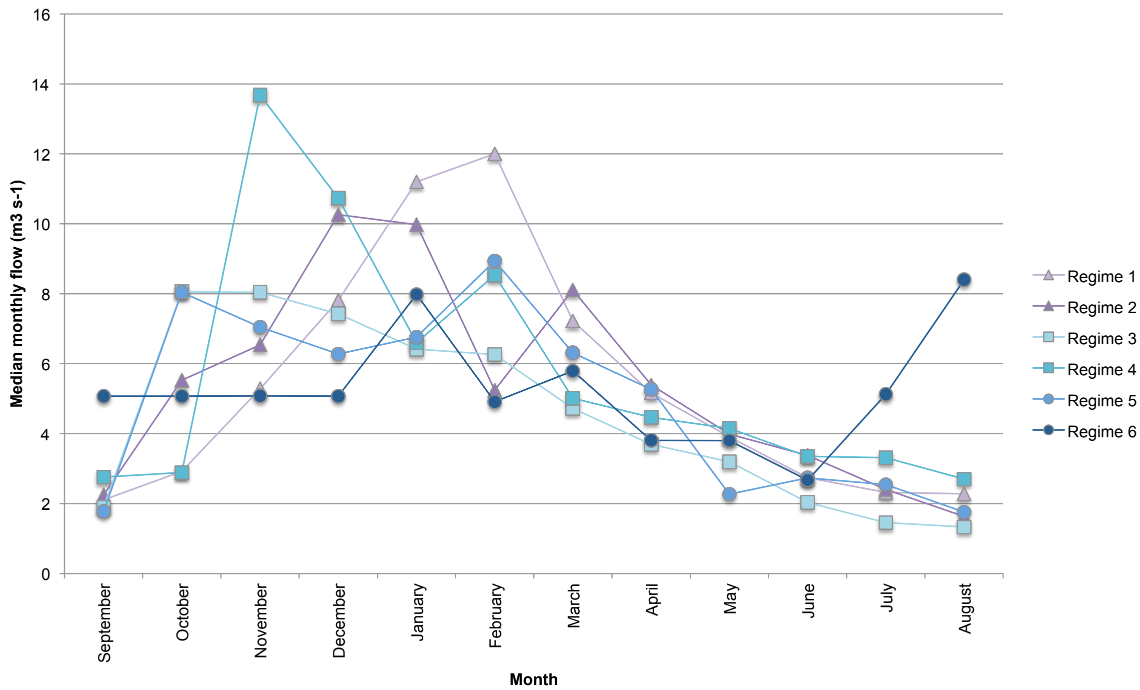

Figure 5.2. Median monthly flows of the six flow regimes from the six southwest rivers, 1966-2009 (excluding 1992, 2000 and 2006).

These subtle changes in ecologically important autumn and spring flows for salmon across the southwest region may suggest a regional management could be adequate. However, to ensure that region-level analysis is not removing potentially important flow variability, each individual river within the region will now be analysed independently.

5.2.1. Local analysis: The River Lynher

The River Lynher flows through east Cornwall and is approximately 34 km long. It rises on Bodmin moor, approximately 920 feet (280m) above sea level, and flows into the River Tamar at the Hamoaze, which meets the sea at Plymouth Sound. The River Lynher has four main tributaries, the largest of which is the River Tiddy, and smaller tributaries, including Deans Brook, Withey Brook, Marke Valley and Darleyford streams.

The River Lynher flow data come from the Pillaton Mill gauging station (station number 47004 according to the UK Hydrometric Register), with a catchment area of 135.5 km^2. The headwaters are peat covered granite moorland and the middle reach crosses Carboniferous shale and sandstone inlier. The catchment comprises of approximately 61% grassland, 20% arable land, 14% woodland,

and 2% mountain/heath/bogland. The mean annual rainfall in the area is 1466 mm, with a mean runoff of 1036 mm. The Lynher receives imports from Sibleyback Reservoir, which exceed direct public water supply abstraction and therefore have a moderate net effect at low flows.

The CA of the PC loading from the River Lynher (from 1964-2009, where 1966 was removed as an outlier) fits into four distinct flow regime groups (Figure 5.3), where:

- Regime 1: the largest cluster occurred 45.5% of the time (20 years in total) and had a single, high magnitude peak in median flow in January/February, with March flows initiating the spring/summer flow recession.
- Regime 2: occurred 27.3% of the time (12 years in total) and had two peaks, the first in December followed by a second, lower magnitude peak in March. The two peaks are the result of low median flows January and February.
- Regime 3: occurred 20.4% of the time (9 years in total) and had a single, high magnitude peak in January. This regime also had the highest median monthly flow in July.
- Regime 4: occurred 6.8% of the time (3 years in total) and had an early high magnitude peak between October and December, followed by lower median flows in January.

The timing of the high flow events occurred in January for regimes 1 and 2 and February for regime 3 and 4. Regime 4, a rare variant, had the highest magnitude high flow peaks of the four regimes. The 1-day minimum was typically lowest for regime 2 (0.574 $m^3 s^{-1}$). The greatest 1-day maximum flow was from regime 4 (171.6 $m^3 s^{-1}$). Despite regime 3 having the highest 1-day maximum flow, the highest large flood peak was during regime 2 (48.3 $m^3 s^{-1}$). Large flood events only occurred during regimes 1 and 2. Regime 2 had the greatest large flood peak and it typically occurred in December. The largest variation between 1-day minimum and maximum flow was in regime 4 (Appendix D2). The timing of the beginning of the sustained rise in autumn flows on the Lynher was October for the most common regimes 1, 2 and 3 (this was the case in regime 3 because despite in high flows in July, September had reduced flows) and September for regime 4. Spring flows were similar for all regimes, apart from slightly higher flows in regime 2 in March and marginally lower flows for regime 1 and 2 in May.

The occurrence of regimes over time indicated the most variable decade on the River Lynher was during the 1990s. The dominance of regime 1 decreases over the time, until the end of the 2000s when regime 1 starts to increase in dominance again. Regime 4 was only present three times and two of these occurrences were during the 2000s (Appendix D3).

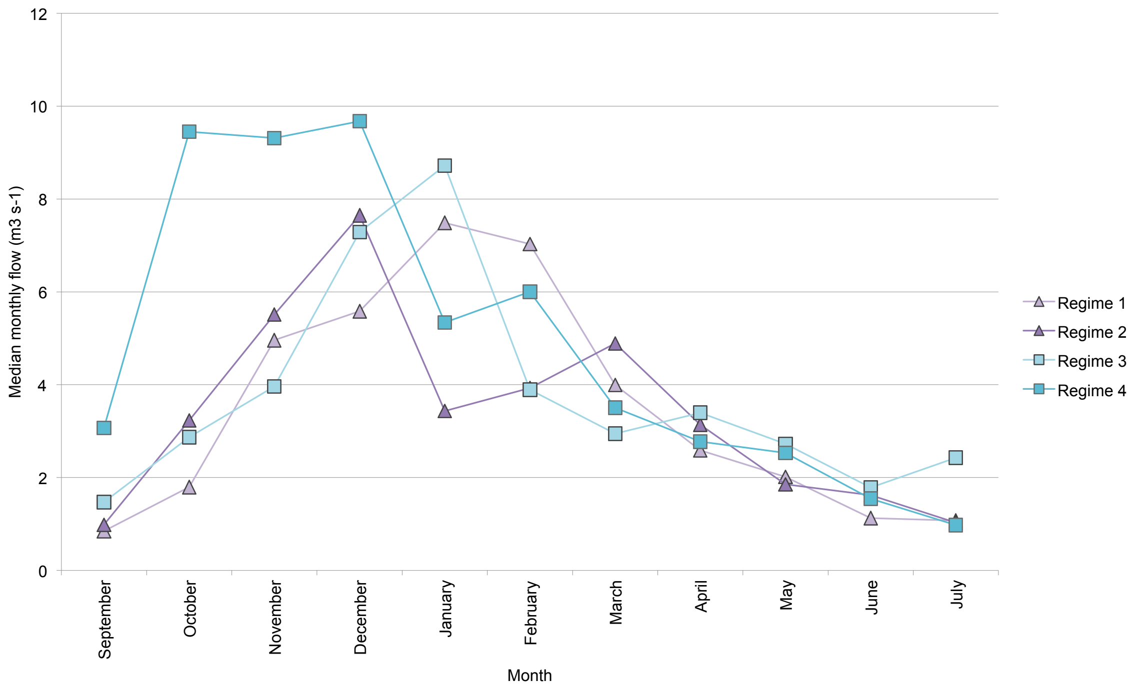

Figure 5.3. Median monthly flows for the four flow regimes on the River Lynher, 1964-2009 (with 1966 removed).

5.2.2. The River Tamar

The River Tamar is situated on the border of the counties of Devon and Cornwall. Its source is only 6km from the coast at Horsebridge. It then flows southward into the Hamoaze, before entering Plymouth South. Tributaries of the Tamar include the rivers Ottery, Inny, Lynher, Kensey, Deer and Tavy.

The River Tamar flow data come from the Gunnislake gauging station (station number 47001 according to the UK Hydrometric Register), with a catchment area of 916.9 km^2. This catchment is classified as fairly responsive to rainfall events, with moderate relief draining lower Carboniferous slates, shales, grits and volcanics. It has significant alluvial flats in the middle reaches and Devonian slates in the lower reaches. The catchment is predominately rural, with land-use within the catchment comprising of approximately 63% grassland, 22% arable land, 11% woodland and less than 1% mountain/heath/bogland. The mean annual rainfall in the area is 1105mm, with a mean runoff of 869mm. The construction of Roadford Reservoir is believed to have had a significant effect on the River Wolf low flows since 1989 (the River Wolf merges with the River Thrushel near Stowford and then joins the River Lew at Tinhay near Lifton and becomes the River Lyd. The River Lyd joins the River Tamar at the Devon/Cornwall border just east of Launceston).

The CA of the PC loading from the River Tamar (from 1958-2009, where 2006 was removed due to lack of data) fit into four distinct flow regime groups (Figure 5.4), where:

- Regime 1: the largest cluster occurred 64.7% of the time (33 years in total) and had a single, high magnitude peak of median flow in January.
- Regime 2: occurred 23.5% of the time (12 years in total) and also had a single high magnitude peak in January, however the regime had the lowest median flows of all regimes between in October- December and in February, and the highest median flows in April.
- Regime 3: occurred 7.8% of the time (4 years in total) and had three peaks, the first in September, followed by a similar magnitude peak in December, and a lower magnitude peak in February. Regime 3 had the highest median flows between May- October.
- Regime 4: occurred 3.9% of the time (2 years in total) and had a single, high magnitude peak in median flow in February, and the lowest median flows between March-May.

The high flow timing occurred in December for regimes 3 and 4, March for regime 2 and during February for regime 1. Regime 4 had the greatest high peak magnitude (88.9 $m^3 s^{-1}$). The 1-day minimum was lowest for regime 3 (2.148 $m^3 s^{-1}$), and the greatest 1-day maximum flow was also regime 3 (231.5 $m^3 s^{-1}$), therefore the largest variations between 1-day minimum and maximum flow was in regime 3. The highest large flood peak also occurred during regime 3 (355 $m^3 s^{-1}$). The typical timings of large flood events varied for the regimes; regime 1 and 3 typically occurred in December, regime 2 in November and regime 4 in February (Appendix D4).

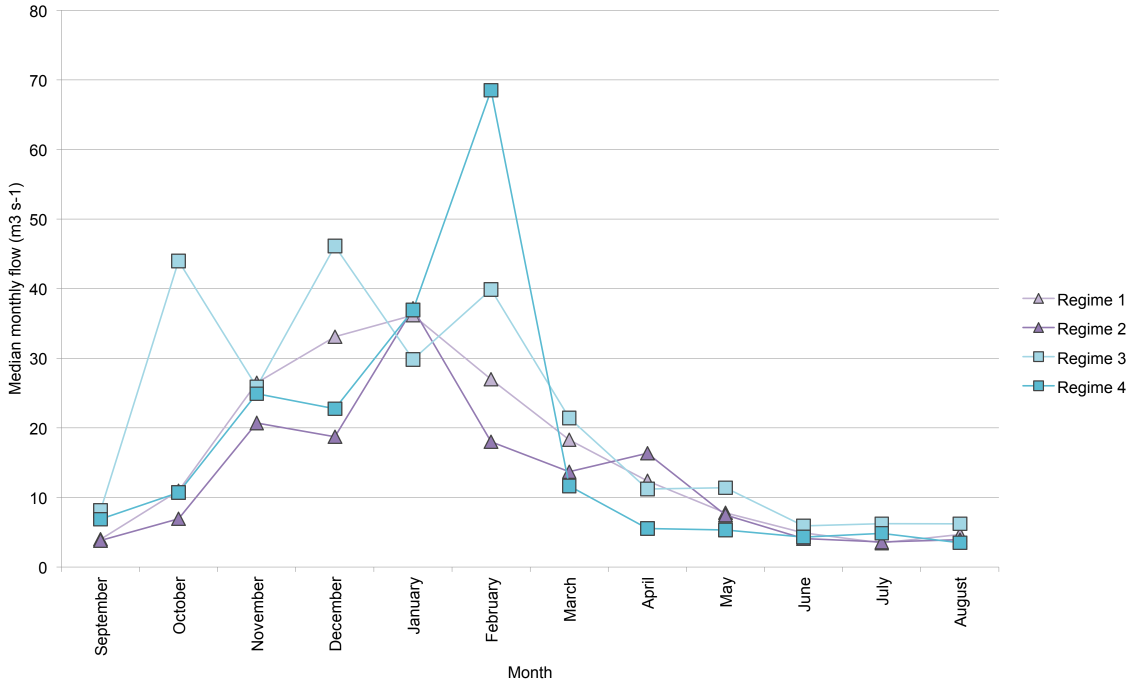

Figure 5.4. Median monthly flows for the four flow regimes on the River Tamar, 1958-2009 (where 2006 was removed).

There was little difference in the timing of the sustained rise in autumn flows on the Tamar, with all starting with a small increase in flow from October, but becoming more pronounced in November for regime 1, 2 and 3. Spring flows were similar for all regimes, with the less common regimes (3&4) having typically lower flows in April.

The occurrence of regimes over time for the River Tamar indicates the dominance of regime 1 decreases slightly over time, as the occurrence of regime 3 increases in the 1980s and regime 4 in the 1990s (Appendix D5).

5.2.3. The River Axe

The River Axe flows through the counties of Dorset, Somerset and Devon. It rises near Beaminster in Dorset, flows by Axminster and joins the English

Channel at Axmouth, near Seaton, in Lyme Bay. During its 22-mile (35 km) course it is fed by various streams and by the tributary rivers Yarty and Coly.

The River Axe flow data comes from the Whitford gauging station (station number 45004 according to the UK Hydrometric Register), with a catchment area of 288.5 km^2. It's a catchment of moderate relief draining chalk and greensand headwaters. The middle and lower reaches are Mercia Mudstone, Lias clays and more greensand. The land-use within the catchment comprises of approximately 56% grassland, 31% arable land, 9% woodland and >1% mountain/heath/bogland. The mean annual rainfall in the area is 1034 mm, with a mean runoff of 583 mm.

The CA of the PC loading from the River Axe (from 1965-2009, where 2008 was removed as an outlier) fit into four distinct flow regime groups (Figure 5.5), where:

- Regime 1: the largest cluster occurred 63.6% of the time (28 years in total) and had a single, high magnitude peak in median flow in January, with February flows initiating the spring/summer flow recession.
- Regime 2: occurred 18.2% of the time (8 years in total) and had a single, early high magnitude peak in median flow in December/January, followed by a dry February.
- Regime 3: occurred 9.1% of the time (4 years in total) and had two peaks, the first in December followed by a second, higher magnitude peak in February, as a result of a dry January.
- Regime 4: occurred 9.1% of the time (4 years in total) and had a single, high magnitude peak in November/ December. Regime 4 had the lowest median flows of all the regimes between January and March, and again between May and August. This characterises a wet autumn, followed by dry winter and summer.

The high flow timing for regime 1 and 2 were both typically in January, whereas regime 3 was typically in March and regime 4 in February. The largest high flow peak was in regime 3, with an average peak of 13.78 $m^3 s^{-1}$. The 1-day minimum was lowest for regime 4 (0.858 $m^3 s^{-1}$). The greatest 1-day maximum flow was from regime 3 (75.89 $m^3 s^{-1}$). The highest large flood peak was during regime 1 (118.1 $m^3 s^{-1}$). The timing of the large flood was typically in January for regime 1, December for regime 2, September for regime 3 and February for regime 4. The largest variation between 1-day minimum and maximum flows was in regime 3 (Appendix D6). The timing of the sustained rise in autumn flows on the Axe was typically from October in all regimes (except perhaps regime 3 which did see an increase in flow August, however this reduced in September and when began to increase again in October). Spring flows were similar for the most common regimes (1&2) for April and May. The largest variations in spring flows were in March.

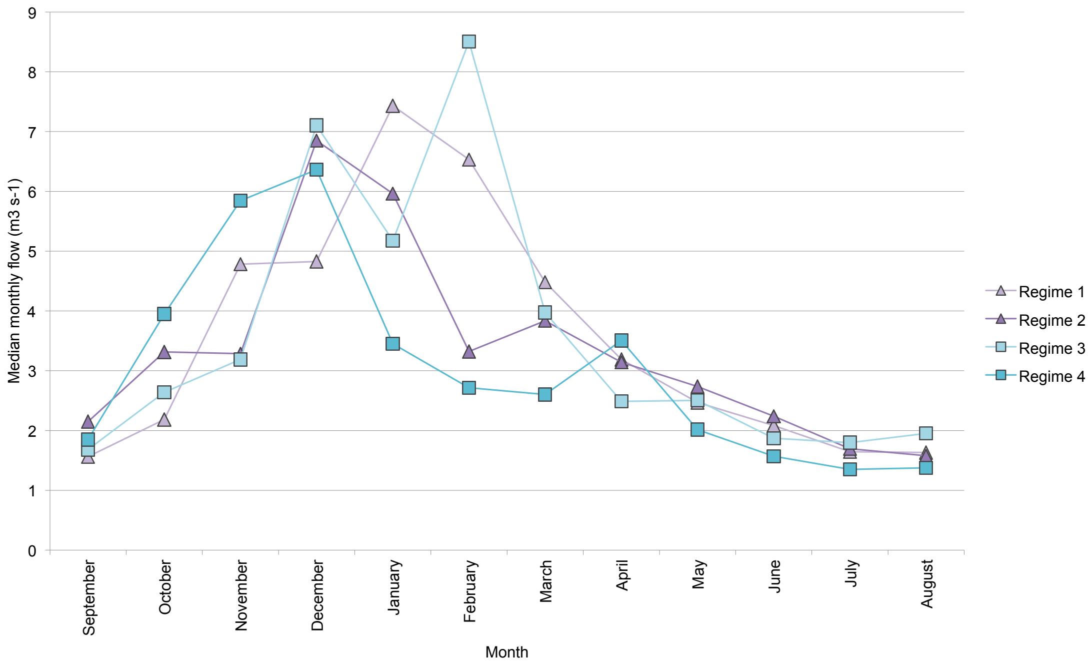

Figure 5.5. Median monthly flows of the four flow regimes on the River Axe, 1965-2009 (where 2008 was removed).

The occurrence of regimes over time shows a decline in dominance of regime 1 for the River Axe in the late 1990s and 2000s, and an increase in regime 3 over this time period (Appendix D7).

5.2.4. The River Camel

The River Camel is located in Cornwall, rising on the edge of Bodmin Moor. The river discharges into the Celtic Sea area of the Atlantic Ocean between Stepper Point and Pentire Point, having covered a distance of approximately 30 miles.

The River Camel flow data come from Denby gauging station (station number 49001 according to the UK Hydrometric Register), with a catchment area of 208.8 km^2. The upper catchment drains Devonian slates and Bodmin Moor Granite. The lower catchment drains Devonian slates and grits. The land-use within the catchment comprises of approximately 44% grassland, 40% arable land, 9% woodland and <1% mountain/heath/bogland. The mean annual rainfall in the area is 1405 mm, with a mean runoff of 915 mm.

The CA of the PC loading from the River Camel (from 1965-2009) fit into four distinct flow regime groups (Figure 5.6), where:

- Regime 1: the largest cluster occurred 56.8% of the time (25 years in total) and had a single, high magnitude peak in median flow in January/February.
- Regime 2: occurred 20.5% of the time (9 years in total) and had a single, high magnitude peak in median flow in November/December, resulting in a wet autumn followed by dry winter.
- Regime 3: occurred 15.9% of the time (7 years in total) and had a single, high magnitude peak in median flow in December/January.
- Regime 4: occurred 6.8% of the time (3 years in total) and had two peaks, the first in October followed by a second, higher magnitude peak in December, as a result of a dry November. Regime 4 also has the highest median flows between July and September.

The high flow timing varied for each regime; regime 1 occurred typically in November, regime 2 in February, regime 3 in March and regime 4 in June. The largest high flow peak was in regime 4, with an average peak of 10 $m^3\ s^{-1}$. The 1-day minimum was lowest for regime 1 (0.729 $m^3\ s^{-1}$), and the greatest 1-day maximum flow was for regime 4 (53.65 $m^3\ s^{-1}$). Only regimes 1 and 2 had large flood events during the timeframe, the greatest of which occurred in regime 2 (78 $m^3\ s^{-1}$) typically in September. For regime 1 the large flood events typically occurred in January. The largest variations between 1-day minimum and 1-day maximum flow were in regime 4 (Appendix D8). The timing of the sustained rise in autumn flows on the Camel was gradual between September and October for regime 1 and 3, with a true increase in flow for these regime occurring in

November. Regime 2 increased substantially from October. The spring flows were similar for all regimes. Regime 4 (a rare variant that only occurred 3 times during the records) saw high summer flows in July and August. The spring flows for all the regimes were very similar on the Camel.

The occurrence of regimes over time on the River Camel indicates regime 1 was slightly more dominant in the early 1970s, with regime 3 becoming more common in the early 1980s. Regime 4 occurred during the 1960s, 1990s and 2000s (Appendix D9).

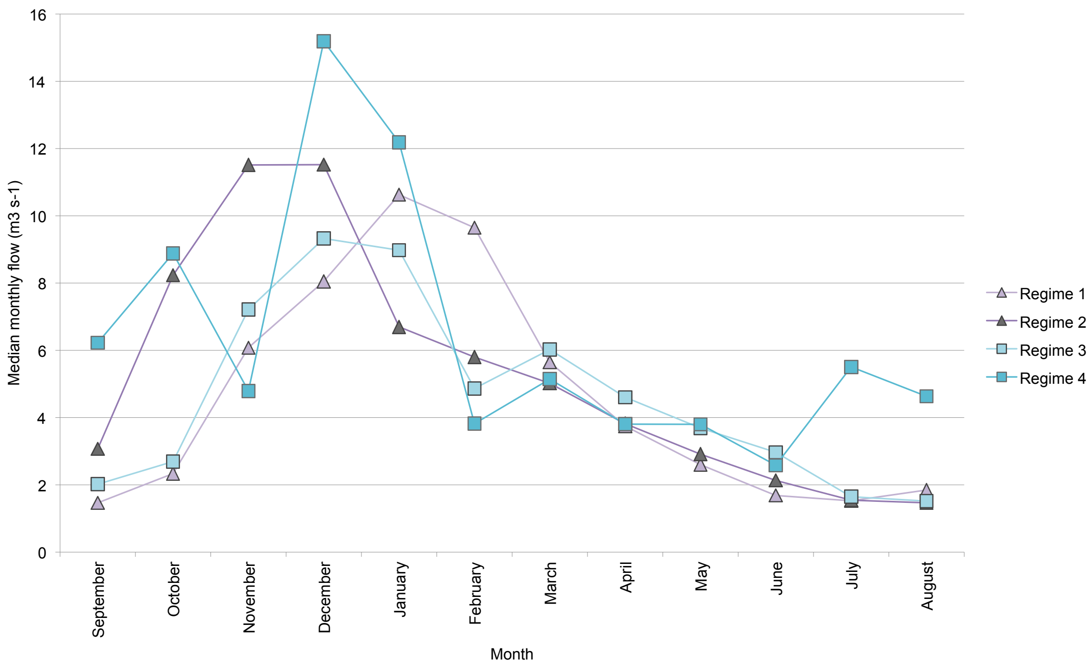

Figure 5.6. Median monthly flows of the four flow regimes on the River Camel, 1965-2009.

5.2.5. The River Frome

The River Frome, in Dorset, is approximately 48 km long. It is a ground-fed chalk stream, which rises in the Dorset Downs at Evershot, and passes through Maiden Newton, Dorchester, West Stafford and Woodsford. At Wareham it flows into Poole Harbour via the Wareham Channel.

The River Frome flow data comes from the East Stoke gauging station (station number 44001 according to the UK Hydrometric Register), with a catchment area of 414.4 km^2. The catchment comprises of approximately 47% arable land, 37% grassland, 9% woodland, and 1% mountain/heath/bog. The mean annual rainfall in the area is 1020 mm, with a mean runoff of 487 mm.

The CA of the PC loading from the River Frome (from 1966-2009, where 1992, 2000 and 2006 were removed due to lack of data and 1994 was removed as an outlier) fit into four distinct flow regime groups (Figure 5.7), where:

- Regime 1: the largest cluster, which occurred 53.7% of the time (22 years in total), had a single high magnitude peak in median flow in February. Regime 1 had the lowest median monthly flows of all the different regimes between October and December.
- Regime 2: occurred 24.4% of the time (10 years in total) and had a single early high magnitude peak in median flow in December and the highest median monthly flows in September and October. Regime 2 also had the lowest median monthly flows between March and July.
- Regime 3: occurred 12.2% of the time (5 years in total) and had two peaks, the first in December followed by a similar magnitude peak in February. This coincided with comparatively low median flows in January.
- Regime 4: occurred 9.7% of the time (4 years in total). This regime had no clear peaks, but was characterised by low median monthly flows between November and February and higher median flows in March and April, and again in June.

On the River Frome the high flow typically occurred in December for regimes 1 and 2, and November for regimes 3 and 4. The 1-day minimum was lowest for regime 4 (1.742 $m^3 s^{-1}$), and the greatest 1-day maximum flow was for regime 2 (22.37 $m^3 s^{-1}$). Only regimes 1 and 2 had large floods events during the time period, where regime 2 had the highest peak (26 $m^3 s^{-1}$) in January. Regime 1's large flood typically occurred in February. Overall, the parameters for the regimes were relatively consistent between the different regimes, however the largest variations between 1-day minimum and 1-day maximum flows were in regime 2 (Appendix D10). The timing of the sustained rise in autumn flows on the Frome occurred in regime 1 from November and October in regimes 2,3 and

4. The spring flows split into two groups, notably regime 1 had higher May flows and regime 4 higher June flows.

The occurrence of regimes over time shows a decline in regime 1 for the River Frome in the 1990s and 2000s, and an increase in regime 2 and 3 over this same time period. The 1960s and 1970s are dominated by regime 1 (Appendix D11).

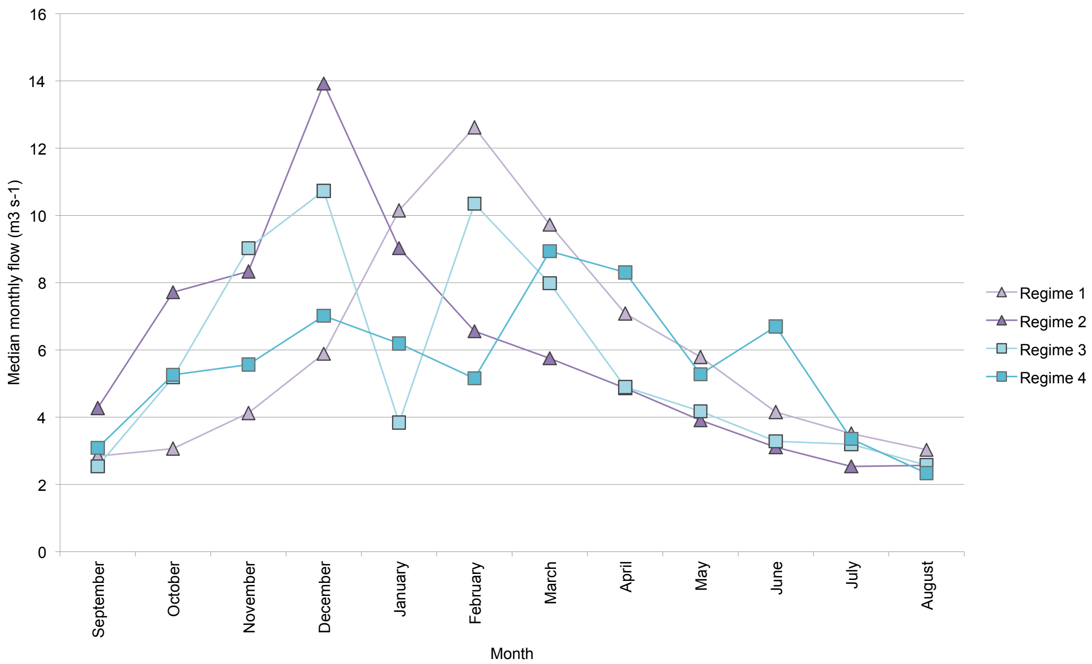

Figure 5.7. Median monthly flows of the four flow regimes on the River Frome, 1966-2009 (1992, 1994, 2000 and 2006 were removed).

5.2.6. Southwest river summary

Overall, the most common regime type over the 6 rivers had a single high magnitude peak in January, followed by a typical spring/summer flow recession. This was the most common regime on the Axe and Tamar, the second most common regime type also on the Tamar and the third most common regime on the Lynher.

The second most common regime type was characterised by a January/February peak. This slightly longer magnitude peak, again typically followed by a spring/summer flow recession, was found as the most common regime type on the Camel, Lynher and Dart. The most common regime type on the River Frome had a February high magnitude peak.

Twenty-five percent of the regimes for the 6 different rivers had two high magnitude peaks, which were predominately the result of low winter or summer flows. For example, regime 4 on the River Axe had a peak in the late autumn November-December, but was followed by a low flow winter, then a small increase in flow in April; regime 4 on the Camel had a high flow summer, followed by low flows in November and a high magnitude flow in December/January. The two magnitude peaks typically occurred in the least common regimes (regimes 3 or 4), apart from on the River Lynher where regime 2 had a double peak in December followed by March, as a result of low flows in January and February.

For 50% of the rivers, the largest high flow peak occurred within regime 4 (on the Camel, Tamar and Lynher), while on the Axe and Dart it occurred during regime 3, and on the Frome the high flow peak was the same for regime 1 and 2. For the most commonly occurring regime (regime 1), the timing of the high flows occurred in January for 50% of the rivers (Axe, Lynher and Dart). For the remaining rivers, the most common high flows occurred in February (Tamar), November (Camel) and December (Frome).

The 1-day minimum occurred within regime 1 on the Camel and Dart, within regime 2 on the Lynher, within regime 3 on the Tamar and within regime 4 on the Frome and Axe. The highest 1-day maximum flow was not found within regime 1 on any of the rivers. On the Camel and Lynher, the 1-day maximum occurred in regime 4, on the Axe and Tamar within regime 3 and for the Dart and Frome within regime 2.

The large flood events occurred within regime 1 for 50% of the rivers (Camel, Axe and Dart). The largest flood event did not occur in regime 4 for any of the rivers. On the Tamar it occurred within regime 3 and for the Lynher and Frome within regime 2. Although the timing of the small flood events varied between rivers and regimes, the most common months for large flood events were typically in December, January and/or February for most of the rivers.

The 6 different southwest regimes types do not match exactly with any of the 7 national regime types, because despite having similar patterns, the timing or longevity of the peaks varied for every regime between the scales of analyses. At the local level, approximately 25% of the individual river regimes (6 out of 24 regimes) showed the same overall trends in median flows as the six southwest regional regimes, which represented 47% of the flow years. Again, despite similarities, slight differences in the timings of the two peak flows or duration of peak flows resulted in local versus regional differences.

The autumn rise in flows predominantly started in October, apart from on the River Frome (the furthest east of the southwest rivers), where the most dominant autumn rise occurred in November. Regional, these elevated autumn flows are occurring quite late, which could result in salmon waiting in the estuary from the late summer before sufficient sustained flows encourage them to move into the rivers. Evidence suggests this can decrease survival, which will be covered further in the discussion (chapter 7).

This analysis indicates weather events are interacting with the different catchments in varying ways, resulting in distinct flow regime types within the region and between years. This illustrates substantial flow variability is lost when grouped, using this method, at the regional level. To investigate these findings further, the northern and Welsh regions will also be analysed.

5.3 NORTHERN RIVER ANALYSES

The northern river analyses covers rivers from the northern east and west locations in the UK and southern Scotland. The EA (2009a,b) recognised that the main pressures on the water environment in these regions were; diffuse pollution from agricultural activities, point source pollution from water industry sewage works, diffuse pollution from urban sources, physical modification of water bodies, point source pollution from industrial discharges, water abstraction and artificial flow regulation.

Figure 5.8. Map of rivers in the northern region (where the red dot indicates the location of the gauging station).

The CA of the PC loading from the six northern rivers (from 1970-2009, where 1975, 1976, 1980, 2002, 2003 and 2006 were removed due to lack of data) fit into six flow regime groups, where (Figure 5.9):

- Regime 1: the largest cluster, which occurred 71.3% of the time (149 years in total), and had a high flow autumn/early winter with single high magnitude peak in median flow in January.
- Regime 2: occurred 13.8% of the time (29 years in total) and had a high flow autumn, with high magnitude peak in median flow in January, and smaller magnitude peaks in March.
- Regime 3: occurred 5.7% of the time (12 years in total) and had three peaks; the first highest magnitude peak in November, followed by two similar lower magnitude peaks in January and March. Regime 3 had the highest magnitude median flows in June. Overall, this regime had a high flow autumn and winter, with low flow summer.

- Regime 4: occurred 3.4% of the time (7 years in total). This regime had no clear peaks, but was characterised by low autumn and winter flows.
- Regime 5: occurred 2.9% of the time (6 years in total) and had multiple peaks; similar magnitude peaks in September and December, followed by a lower magnitude peak in April and the highest magnitude peak in August. Regime 5 had the lowest median monthly flows in February and March.
- Regime 6: occurred 2.9% of the time (6 years in total) and had two low magnitude peaks; the first lower magnitude peak in November, followed by a higher magnitude peak in March.

There were three true regimes in the north analysis, regimes 1, 2 and 3, although regime 1 was by far the most dominant. Regime 6 only comprised of the year 1992 for all rivers, apart from the River Coquet (where 1993 was found in regime 6). This was also the case for regime 5, which consisted of 1985 for all rivers, apart from River Coquet (where 1986 was found), and regime 4 which comprised 1971 for all rivers, apart from the River Coquet (where 1972 was found). Regime 4 also had an additional year of 1981 for the River Coquet. The one year out phenomenon found on the northern analysis for the River Coquet during these years, was the same pattern found in the national analysis, although for some different years.

The median monthly flows for the northern regime analysis indicate that at the regional level the hydrological year appears to start earlier than September for most of the less dominant regime types. However, in regime 1, the hydrological year did start in September, which occurs 71% of the time.

The high flow timing typically occurred in January for regime 1, February for regime 2, November for regime 3 and 4 and October for regime 5 and 6. The 1-day minimum was lowest for regime 6 (0.74 $m^3 s^{-1}$) and the greatest 1-day maximum flow was from regime 6 (224 $m^3 s^{-1}$). The highest large flood peak also occurred during regime 6 (443.6 $m^3 s^{-1}$). The typical timings of large flood events varied from December in regime 1 and 5, January in regime 2 and 6, February in regime 3 and October in regime 4 (Appendix E1).

The timing of the sustained rise in autumn flows in the northern region was predominately October (regime 1), occurring approximately 74% of the time. The remaining regimes autumn rise varied; occurring early in August for regime 2 and 5, followed by October for regime 3. Regime 4 had no clear sustained rise. The spring flows highly variable in early spring (March and April), a pattern not so noticeable in the southwest rivers, although the most the extreme highest and lowest flows did tend to come from the least dominant regimes. This still could, however, have ecological consequences for juvenile Atlantic salmon.

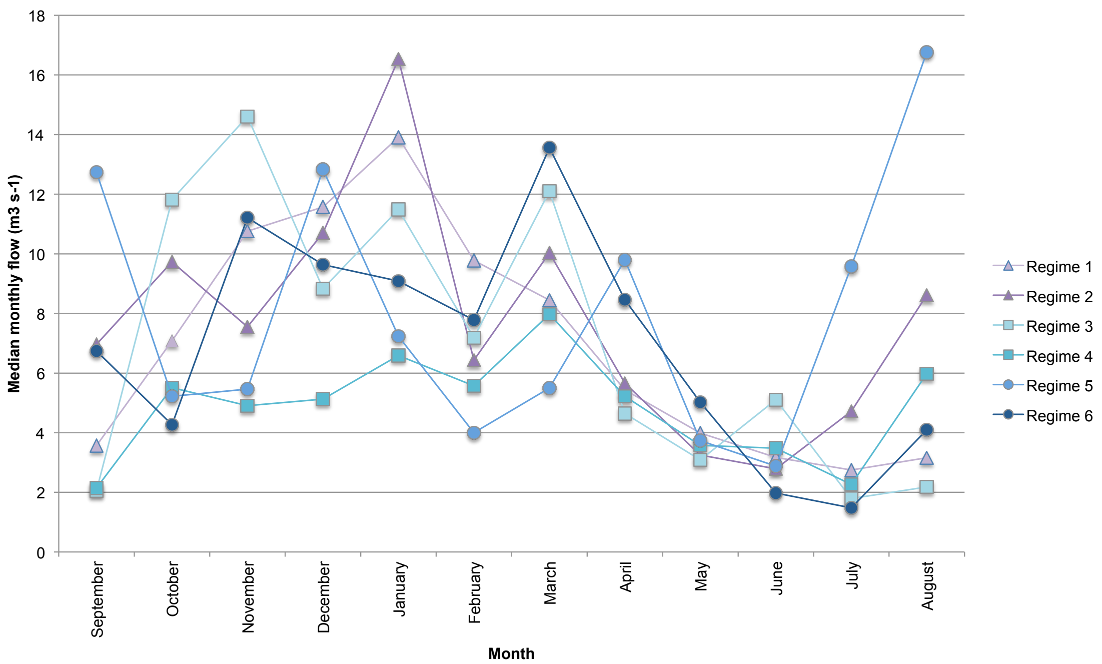

Figure 5.9. Median monthly flows of the six flow regimes from the six northern rivers, 1970-2009 (excluding 1975, 1976, 1980, 2002, 2003 and 2006).

5.3.1. Local analysis: The River Lune

The River Lune flows through the counties of Cumbria and Lancashire. It is formed at Wath, Cumbria, at the confluence of Sandwath Beck and Weasdale Beck. The river then passes near Low Borrowbridge at the foot of Borrowdale, and flows through south Cumbria, finally meeting the Irish Sea at Plover Scar near Lancaster, after a total journey of about 44 miles (71 km). The Lune is tidal below Skerton Weir in Lancaster.

The River Lune flow data come from Killington New Bridge gauging station (station number 72005 according to the UK Hydrometric Register), with a catchment area of 219km^2. The catchment is classified as wet high relief catchment, with silurian slates to the west, Carboniferous conglomerate and Limestone north and peat moss on high moors to the northwest, and heather moss in the north. The lower valleys are covered with Boulder Clay. The land-use within the catchment comprises approximately 83% grassland, 8% mountain/heath/bogland, 4% woodland and 1% arable land. The mean annual rainfall in the area is 1659 mm, with a mean runoff of 1474 mm.

The CA of the PC loading from the River Lune (from 1970-2009, where 1975, 1979, 1980, 2001 were removed due to lack of data and 1973, 1974 and 1985 were removed as outliers) fit into three distinct flow regime groups (Figure 5.10), where:

- Regime 1: the largest cluster occurred 51.1% of the time (17 years in total) and had a single, high magnitude peak in median flow in December/January, with February flows initiating the spring/summer flow recession.
- Regime 2: occurred 27.3% of the time (9 years in total) and had two peaks; the first in January followed by a second, lower magnitude peak in March. The two peaks were the result of low median flows in December and February.
- Regime 3: occurred 21.2% of the time (7 years in total) and had a single, high magnitude peak in February, the magnitude of which was nearly double that of the highest median magnitudes for regime 1 and 2. Regime 3 also had the lowest median flows of all the regimes in April, followed by the highest regime flow in May. Overall, regime 3 had the lowest winter flows.

The high flow timing of regime 1 was typically in December, and had the highest peak of the three regimes, with an average peak of 26.48 $m^3 s^{-1}$. Regime 2's high flow timing was typically in March and regime 3's in February. The 1-day minimum was lowest for regime 2 (0.642 $m^3 s^{-1}$), and the greatest 1-day maximum flow was for regime 3 (171.6 $m^3 s^{-1}$). Despite regime 3 having the highest 1-day maximum flow, the greatest large flood peak was during regime 2

(441 m^3 s^{-1}). The typical timings of large flood events for all regimes were in January. The largest variation between 1-day minimum and maximum flow was in regime 3 (Appendix E2). The rise in autumn flows on the Lune occurred more subtly than on most southwest rivers, with all three regimes increasing slowly in flow from October. The spring flows were most variable early in the season in March, with regime 2 having the highest flows. During April and May regime 1 and 2 had very similar flows, with regime 3 acting as the outlier.

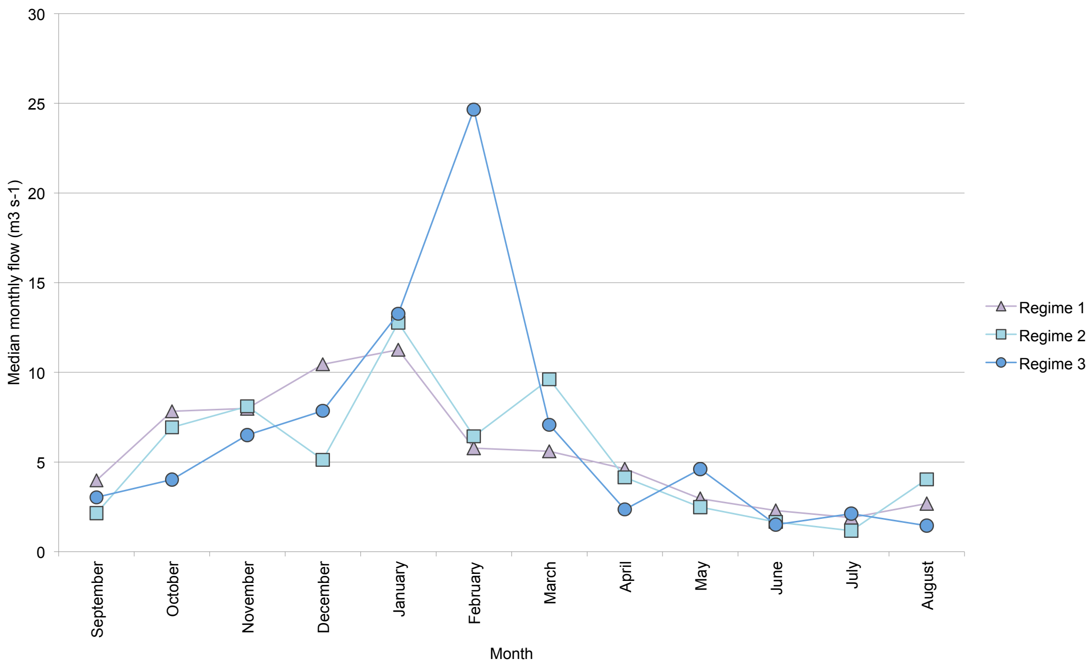

Figure 5.10. Median monthly flows for the three flow regimes on the River Lune, 1970-2009 (1973, 1974,1975, 1979, 1980, 1985 and 2001 were removed).

The occurrence of regimes over time shows a clear decline in regime 1 for the River Lune in the 1990s and 2000s, and an increase in regime 2 and 3 over this same time period (Appendix E3). However, there are gaps in the regime classification in the 1970s and early 1980s, which makes these changes difficult to generalise.

5.3.2. The River Ribble

The River Ribble flows through the counties of North Yorkshire and Lancashire. The Ribble begins at the confluence of the Gayle Beck and Cam Beck near the viaduct at Ribblehead. It flows through Settle, Clitheroe, Ribchester and

Preston, before emptying into the Irish Sea between Lytham St. Annes and Southport. The River Ribble has a length of approx. 75 miles (121 km).

The River Ribble flow data is from the Samlesbury gauging station (station number 71001 according to the UK Hydrometric Register), which has a catchment area of 1145 km^2. The catchment is of mixed geology with Carboniferous Limestone, Millstone Grit and Coal Measures overlain with Boulder Clay. The land-use within the catchment comprises of approximately 71% grassland, 9% mountain/heath/bogland, 9% woodland and 3% arable land. The mean annual rainfall in the area is 135 mm, with a mean runoff of 906 mm.

The CA of the PC loading from the River Ribble (from 1961-2009, where 1981 and 2000 was removed due to lack of data and 1961, 1962, 1966, 1967, 1971,1998 and 2001 were removed as outliers) fit into three flow regime groups (Figure 5.11), where;

- Regime 1: the largest cluster occurred 52.5% of the time (21 years in total) and had a single, high magnitude peak in median flow in January, and the highest median flows in October and March. Regime 1 had the lowest spring flows.
- Regime 2: occurred 27.5% of the time (11 years in total) and had a single, early high magnitude peak in November, followed by the lowest median flows in December, and the highest median flows in April. Overall, regime 2 had a low flow winter.
- Regime 3: occurred 20.0% of the time (8 years in total) and had a single, early high magnitude peak in December (in highest magnitude peak from the three regimes), followed by the lowest median flows in January through to March, and the highest median flows in August. Regime 3 had the lowest flow in the winter period from January to March.

Regime 1 had the largest high flow peak of the three regimes, which was typically 86.8 $m^3 s^{-1}$. High flows typically occurred in January for regimes 1 and 3, and February for regime 2. The 1-day minimum was lowest for regime 1 (3.57 $m^3 s^{-1}$), and the highest 1-day maximum flow was from regime 3 (345.5 $m^3 s^{-1}$). Despite regime 3 having the highest 1-day maximum flow, the highest large flood peak was during regime 1 (644.3 $m^3 s^{-1}$). The typical timings of large flood events for all regimes were in December. The largest variation between 1-day minimum and maximum flow was in regime 3 (Appendix E4). On the River Ribble rather than a sustained rise in autumn flows, the regimes are characterised by high magnitude one-month large peaks. The most common regime, occurring over half the time, had the clearest autumn rise building from October. The spring flows remained high in regime 1 in March (with comparable flow levels to the regime's October and November median flows). This was then followed by the driest comparable April and May flows from all the regimes.

The occurrence of regimes remains fairly constant for the Ribble through the analysis period from the early 1960s to late 2000s. Regime 1 appears to become slightly more dominant in the 1980s and 1990s, however there are gaps in the regime classification in the 1960s and early 2000s, so this could be an artefact of the missing data (Appendix E5).

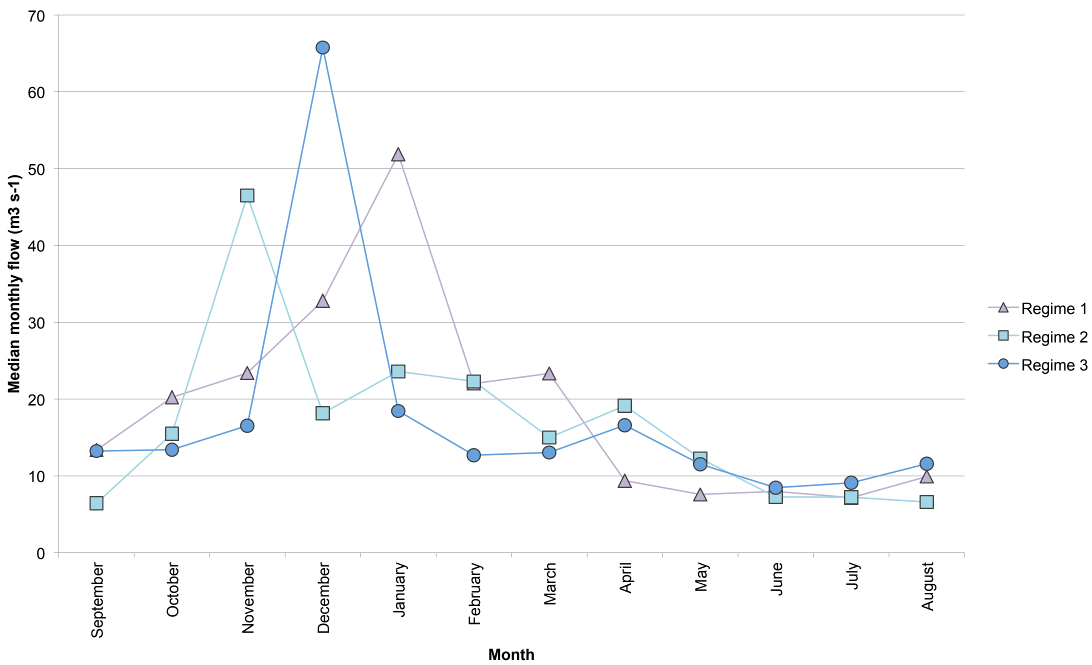

Figure 5.11. Median monthly flows for the three flow regimes on the River Ribble, 1961-2009 (1961, 1962, 1966, 1967, 1971, 1981 and 1998 were removed).

5.3.3. The River Kent

The River Kent is a short river in the county of Cumbria. The river originates in hills surrounding Kentmere, and flows for around 20 miles (32 km) into the north of Morecambe Bay, having passed through Kentmere, Staveley, Burneside, Kendal and Sedgwick on the way.

The River Kent flow data is from the Sedwick gauging station (station number 73005 according to the UK Hydrometric Register), with a catchment area of 209km^2. It is classified as a high relief catchment, draining impervious Pre-Cambrian to Silurian rocks, where heather moorland and peat predominate. Carboniferous Limestone provides good grazing, especially south of Kendal on Drift cover. The land-use within the catchment comprises of approximately 81% grassland, 6% woodland, 6% arable land and 4% mountain/heath/bogland. The mean annual rainfall in the area is 1749 mm, with a mean runoff of 1357 mm.

The CA of the PC loading from the River Kent (from 1969-2009, where 1969, 1974, 1975, 1985 and 1991 were removed as outliers) fits into three distinct flow regime groups (Figure 5.12), where;

- Regime 1: the largest cluster occurred 52.8% of the time (19 years in total) and had two high magnitude peaks: an early peak in October, followed by a higher magnitude peak in January. This regime also had the highest median regime flows in February and the lowest median regime flows in August.
- Regime 2: occurred 33.3% of the time (12 years in total) and had two high magnitude peaks: an early high magnitude peak in November, followed by a lower magnitude peak in March. Regime 2 had the highest regime median flows in August and September, and lowest flows in January.
- Regime 3: occurred 13.9% of the time (5 years in total) and had a single, high magnitude peak in January (the highest magnitude peak of the three regimes), followed by the lowest regime median flows in February and March and preceded by the lowest median flows in October and November. Regime 3 also had the highest regime median flows in April, June and July.

Regime 2 had the largest high flow peak of the three regimes with high flow peak of typically 22.6 $m^3 s^{-1}$. The high flow typically occurred in December for regime 1, January for regime 2 and March for regime 3. The 1-day minimum was lowest for regime 1 (0.805 $m^3 s^{-1}$), and the highest 1-day maximum flow was from regime 2 (83.37 $m^3 s^{-1}$). The highest large flood peak was during regime 1 (176.6 $m^3 s^{-1}$). The typical timings of the large flood events for all regimes were in January. The largest variation between 1-day minimum and maximum flow was in regime 2 (Appendix E6). The timing of the sustained rise in autumn flows on the Kent varied between all regimes; it was September for regime 1, August for regime 2 and November for regime 3. The spring flows were highest early in the spring for regime 2 and then were similar for April for the top two regimes, which account for approximately 86% of the timeframe. In May regime 1 had the lowest flows.

The occurrence of regimes shows that regime 1 appears to become more dominant over time, particularly in the late 1990s and early 2000s, although some of the early dataset is missing. The late 1970s and early 1980s are dominated by regime 2. Regime 3 is absent from the 1980s, after appearing twice consecutively in the early 1970s and then occurs three times in the 1990s and 2000s combined (Appendix E7).

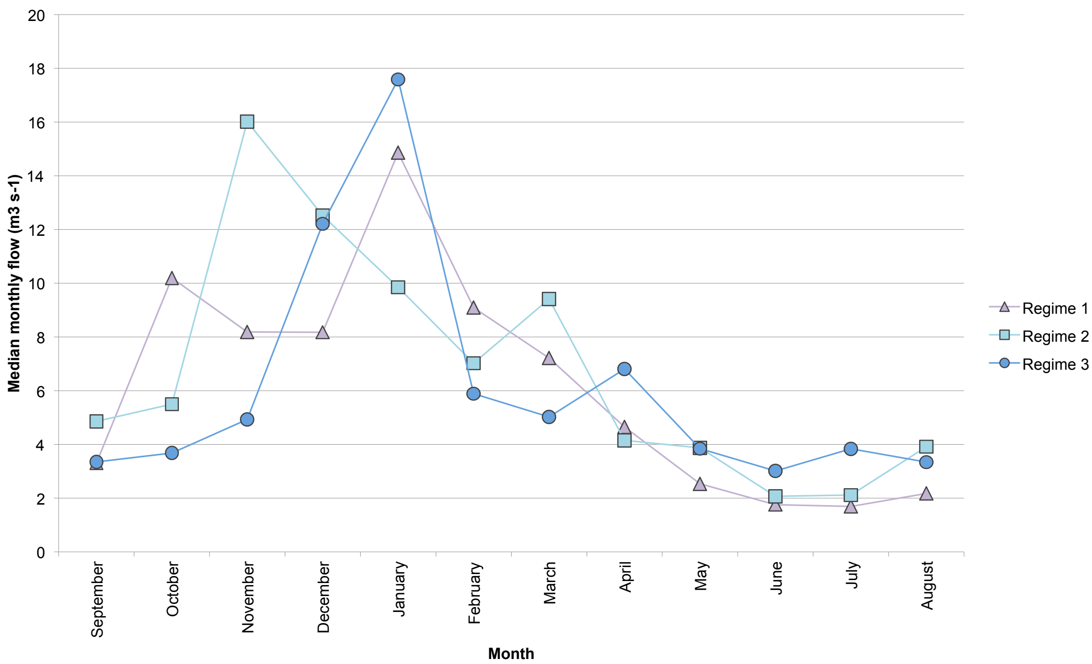

Figure 5.12 Median monthly flows for the three flow regimes on the River Kent, 1969-2009 (1969, 1974, 1975, 1985 and 1991 were removed).

5.3.4. The River Coquet

The River Coquet runs through the county of Northumberland, discharging into the North Sea on the east coast at Amble. The river, about 40 miles (64 km) in length, rises in the Cheviot Hills and follows a generally easterly course.

The River Coquet flow data come from the Morwick gauging station (station number 22001 according to the UK Hydrometric Register), with a catchment area of 569.8 km^2. The upland catchment drains predominantly from Cheviots, Carboniferous Limestone and low permeability Devonian Igneous series. The land-use within the catchment comprises of approximately 53% grassland, 18% arable land, 16% woodland and 12% mountain/heath/bogland. The mean annual rainfall in the area is 875 mm, with a mean runoff of 464 mm.

The CA of the PC loading from the River Coquet (from 1964-2009, where 2006 was removed due to lack of data and 1967, 1968 and 1976 were removed as outliers) fit into three flow regime groups (Figure 5.13), where;

- Regime 1: the largest cluster occurred 73.2% of the time (30 years in total) and had a single, high magnitude peak in median average flow between December and February. This was preceded by the lowest regime median flows between August and November.
- Regime 2: occurred 14.6% of the time (6 years in total) and had a single high magnitude peak in January. Regime 2 had the highest median monthly flows in August.
- Regime 3: occurred 12.2% of the time (5 years in total) and had two peaks, the first between November and January, followed by a second equal magnitude peak in April. Regime 3 had the lowest median flows of any regime in February.

Regime 3 had the largest high flow peak of the three regimes with high flow peak of typically 32.68 $m^3 s^{-1}$. The high flow typically occurred in January for regimes 1 and 3, and March for regime 2. The 1-day minimum was lowest for regime 1 (0.935 $m^3 s^{-1}$), and the highest 1-day maximum flow was from regime 3 (134.5 $m^3 s^{-1}$). The highest large flood peak was during regime 3 (279.9 $m^3 s^{-1}$). The average typical timing of large flood events for regime 1 was in January, regime 2 was in December and regime 3 was in April. The largest variation between 1-day minimum and maximum flow was in regime 3 (Appendix E8). The timing of the sustained rise in autumn flows on the Coquet was September for regime 1, and August for regime 2 and 3 (although regime 2 did have low flows in September). The spring flows were similar for all regimes, apart from in April when the least common regime, 3, had double the flow (comparable to winter flows) of the other regimes.

The occurrence of regimes shows that regime 1 appears to decline slightly in dominance over time on the River Coquet, particularly from the late 1980s, and over this same time period regime 4 increases in occurrence. The 1970s and early 1980s were dominated by regime 1 (Appendix E9).

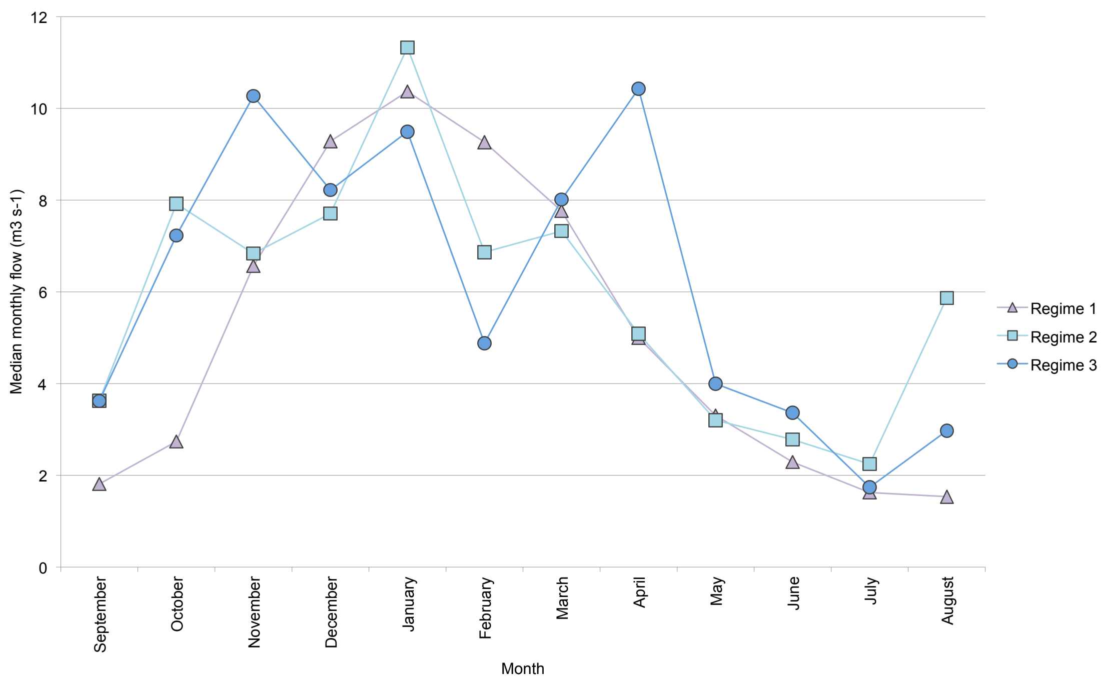

Figure 5.13. Median monthly flows for the four flow regimes on the River Coquet, 1964-2009 (1967, 1968, 1976 and 2005 were removed).

5.3.5. The River Tweed

The River Tweed is 97 miles (156 km) long and flows primarily through the Borders region of Great Britain. It rises on Tweedsmuir at Tweed's Well, near where the Clyde draining northwest, and the Annan draining south. It drains the entire Borders region. Its lower reaches are near Berwick-upon-Tweed.

The River Tweed flow data come from the Boleside gauging station (station number 21006 according to the UK Hydrometric Register), with a catchment area of 1500km^2. The catchment is classified as a wet, high relief catchment, with silurian slates to the west, Carboniferous conglomerate and limestone to the north and peat moss on high moors to the northwest. The lower valleys are Boulder Clay covered. The land-use within the catchment comprises of approximately 47% grassland, 27% mountain/heath/bogland, 20% woodland and 5% arable land. The mean annual rainfall in the area is 1228mm, with a mean runoff of 815 mm.

The CA of the PC loading from the River Tweed (from 1962-2009, where 2002 was removed due to lack of data and 1963, 1967, 1968, 1981, 1985 and 2004 were removed as outliers) fit into three flow regime groups (Figure 5.14), where;

- Regime 1: the largest cluster occurred 53.7% of the time (22 years in total) and had a single, high magnitude peak in median flow in January, and the highest median flows of any regime in October and February. Regime 1 has the lowest median regime flows in May, June, August and September.
- Regime 2: occurred 34.1% of the time (14 years in total) and had a single, high magnitude peak in median flow in December, and the highest median flows of any regime in November and May, and the lowest regime median flow in January and July.
- Regime 3: occurred 12.2% of the time (5 years in total) and also had a single, high magnitude peak in median flow in January, but the magnitude of the peak is higher than regime 1. Regime 3 had the lowest median flows of any regime in November and between February and April.

Regime 1 had the largest high flow peak of the three regimes with high flow peak of 57.5 m^3 s^{-1}. The high flow typically occurred in December for regime 1, November for regime 2 and June for regime 3. Regime 3 had both the lowest 1-day minimum (5.565 m^3 s^{-1}) and highest 1-day maximum flow (314.3 m^3 s^{-1}). Despite regime 3 having the highest 1-day maximum flow, it did not have any large flood events during the timeframe. The highest large flood peak was during regime 2 (548 m^3 s^{-1}). The timings of the typical large flood events for regime 1 and 2 were in December. The largest variation between 1-day minimum and maximum flow was in regime 3 (Appendix E10). The timing of the sustained rise in autumn flows on the Tweed was September for regime 1 and August for regime 2 and 3 (although regime 3 had a low flow winter). The spring flows were similar for all regimes, apart from in March were the least common regime, 3, had notably lower flows.

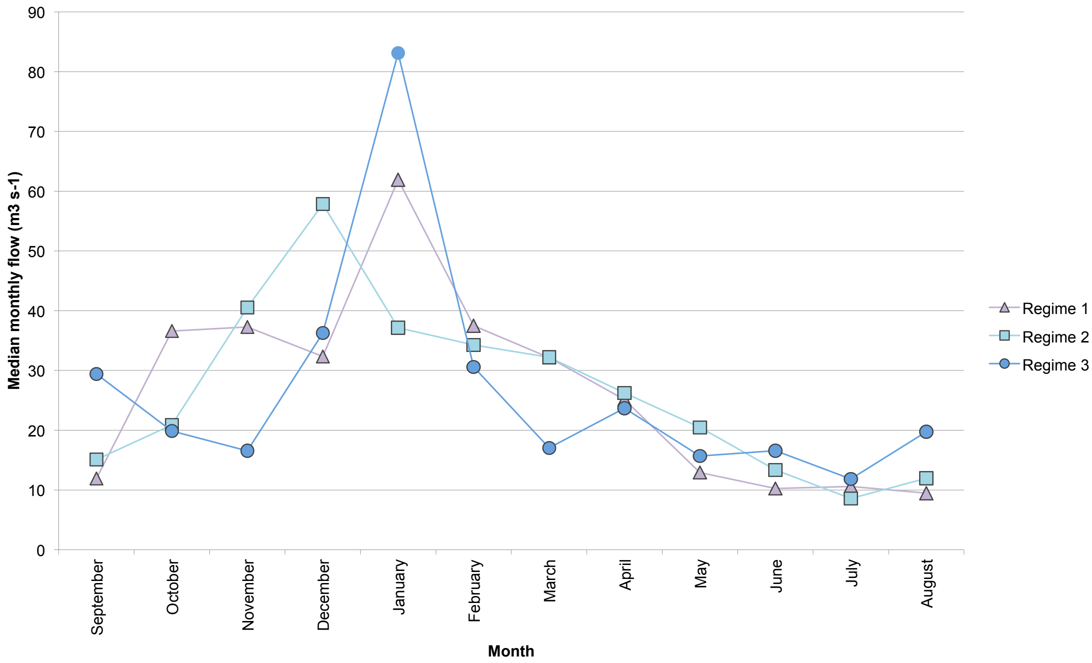

Figure 5.14. Median monthly flows for the three flow regimes on the River Tweed, 1962-2009 (1963, 1967, 1968, 1981, 1985, 2002 and 2004 were removed).

The occurrence of regime 1 on the River Tweed appears to increase from the 1970s. The 1960s are dominated by regime 2 and 3, although three years of data are missing during this decade. By the 1970s the dominance of all regimes appears to stabilise and remain relatively constant (Appendix E11).

5.3.6. The River Tyne

The River Tyne rises in the Moorfoot Hills, in Midlothian near Tynehead, to the south of Edinburgh. It continues for approximately 30 miles in a northeast direction and empties into the North Sea near Belhaven.

The River Tyne flow data are from the East Linton gauging station (station number 20001 according to the UK Hydrometric Register), with a catchment area of 307km^2. The catchment is characterised by steep headwaters in the Lammermuir Hills and a broad flat valley. The land-use within the catchment comprises of approximately 51% arable land, 28% grassland, 13% woodland and 7% mountain/heath/bogland. The mean annual rainfall in the area is 731 mm, with a mean runoff of 289 mm.

The CA of the PC loading from the River Tyne (from 1961-2009, where 1997, 2003 and 2006 were removed due to lack of data and 1963, 1965, 1966, 1983, 1984, 2007, 2008 and 2009 were removed as outliers) fit into three distinct flow regime groups (Figure 5.15), where;

- Regime 1: the largest cluster occurred 68.4% of the time (26 years in total) and had a single, high magnitude peak in median flow in January, preceded by the lowest median flows of any regime in October and November.
- Regime 2: occurred 18.4% of the time (7 years in total). This regime had low median flows for all months, with no defined peak in flow. Regime 2 had the lowest median monthly flows of any regime between December-April, and again between August- September.
- Regime 3: occurred 13.2% of the time (5 years in total) and had two peaks, the first in November followed by a second, lower magnitude peak in February. Regime 3 had the highest median monthly flows of any regime in October, December and between June-August, and had the lowest monthly median flow of any regime in May.

Regime 2 had the largest high flow peak of the three regimes with high flow peak of typically 5 $m^3\ s^{-1}$. The high flow typically occurred in February for regime 1, January for regime 2 and June for regime 3. The 1-day minimum was lowest for regime 2 (0.517 $m^3\ s^{-1}$), and the highest 1-day maximum flow was from regime 3 (40.79 $m^3\ s^{-1}$). Only regime 1 had any large flood events during the time period, of which the peak was 87 $m^3\ s^{-1}$ and the average timing was July. The largest variation between 1-day minimum and maximum flow was in regime 2 (Appendix E12). The timing of the sustained rise in autumn flows on the Tyne was October for regime 1 and 2 and August for regime 3. The spring flows were varied and highest in March and April for regime 1.

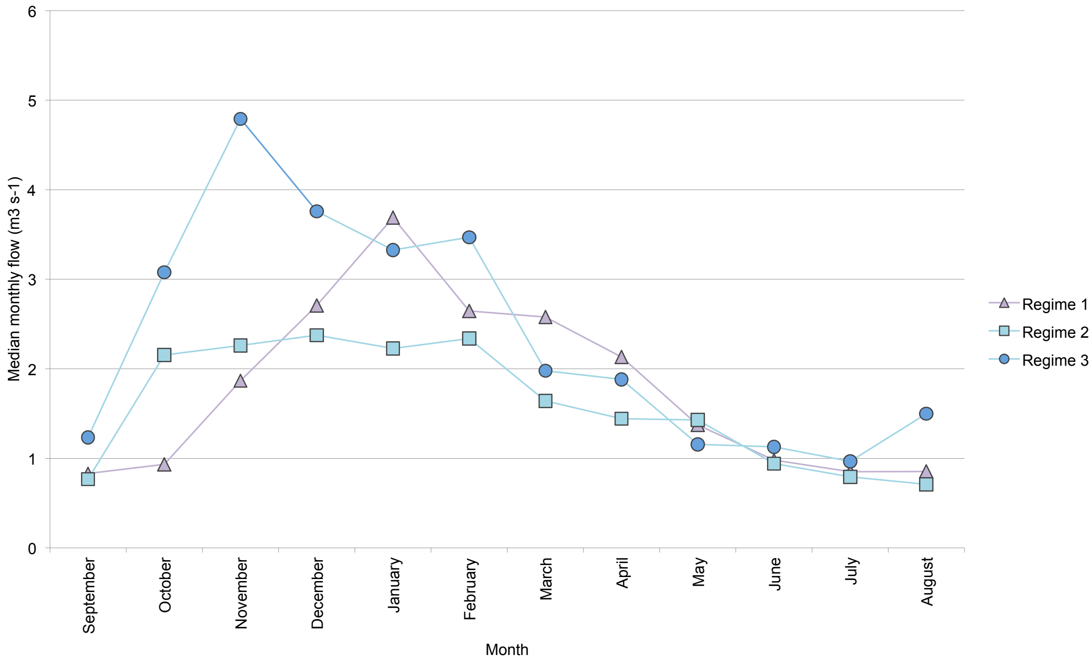

Figure 5.15. Median monthly flows for the three flow regimes on the River Tyne, 1961-2009 (1963, 1965, 1966, 1983, 1984, 1997, 2003, 2006, 2007, 2008 and 2009 were removed).

On the River Tyne the occurrence of regime 1 appears to increase in dominance from the 1980s. Regime 2 is more common from the late 1960s to early 1980s, and regime 3 becomes more common in the late 1990s and early 2000s (Appendix E13).

5.3.7. Northern river summary

Overall, the most common regime over the 6 rivers in this region was characterised by a single high magnitude peak in January; this occurred on all rivers apart from the River Lune and overall made up 33.3% of the regimes types found. This was the most common regime on the Tyne, Tweed and Ribble. The River Kent was the only river where the most commonly occurring regime had two peaks (with the first peak in early in October, followed by a second higher magnitude peak in January). The second most common regime, regime 2, on the Kent also had two peaks (an early peak in November, followed a lower magnitude peak in March). Otherwise, on the Tyne, Coquet and Lune the two peak regimes were the third, least common regimes, although two out of the three regimes present on the river Lune had two high magnitude peaks.

On 50% of the rivers, the largest high flow peak occurred within regime 1 (on the Tweed, Ribble and Lune), on the Coquet during regime 3 and on the rivers Tyne and Kent it occurred during regime 2. For the most commonly occurring regime, regime 1, the timing of the high flows ranged from December on the rivers Lune, Kent and Tweed, January on the Ribble and Coquet and February on the Tyne.

On 50% of the rivers the 1-day minimum occurred within regime 1 (on the Coquet, Kent and Lune), it occurred within regime 2 on the Tyne and Lune, and within regime 3 on the Tweed. The highest 1-day maximum flow was not found within regime 1 on any northern river, in fact for five out of the six rivers the 1-day maximum flow occurred during the least common, regime 3. Only on the River Kent was the 1-day maximum flow found within regime 2.

The large flood events occurred within regime 1 for 50% of the rivers (Ribble, Tyne and Kent). The River Coquet was the only river where the large flood event occurred within the least common regime 3, although on two of the rivers (Tyne and Tweed) regime 3 did not have any large flood events during the timeframe. On the rivers Kent, Coquet and Lune the large flood events typically occurred in January. On the Ribble and Tweed, large flood events typically occurred in December, whereas on the Tyne the average timing was July. Four out of the six rivers had their largest variations between 1-day minimum and maximum flows in regime 3 (Lune, Ribble, Coquet and Tweed), and for the remaining two rivers, this was found during regime 2 (Tyne and Kent).

Of the northern regimes types, 33.3% matched with the 7 national regime types, although this did account for 74.5% of the flow years. At the local level, approximately 44% (8 out of 18 regimes) of the individual river regimes corresponded with the 6 northern regional regimes, however this accounts for 51% of the river flow years.

The autumn rise in flows predominantly started in September or October for the northern rivers. In the regional analysis, 16.7 of years had early autumn rises in August. There tended to be a greater variability in the magnitude of spring median flows in the north, however this was predominately in the least common regime types.

5.4 Welsh Rivers

Wales borders England to the east, with the Atlantic Ocean and Irish Sea to its west. The EA (2009d) recognised that the main pressures on the water environment in Wales were; diffuse pollution from agricultural and other rural activities, diffuse pollution from historical mines, physical modification of water bodies, point source pollution from water industry sewage works, acidification, water abstraction and artificial flow regulation.

Figure 5.16: Map of Welsh rivers (where the red dot indicates the location of the gauging station).

The CA of the PC loading from the six Welsh rivers (from 1976-2009, where 1997 was removed due to lack of data) fit into six flow regime groups, where (Figure 5.17):

- Regime 1: the largest cluster, which occurred 48.5% of the time (80 years in total), had a single high magnitude peak in median flow between November and January.
- Regime 2: occurred 21.2% of the time (35 years in total) and had a single early high magnitude peak in median flow between October and November, followed by a low flow winter.
- Regime 3: occurred 12.1% of the time (20 years in total) had a single high magnitude peak in median flow in January, after a low flow winter.
- Regime 4: occurred 9.1% of the time (15 years in total) and had three peaks, the first in November, followed by a lower magnitude peak in January, followed to the highest magnitude peak in March. Regime 4 had the lowest median monthly flows in July and August.
- Regime 5: occurred 6.1% of the time (10 years in total) and had two main peaks, the first in December followed by a lower magnitude peak in April. Regime 5 had the lowest median monthly flows in October and between January and March, and the highest median monthly flows in April and June.
- Regime 6: occurred 3.0% of the time (5 years in total) and had an early high magnitude peak in median flow in January, followed by the highest median monthly flows in August. Regime 6 also had the lowest median monthly flows in June.

There were five true regimes in the Welsh analysis, regime 1, 2, 3, 4 and 5. Regime 6 only comprised of the year 2008. The median monthly flows for this analysis indicate that the hydrological year appears to start in August for regimes 5 and 6, however, these are the less dominant regime types, occurring approximately less than one in every ten years when combined.

The high flow timing typically occurred in December for regime 1, November for regime 2 and 6, January for regime 3 and 4 and August for regime 5. The 1-day minimum was lowest for regime 4 (0.79 $m^3 s^{-1}$) and the greatest 1-day maximum flow was also from regime 4 (216.3 $m^3 s^{-1}$). The highest large flood peak also occurred during regime 2 (373.6 m^3 s^{-1}). The typical timings of large flood events varied from December in regime 1 and 5, January in regime 2, 3 and 6, and March in regime 4 (Appendix F1).

The timing of the sustained rise in autumn flows in the Welsh region varied between regimes. The most dominant regimes 1 and 2 occurred in October, regime 3 and 5 started to rise early in July, and regime 4 in September. The spring flows were similar for all regimes. The spring flows varied dramatically in March (although the most common regime type, 1, was in the middle of the two flow extremes found this month) and April, however all regimes had similar flows in May.

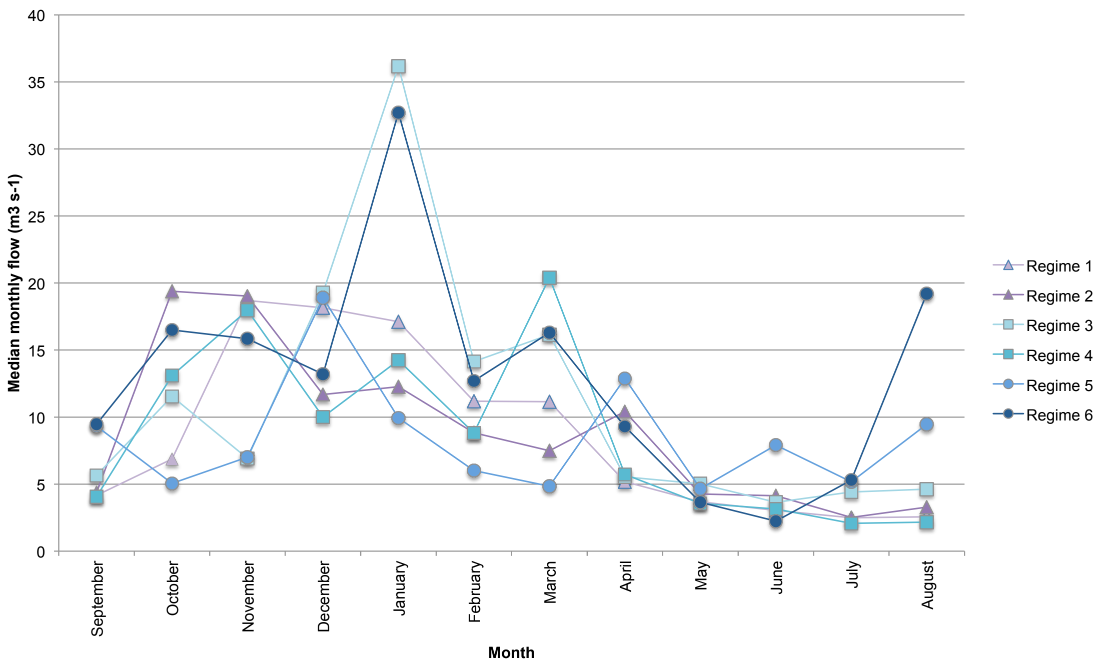

Figure 5.17. Median monthly flows of the six flow regimes from the six Welsh rivers, 1970-2009 (excluding 1975, 1976, 1980, 2002, 2003 and 2006).

5.4.1. The River Conwy

The River Conwy is in north Wales, and is approximately 43 km long. It rises on the Migneint moor, following a generally northern direction before reaching the sea at Conwy Bay.

The River Conwy flow data come from the Cwm Llanerch gauging station (station number 66011 according to the UK Hydrometric Register), with a catchment area of 344.5 km^2. It is a very wet upland catchment (mainly mountainous) formed of mostly impermeable Palaeozoic formation and volcanics. The catchment comprises predominately of 65% grassland, with bare rock and heath (upland hill farming) and 15% forested (predominately in the lower catchment). The mean annual rainfall in the area is 2183 mm, with a mean runoff of 1720 mm.

The CA of the PC loading from the River Conwy (from 1969-2009, where 2007 was removed as an outlier) fit into five flow regime groups (Figure 5.18), where:

- Regime 1: the largest cluster occurred 35% of the time (14 years in total) and had a single, high magnitude peak in median flow in December, and the highest median monthly flows of the different regimes in May.
- Regime 2: occurred 30% of the time (12 years in total) and had a high magnitude peak in median average flow in January/February. This regime also had a high flow autumn and winter.
- Regime 3: occurred 15% of the time (6 years in total) and had two peaks, the first in November followed by a lower magnitude peak in March. This regime had a low flow winter.
- Regime 4: occurred 12.5% of the time (5 years in total) and had two peaks, the first in October followed by a lower magnitude peak in January, which was the result of low flows in November and December. This regime had the highest median monthly flows of the different regimes between July-October.
- Regime 5: occurred 7.5% of the time (3 years in total) and had two low magnitude peaks, the first in November followed by a similar magnitude peak in February. Between September and April, regime 5 typically had lowest median flows, therefore it was characterised by a low flow autumn and winter.

The high flow timing varied for each regime; regime 1 in February, regime 2 in January, regime 3 in March, regime 4 in December and regime 5 in November. Regime 1 had the greatest high peak magnitude with an average peak of 48.32 $m^3 s^{-1}$. The 1-day minimum was lowest for regime 5 (0.649 $m^3 s^{-1}$), and the greatest 1-day maximum flow was from regime 3 (243 $m^3 s^{-1}$). Large flood events occurred in all regimes, and were in March for regimes 1 and 4, February for regimes 2 and 5 and January for regime 3. The largest flood peak was found in regime 3 (375 $m^3 s^{-1}$). The largest variation between 1-day minimum and maximum flow was also in regime 3 (Appendix F2). The timing of the sustained rise in autumn flows on the Conwy began in August for regime 1 (however it flows did decline in October) and 3, September for regime 2 and 5 and July for regime 4. The spring flows did varied; interestingly regime 1 had the highest May flows, which may allow juvenile salmon better access to riparian feeding habitats.

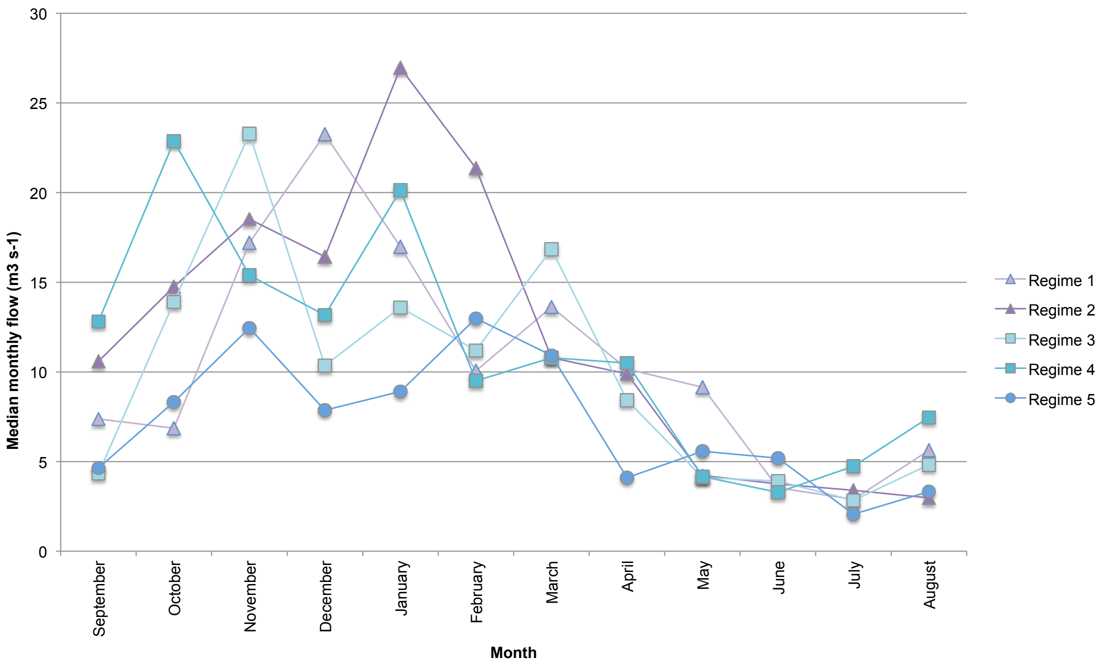

Figure 5.18. Median monthly flows for the five flow regimes on the River Conwy, 1969-2009 (2007 was removed).

The occurrence of regimes over time shows regime 5 was only found in the early 1970s and 1990s. Regime 1 was less common during the 1990s, but regained dominance in the 2000s. Regime 3 was not found in the 1970s (Appendix F3).

5.4.2. The River Teifi

The River Teifi is approximately 120.7 km long (making it the largest river solely in Wales). Its source is in lake Llyn Teifi, in northern Ceredigion. The river flows through Pontrhdfendigaid before reaching the main river valley floor. Here it passes through the Tregaron Bog and finally flows into the sea below the town of Cardigan.

The River Teifi flow data come from the Glan Teifi gauging station (station number 62001 according to the UK Hydrometric Register), with a catchment area of 893.6 km^2. The geology is mainly impermeable Ordovician and Silurian deposits, with peaty soils in the hills. The catchment comprises of approximately 79% grassland, 12% woodland, 3% arable land, and 2% mountain/heath/ bogland. The mean annual rainfall in the area is 1377 mm, with a mean runoff of 1010 mm. The Tregaron Bog (10 sq.km.) has partial effect on flows, but considered a 'natural' regime.

The CA of the PC loading from the River Teifi (from 1960-2009, where 1970 was removed due to lack of flow data) fit into five flow regime groups (Figure 5.19), where:

- Regime 1: the largest cluster occurred 47.0% of the time (23 years in total) and had a single, high magnitude peak in median average flow in January, followed by a typical spring recession.
- Regime 2: occurred 20.4% of the time (10 years in total) and had two peaks, the first in October followed by a second, lower magnitude peak in January, as a result of low flows in December.
- Regime 3: occurred 16.3% of the time (8 years in total) and had a single, high magnitude peak in December, and the highest median monthly flows in April.
- Regime 4: occurred 10.2% of the time (5 years in total) and had two peaks, the first between October- December followed by a second, similar magnitude peak in March. This regime had high flows in autumn and early spring.
- Regime 5: occurred 6.1% of the time (3 years in total) and had a high magnitude peak in November, followed by the lowest median monthly flows in December and January. Regime 5 also had the lowest median monthly flows in March and April and the highest median monthly flows in July. This regime had a low flow winter and early spring.

Regime 1 had the highest peak flow of the five regimes. The timing of the high flow events occurred in January for regimes 1 and 2, and February for regime 3, December for regime 4 and June in regime 5. The 1-day minimum was lowest for regime 1 (2.492 $m^3 s^{-1}$). The greatest 1 day maximum flow was from regime 3 (199.4 $m^3 s^{-1}$). The highest flood peak was during regime 2 (373.6 $m^3 s^{-1}$). Large flood events occurred during all regimes, in January for regime 1, September for regime 2, December for regime 3, March for regime 4 and November for regime 5. The largest variation between 1-day minimum and maximum flow was in regime 3 (Appendix F4). The timing of the sustained rise in autumn flows on the Teifi was November for regime and October for remaining regimes, apart from regime 5 which was characterised by a very low flow winter apart from significant flows in November. The spring flows did vary for all regimes, particularly in regime 4 in March, which was considerably higher than the other regimes, with flow averaging 47.1 $m^3 s^{-1}$.

The occurrence of regimes over time indicates regime 1 was most dominant during the 1960s and 1970s, becoming less dominant particularly in the 2000s. Regime 4 was not found in the 1990s or 2000s, whereas regime 2 became more common from the late 1980s (Appendix F5).

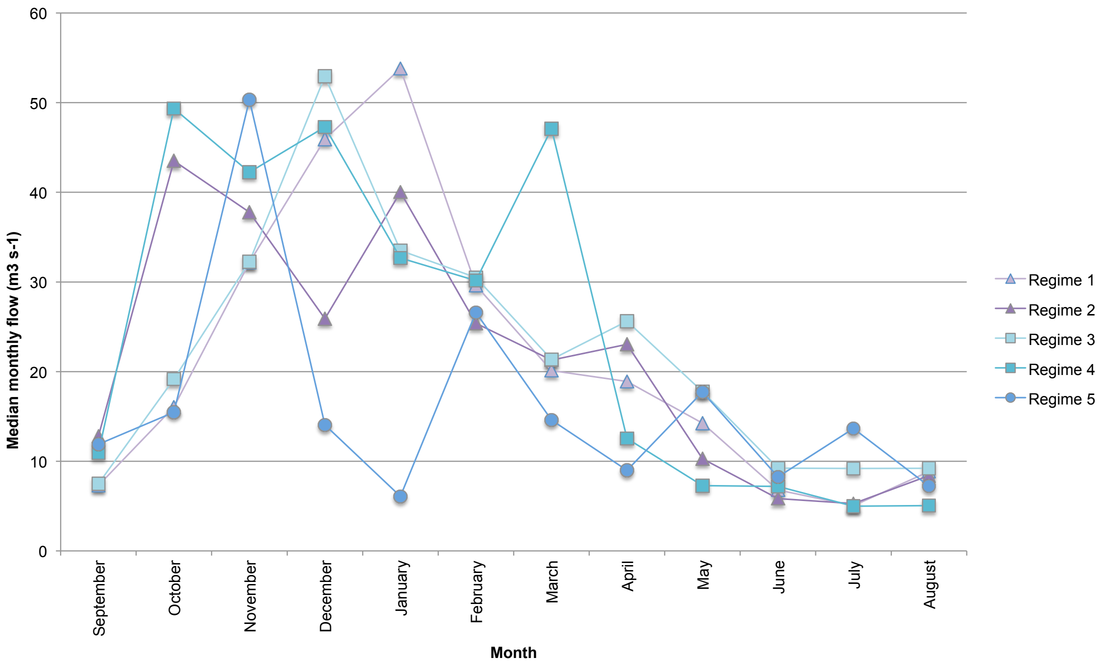

Figure 5.19. Median monthly flows for the five flow regimes on the River Teifi, 1960-2009 (with 1970 removed).

5.4.3. The River Dyfi

The River Dyfi (also known as Dovey) rises in the small lake, Creiglyn Dyfi, which is about 580 m above sea level. It flows south into Cardigan Bay at Aberdyfi. The only large town on its route is Machynlleth.

The River Dyfi flow data come from the Dyfi Bridge gauging station (station number 64001 according to the UK Hydrometric Register), with a catchment area of 471.3 km^2. The geology is impermeable with Silurian formations, minor Boulder Clay and alluvium deposits. The catchment is predominately rural, with land-use within the catchment comprising of approximately 62% grassland, 29% woodland, 6% mountain/heath/bogland and <1% arable land. The mean annual rainfall in the area is 1889mm, with a mean runoff of 1544mm.

The CA of the PC loading from the River Dyfi (from 1963-2009, where 1967, 1971, 1972, 1973, 1974 and 1975 were removed due to lack of flow data and 1985 was removed as an outlier) fit into five flow regime groups (Figure 5.20), where:

- Regime 1: the largest cluster occurred 27.5% of the time (11 years in total) and had two low magnitude peaks: the first in November, followed by a similar magnitude peak in February. Regime 1 had the lowest median flows in December, and also the lowest median flows between May and September, therefore characterised by a low flow early winter.
- Regime 2: occurred 25.0% of the time (10 years in total) and had three peaks, the first in October, followed by a higher magnitude peak in January, and the lowest magnitude peak in March. Regime 2 had the highest median flow in September.
- Regime 3: occurred 22.5% of the time (9 years in total) and had a single, high magnitude peak in median average flow in December, and the lowest median flows in February and March.
- Regime 4: occurred 17.5% of the time (7 years in total) and had two peaks, the first higher magnitude peak in November, followed by a lower magnitude peak in March. Regime 4 had the highest median flows in August, and the lowest median flow in October.

- Regime 5: occurred 7.5% of the time (3 years in total) and had two peaks, the first higher magnitude peak in December, followed by a lower magnitude peak in February. Regime 4 had the lowest median flows in November and January.

The high flow timing varied for the different regimes, for regimes 1 and 5 occurring in January, regime 2 in December, regime 3 in November and regime 4 in February. Regime 2 had the greatest high peak magnitude with an average peak of 54.34 $m^3 s^{-1}$. The 1-day minimum was lowest for regime 1 (0.402 $m^3 s^{-1}$), and the greatest 1-day maximum flow was in regime 5 (224.9 $m^3 s^{-1}$). The largest variation between 1-day minimum and maximum flow was in regime 5. The highest large flood peak was also during regime 2 (317.7 $m^3 s^{-1}$). The typical timings of large flood events varied for the regimes, where for regimes 1 and 3 they typically occurred in November, regimes 2 and regime 4 they occurred in March and for regime 5 they occurred in June (Appendix F6). The timing of the sustained rise in autumn flows on the Dyfi was October for regime 1, September for regime 2 and August for regimes 3, 4 and 5. The spring flows did vary between regimes, with two most common regimes, 1 and 2, having some of the lowest spring flows in April and May.

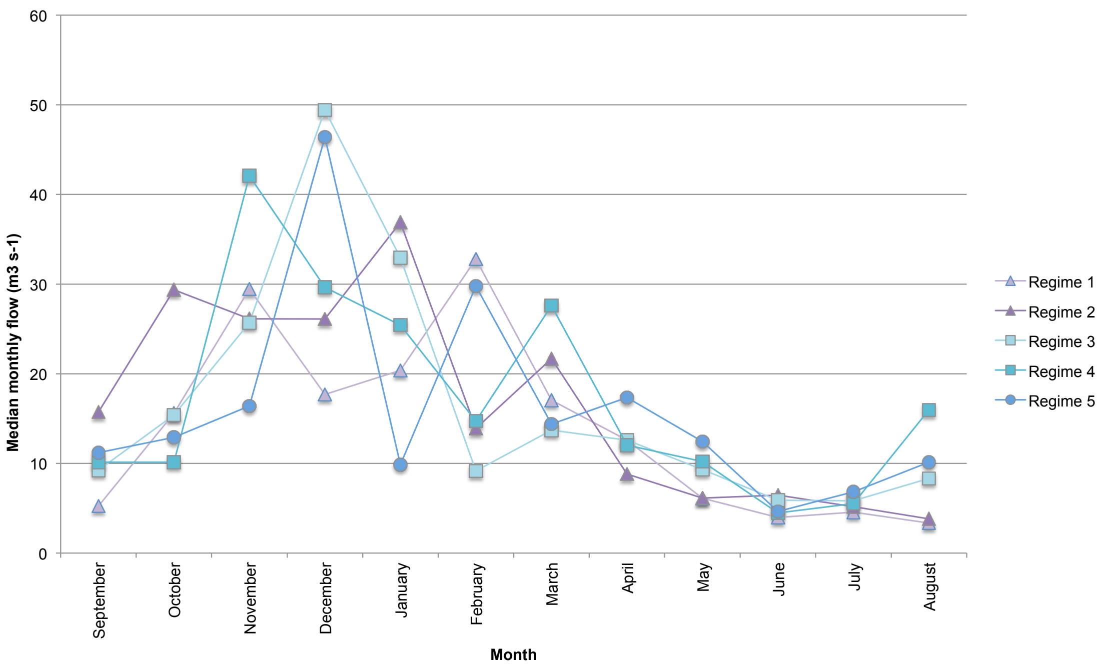

Figure 5.20 Median monthly flows for the five flow regimes on the River Dyfi, 1963-2009 (where 1967, 1971, 1972, 1973, 1974, 1975 and 1985 were removed).

Due to the lack of flow data for the early 1970s, it is difficult to interpret changes in the regime occurrence. However, regime 1 appears to become more dominant in the 1990s and 2000s compared with the 1980s. Regime 3 becomes more dominant in the 2000s, as regime 2 becomes less dominant. Regime 4 is most common during the late 1970s and 1980s. Regime 5 only occurs in the 1960s, 1990s and 2000s (Appendix F7).

5.4.4. The River Western Cleddau

The River Cleddau consists of the Eastern and Western Cleddau rivers in Pembrokeshire, West Wales. They unite to form the Daugleddau estuary, which forms Milford Haven harbour. The Western Cleddau has two branches: the eastern rises at Llygad Cleddau and the western branch rises at Penysgwarne. The river becomes tidal at Haverfordwest. Its length is approximately 40km, of which 9km is tidal.

The River Western Cleddau flow data come from Prendergast Mill gauging station (station number 61001 according to the UK Hydrometric Register), with a catchment area of 197.6 km^2. It is a mostly lowland catchment, with geology of impermeable Ordovician formations with igneous intrusions. The land-use within the catchment comprises of approximately 78% grassland, 13% arable land, 5% woodland and >1% mountain/heath/bogland. The mean annual rainfall in the area is 1305 mm, with a mean runoff of 869 mm. The flow regime is considered generally natural, with some effects of abstractions and effluent returns.

The CA of the PC loading from the River Western Cleddau (from 1966-2009, where 1985 was removed as an outlier) fit into five flow regime groups, where (Figure 5.21):

- Regime 1: the largest cluster occurred 42.9% of the time (18 years in total) and had a single, high magnitude peak in median flow in January, with February flows initiating the spring/summer flow recession. Regime 1 had the lowest median monthly flows between May and August of all the regime types.

- Regime 2: occurred 28.6% of the time (12 years in total) and had a single, early high magnitude peak in median flow in November/December and was characterised by a wet late autumn/early winter period.
- Regime 3: occurred 11.9% of the time (5 years in total) and had two peaks, the first in November followed by a second, lower magnitude peak in February.
- Regime 4: occurred 9.5% of the time (4 years in total) and had a single, high magnitude peak in December. Regime 4 also had the highest median monthly flows between May-July, indicating a wet late spring/early summer. This regime also had the lowest February median flows.
- Regime 5: occurred 7.1% of the time (3 years in total) and had a single, high magnitude peak in March, following a wet autumn and dry early winter (January and February). Regime 5 also had the highest median monthly flows in September and October.

The high flow timing for regimes 1 and 2 was both typically in January, regimes 3 and 4 were typically in March and regime 5 in October. The largest high flow peak was in regime 2, with an average peak of 12.85 $m^3 s^{-1}$. The 1-day minimum was lowest for regime 5 (0.54 $m^3 s^{-1}$). The greatest 1-day maximum flow was from regime 5 (45.04 $m^3 s^{-1}$). The highest large flood peak was during regime 2 (65.58 $m^3 s^{-1}$). The timing of the large flood was December for regimes 1 and 4, October for regime 2, November for regime 3 and March for regime 5. The largest variation between 1-day minimum and maximum flow was in regime 5 (Appendix F8). The timing of the sustained rise in autumn flows on the Cleddau was October for regime 1, 2, 3 and 4 and September for regime 5. The spring flows in regime 5 in March were dramatically higher than the other regimes, with average flows above 12.5 $m^3 s^{-1}$. However, this was the least common regime, occurring in only 7.1% of years. These high flows could be damaging for juvenile salmon populations, as fish could be washed downstream to unfavourable habitats.

The occurrence of regimes over time shows regime 1 and 2 remain fairly constant throughout the time period. Regime 3 and 4 appear to become slightly more common in the 1990s and 2000s. Regime 5 only occurred in the 1960s and 1980s (Appendix F9).

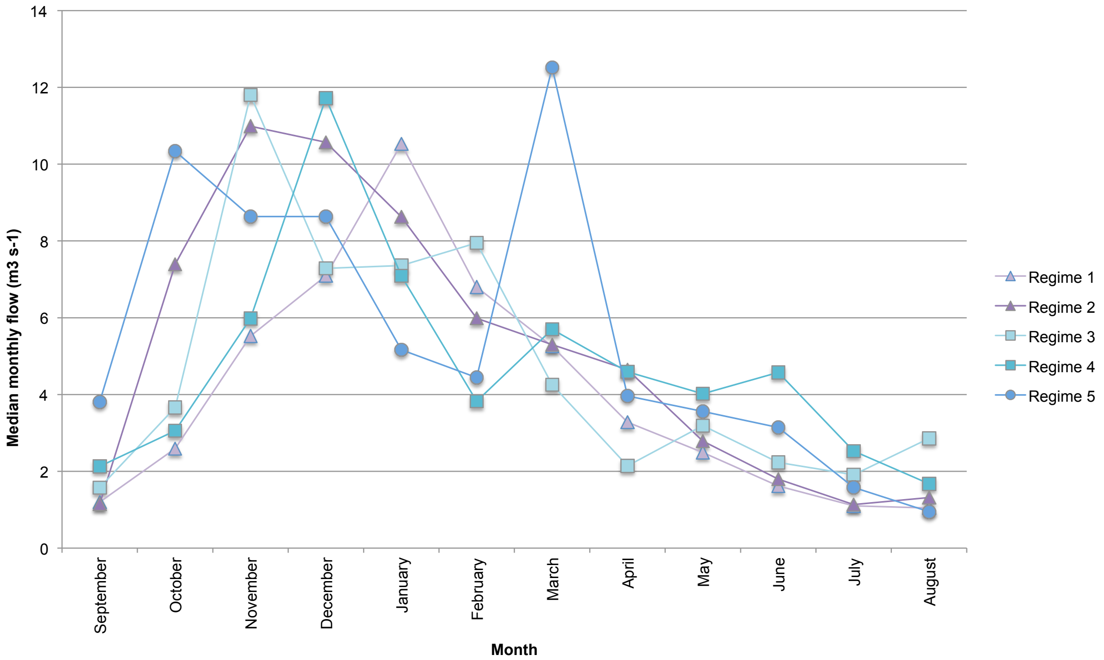

Figure 5.21. Median monthly flows for the five flow regimes on the River Western Cleddau, 1966-2009 (where 1985 was removed).

5.4.5. The River Dysynni

The River Dysynni is in mid-Wales, where it flows from the western end of Tal-y-llyn Lake (the southernmost ribbon lake in Britain) and enters Cardigan Bay through the Broad Water lagoon to the north of Tywyn.

The River Dysynni flow data come from the Pont-y-Garth gauging station (station number 64002 according to the UK Hydrometric Register), with a catchment area of 75.1 km^2. The catchment consists of impermeable Ordovician sediments with volcanic rocks. The land-use within the catchment comprises of approximately 65% grassland, 23% woodland, 8% mountain/heath /bogland and <1% arable land. The mean annual rainfall in the area is 2161 mm, with a mean runoff of 1899 mm. It is considered to have a natural flow regime, but is difficult to gauge at high flows due to its flashy response.

The CA of the PC loading from the River Dysynni (from 1966-2009, where 1988 and 1997 were removed due to lack of flow data and 1967, 1988 and 2007 were removed as outliers) fit into four flow regime groups (Figure 5.22), where:

- Regime 1: the largest cluster occurred 62.5% of the time (25 years in total) and had a single, high magnitude peak in median flow in December and then followed a typical spring flow recession. Regime 1 had the lowest median flows in April.
- Regime 2: occurred 17.5% of the time (7 years in total) and had two peaks, the first in November followed by a second, lower magnitude peak in February. This was the result of low flows in December and January. This regime also has the lowest median flows between July- September.
- Regime 3: occurred 10.0% of the time (4 years in total) and had a relatively low flow autumn, followed by a high magnitude peak in median flow in December and two smaller magnitude peaks in April and June. The winter period was comparatively dry, with high flow peaks retuning in April and continuing to result in a wet summer.
- Regime 4: also occurred 10.0% of the time (4 years in total) and had a very flashy regime, with the highest median magnitude peaks compared against the other regimes in October, January, March and August. Overall, it was the wettest regime type.

The high flow timing varied for each regime, regime 1 occurred typically in January, regime 2 in March, regime 3 in May and regime 4 in February. The largest high flow peak was in regime 4, with an average peak of 12.27 $m^3 s^{-1}$. The 1-day minimum was lowest for regime 1 (0.402 $m^3 s^{-1}$), and the greatest 1-day maximum flow was from regime 4 (48.88 $m^3 s^{-1}$). The greatest large flood peak occurred in regime 1 (82.27 $m^3 s^{-1}$) in November. The large flood also occurred in November for regime 2, in January for regime 3 and March for regime 4. The largest variation between 1-day minimum and maximum flow was in regime 4 (Appendix F.10). The timing of the sustained rise in autumn flows on the Dysynni started early for regimes 1 and 4 with increasing flow from August, regime 2 occurred from September and regime 3 was difficult to determine after a wet summer and apparently low flow autumn. The spring flows for the two dominant regimes, which accounted for approximately 80% of the years, were similar throughout the spring, with higher flows particularly found in regime 4 in March.

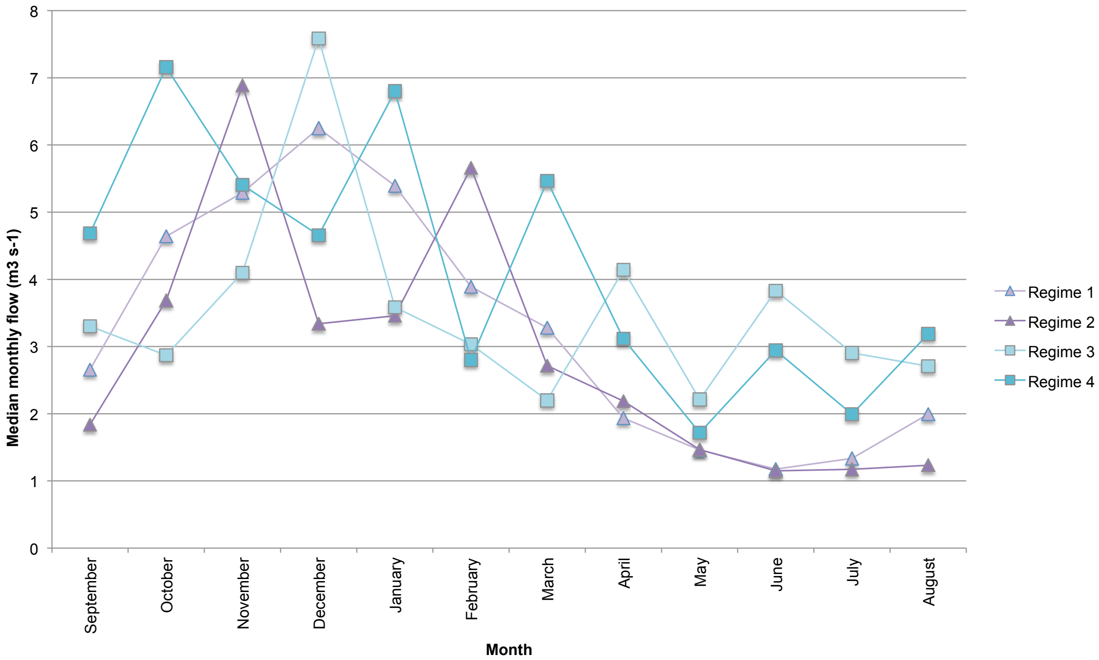

Figure 5.22. Median monthly flows for the four flow regimes on the River Dysynni, 1966-2009 (excluding 1967, 1988, 1997 and 2007).

On the River Dysynni, regime 1 was relatively constant through time, becoming slightly more dominant in the early 1970s. The most variable period was in the 1980s and 1990s, when all four regimes occurred. Regime 4 was only found in the 1980s and 1990s. By the 2000s, only regime 1 and 2 were recorded (Appendix F.11).

5.4.6. Welsh river summary

Overall, the most common regime over the 5 rivers in Wales was a regime with a single high magnitude peak in December; this was the most commonly occurring regime on the Conwy and Dysynni, the third most commonly occurring regime on the Teifi and Dyfi and the fourth most common regime on the Western Cleddau. This regime type was therefore found on all of the five Welsh rivers. The joint second most common regime type was a regime with January/February peak and a regime with two peaks: the first in November and the second in February. The January/February high magnitude peak was the most commonly occurring regime type on the Western Cleddau and Teifi, and the second most commonly occurring regime type on the Conwy. The November and February two peak regime was the most commonly occurring regime type on the Dyfi, the second most common on the Dysynni and the third most commonly occurring regime type on the Western Cleddau. Two peaks were found in 37.5% of the Welsh regimes. This two-peak pattern typically occurred in the less common regimes, predominately 4 or 5, apart from the November/February two-peak regime discussed above. Three of the rivers had regime types with three peaks. On the Dyfi this occurred in regime type 2, which occurred in 10 of the years analysed. This had an initial peak in October, followed by a higher magnitude peak in January and further lower magnitude peak in March.

Typically the most common regime type, regime 1, had a high peak in magnitude in early winter, which declined into a spring flow recession. This occurred on all rivers, apart from on the River Dyfi, where the regime was characterised by two low magnitude peaks, the first in November, followed by a similar magnitude peak in February. On the Dyfi the most common regime type had a low flow early winter. Low flow (dry) winters also occurred on the Conwy in regimes 3 and 5, and the Teifi in regime 5. Regime 4 on the Western Cleddau and regime 3 on the Dysynni were both characterised by wet (high flow) summers.

The largest high flow peak was predominately within the two most frequently occurring regime types in Wales, within regime 1 on the Conwy and Teifi, regime 2 on the Western Cleddau and Dyfi. Only on the Dysynni was the largest high flow peak found in a less commonly occurring regime, regime 4. For the most commonly occurring regime, regime 1, the timing of the high flows occurred in January for 80% of the rivers; all the rivers apart from the Conwy, where the high flow timing for regime 1 was in February. The 1-day minimum occurred within regime 1 on 60% of the rivers, the Teifi, Dyfi and Dysynni. On the Conwy and Western Cleddau the lowest 1-day minimum occurred in regime 5. The highest 1-day maximum flow was not found within regime 1 or 2 on any of the rivers. On the Conwy and Teifi the 1-day maximum occurred in regime 3, on the Dyfi and Western Cleddau in regime 5 and for the Dysynni in regime 4.

The large flood events occurred within regime 2 for 60% of the rivers (Teifi, Dyfi and Western Cleddau). The largest flood event did not occur in regime 5 for any of the rivers. On the Conwy it occurred in regime 3 and for the Dysynni in regime 1. Although the timing of the flood events varied between rivers and regimes, the most common months for large flood events were March (which occurred 29.2% of the time) and November (which occurred 25% of the time).

Of the regional northern regimes types 33.3% matched exactly with the 7 national regime types. However, this did account for 60.6% of the flow years. At the local level, approximately 12.5% (3 out of 24 regimes) of the individual river regimes matched the 5 Welsh regional regimes. This accounts for 32.1% of the river flow years. The autumn rise in flows predominantly started in October in the Welsh region. However, all the rivers apart from the Western Cleddau, had regimes with early August rises in flow. There was variability in the magnitude of spring median flows in the Welsh region, however this was predominately in the least common regime types, as found in the northern region. However, these differences in spring flow could impact juvenile salmon populations during this time.

5.5 REGIONAL SUMMARY

A comparison between the national (chapter 4) and regional regime classifications suggests flow variability is lost, to varying degrees depending on the location, when moving from regional to national scales. In the southwest, none of the regional regimes characteristics directly overlapped with any national regime. However, in the northern region, 74.5% of the flow data overlapped and, in Welsh rivers, it was 60.6%. This is likely to suggest the southwest region regimes are more distinct in comparison to the other two regions. Analyses between regional and local regime classifications indicated approximately 47% of local, individual river regimes were represented regionally for the southwest rivers, 51% for the northern rivers and 32.1% for the Welsh rivers. Therefore by classifying individual rivers under geographical boundaries, substantial proportions of flow variability are again lost. Consequently, despite potentially being influenced by the same weather conditions, the individual catchment characteristics and human modifications within each catchment have a dramatic impact on the flow regime.

The regional level analysis established 6 regime types for each region. However, after removing single year regimes, the southwest had 5 true regimes types, the north had 3 true regime types and Wales had 5 true regime types. This suggests there is a greater degree of inter-annual flow variability in the southwest and Wales, than in the northern rivers studied. The lack of regimes in northern region could be a result of the reduced river flow dataset, with many northern river gauging station records not starting until the 1970s. However, in the regional analysis Wales actually had the least number of flow years analysed, 165 years, compared against 245 and 209 respectively for the southwest and north regions. Another possible attributing fact for the reduced regional flow variability in the north could be because this analysis included the River Tyne, the most regulated river investigated in this study, which may have reduced the variability during the clustering process, leading to variable years on other rivers within the timescale being classified as outliers.

Flow variability locally was represented by 5 regimes for individual rivers in Wales (apart from the River Dysynni which was represented in 4 regimes), 4 regimes in the southwest and 3 regimes in the northern rivers. This could be because the prevailing weather events impacting the UK tend to come from the southwest direction.

In comparing the regional regime types against each other, the patterns include:

- All regions had a regime with a single high magnitude peak in January within the most dominant regions,
- All regions had a two-part magnitude peaks with one in the winter and lower magnitude peak in spring. Although, in the southwest and north regions, this included the second most dominant region types which occurred in December and March, whereas in Wales it was one of the least dominant regimes types (regime 5) and occurred in December and April.

- The southwest and north region both had low flow autumn/winter regimes with no clear peaks. This occurred in 18 years in the southwest and 7 years in the north. This was not found on in the Welsh region.
- The southwest region did not have any clear 3-peak regimes, whereas both the Welsh (regime 4) and north (regime 3) regions had a regime with a high magnitude peak in November, followed by lower magnitude peaks in January and March.

There was no consistency with patterns between the different regions, especially with regard to patterns between the southwest and north. This is therefore likely to be driven by different weather systems; for example, during a low flow ‘drought’ year, local weather events in Wales could have resulted in some lower magnitude peaks, which prevented a flat-lined flow regime.

Overall, natural flow variability is lost when generalising at the national and local scale. This suggests individual river flow analyses should be conducted to get a true measure of between and within year flow variability. The more variable - i.e. the more regimes there are at the local level - the more unrepresentative the national analysis appears to become.

The River Frome behaved differently to the other rivers in the southwest approximately 20% of the time (on average), compared with behaving differently to the other rivers approximately 42% of the time in the national analysis. This suggests the regional analysis better represents individual river regimes than the national analysis. It also demonstrates that, at either scale, chalk streams have a fundamentally different flow regime and therefore should be managed separately.

Across the regions, the 1-day minimum flow occurred in the most commonly occurring regime (regime 1) in 50% of northern rivers, 33.3% of southwest rivers and 60% of Welsh rivers. Further to this, the highest 1-day maximum flow was not found within regime 1 for any of the rivers in any of the regions. This potentially has management implications, as flow variability between years does not necessarily mean safeguarding more water for nature every year.

The early autumn rise in flows only tended to occur in rare variants of regimes across the regions, with the most early autumn rises found in the Welsh region (and in particular the Conwy, which is the most northerly of the Welsh rivers). The lack of sustained early autumn rises could be a problem for Atlantic salmon populations, if they are delayed from entering the rivers due to low flows. Solomon & Sambrook (2004) found that at periods of low freshwater flows (and corresponding high water temperatures and sometimes low dissolved oxygen) Atlantic salmon arriving from sea, which were not able to begin migrating upstream, remained in the estuary or returned to sea. The study found that once the freshwater flows returned, some delayed salmon entered the rivers, but others did not. It is hypothesised that adult salmon have a 'window of opportunity' to readapt to freshwater conditions, and delays due to low flows could impact their ability to do so (Solomon & Sambrook, 2004). Estuaries are also a dangerous place for salmon to wait, with a potential legacy of pollution resulting in poor water quality at different stages of the tide, and a variety of predators looking to exploit migrating salmon.

The variety of spring flows could also be important for Atlantic salmon in their juvenile life stages, where low spring flows will restrict access to feeding habitats, but high spring flows could wash the juveniles downstream to unfavourable conditions. Determining what flows in the spring fall under each category is difficult without understanding the morphology of the river. However, high magnitude flows, like those seen in April on the Coquet (regime 3) and in March on the Western Cleddau (regime 5) and Teifi (regime 4), could reduce salmon juvenile survival.

Furthermore, by classifying each year for each river as a regime type, it is therefore possible to plot the occurrence of these regime types through time. In the southwest all rivers show a decline in the dominance of regime 1 over time to differing degrees and an increasing occurrence of regime 3 and/or 4 (Figure 4.23). The clearest decline in regime 1 over time was on the River Frome, where regime 2 increased over time. On the rivers Tamar and Dart regime 4 was only present in the latter half of the time record. All rivers appear to show increased variability in regimes later in the time period. For northern rivers, only the River Lune indicated a decline in the dominance of regime 1 over time (Figure 4.24). The rivers Ribble, Kent and Tweed demonstrated a slight dip in the dominance of regime 1 to approximately 40% at the beginning of the time record in the early 1960s, but this recovered and stabilised to over 50% dominance by the end of the analysis period. On River Tyne, regime 1 had over 60% dominance for most of the analysis period and there was very little indication of occurrence change during this time. There were no clear differences in regime occurrence between the northeast and northwest rivers. The Welsh analysis showed that over time the Teifi, and to a lesser degree the Conwy, had a decline in the dominance of regime 1 (Figure 4.25). However, on the Dyfi regime 1 became more dominant over time, along with regimes 3 and 5, resulting in the decline of regimes 2 and 4. On the Dysynni, regime 1 stayed relatively constant, however regime 2 became more dominant, resulting in the decline of regime 5. The Western Cleddau regime occurrence remained relatively stable through time, with the exception of the absences of regime 3 in the early 1970s.

Direct comparisons between the different regime occurrences through time are not possible because the regimes represent different flow characteristics for each river. However, the increasing frequency of previously ‘less common’ flow regimes on multiple rivers across the three regions over the timeframe suggests other external factors could be impacting the flow regimes, such as climate change and the presence of more extreme flow events. Local catchment characteristics could be buffering these external factors to differing degrees.

Overall, this chapter highlights the large degree of flow variability within and between years, and between regions and individual rivers, and has started to allude to some potential implications for fish. The next chapter, 6, will now investigate the potential correlations between IHA described flow parameters and Atlantic salmon, to see if the datasets are sufficient to highlight any parameters that could be important in salmon management.