River flow and abstraction

Executive summary

River flow and water abstraction play a critical role in influencing water quality and aquatic biodiversity in the UK. River flow is recognized as the "master variable," essential for sustaining diverse habitats that support various aquatic species. Human water abstraction significantly alters natural flow regimes, leading to reduced water quality and aquatic biodiversity. Approximately 63% of the world's rivers are impacted by abstraction, in England 10.4 billion cubic meters of water is taken non-tidal surface waters and groundwater sources every year for anthropogenic activities. Climate change further complicates this issue, as altered precipitation patterns are expected to increase the frequency of low and high flow events in the UK, conditions our native freshwater aquatic species are not adapted to. The need for sustainable water management practices to balance human water demands and ecological requirements of riverine ecosystem to ensure the resilience and health of aquatic environments amidst ongoing environmental change is critical, and not something the UK is currently prepared for.

Introduction

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. 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. 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 high and low flows and the creation of artificial flow regimes can have catastrophic impacts for the ecological integrity of river systems (Fig. 1).

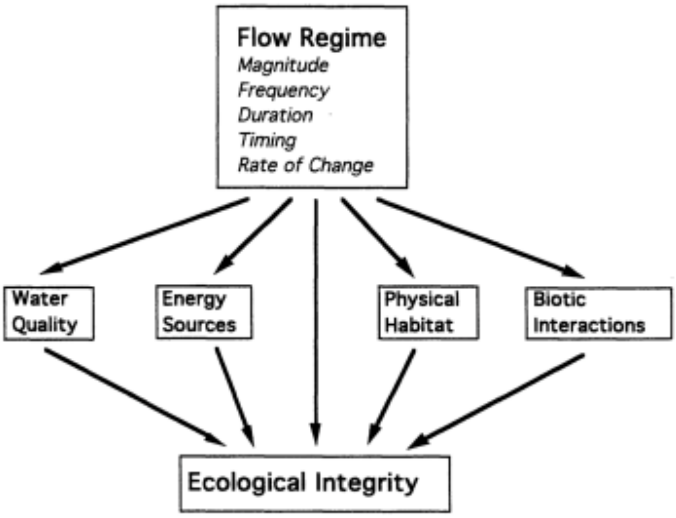

Figure 1: *Five main components of flow regime. Modification of these has cascading effects on ecological integrity of rivers (Poff et al., 1997).*

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. 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), and impoundment (construction of dams for various purposes), have greatly modified the natural flow regimes of many rivers (Poff et al., 1997; Ward & Stanford, 1995). As a result historic, natural cycles of flooding and drought necessary to regulate ecological variables such as population size and species diversity are being severely altered (Lytle & Poff, 2004). Over-abstraction also amplifies the effects of pollutants, as the less water there is, the more concentrated pollution will be. It is estimated that approximately 63% of the world’s rivers have been diverted (Naiman *et al*., 2002). Only 37 per cent of rivers longer than 1,000 kilometres remain free-flowing over their entire length and 23 per cent flow uninterrupted to the ocean (Grill et al., 2019). In the UK, only an estimated 1% of all rivers are free of artificial barriers which impact flow, with a density of 0.75 barriers per 1km of river (AMBER Consortium, 2020).

In England and Wales, the latest available statistics for water abstraction indicate that in 2018 an estimated 10.4 billion cubic metres was abstracted from non-tidal surface and ground waters (DEFRA, 2018). 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.

Climate change is also impacting river flow. Many parts of the world are seeing the amount of rainfall they experience drastically change. By 2050 average annual runoff is predicted to increase significantly in over 47% of the worlds land surface and decrease in over 36%; only 17% therefore sees no significant change (Arnell & Gosling, 2013). The UK has seen an increase in average annual rainfall, with about 7% more rain over the last 30 years than the previous 30 (Met Office, 2023). However, despite this increase in rainfall climate modelling predicts that river flow will most likely be lower in the future than it is now across the country, with streamflow droughts becoming more commonplace and more severe in the future (Parry et al., 2024). This is because climate change is also affecting when rain falls across the UK. In the summer months rain is predicted to fall less often and more intensely which could dramatically alter the streamflow conditions of rivers which we have grown accustomed to and policy is based on.

Changing river flow conditions will have wide ranging consequences for wildlife and wild fish populations, water supply and flood risk. In simple terms less water in rivers will result in the following stressors for wild fish populations:

- Fish are less able to migrate up and down rivers to complete their life cycles.
- Pollutants in the water become more concentrated because of the lack of dilution.
- Increased sedimentation clogs up rivers because they do not have the energy to remove them.
- Reduced shelter and food availability.
- Water temperatures increase and oxygen levels decrease.

River Regimes

To understand the flow conditions of a river system one must first define the rivers 'regime'. A river regime refers to the seasonal variations in the flow or discharge of a river over the course of a year. This pattern is influenced by several factors, including climate, seasonal precipitation, snowmelt, vegetation, and human activities. The regime helps in understanding how the flow rate of a river changes in response to natural events and climatic conditions.

Types of river Regimes:

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There are many different types of river regime found across the globe. Many different natural and human factors can influence a river, and in the simplest terms, a regime can be described as one of the following:

- **Simple regimes**: where there is only one dominant factor affecting river flow.
- **Mixed or double regimes**: where there are two dominant factors.
- **Complex regimes**: where there are multiple dominant factors.

Due to extensive human modifications of river systems across the globe, most rivers today cannot be truly defined as simple regimes anymore. The UK Centre for Ecology and Hydrology estimates that only 15% of the UK's rivers flow regimes could be considered 'natural', and if you also include river barriers changing river flow dynamics this number drops to only 1% (AMBER Consortium, 2020; CEH, 2015).

There is some debate to the defined number of natural flow regimes which exist in rivers. With seemingly endless unique river regimes depending on their geography. Although it is generally thought that around seven main river regimes exist:

1. Glacial Regimes

- **Primary Driver:** Melting of glaciers and ice sheets.
- **Flow Characteristics:** Peak flow occurs during the summer months when glacial melt is at its highest. Winter flows are much lower as ice remain frozen. Glaciated deserts such as Antarctica would be the truest examples of glacial regimes although mountainous rivers which also receive high snowfall as well as glacial melt may also be considered glacial regimes in many cases.
- **Locations:** Common in high-altitude and polar regions with significant glacial coverage.
- **Example:** The Rhône River in the Alps and the Onyx River in Antarctica.

2. Nival Regime

- **Primary Driver:** Snowmelt.
- **Flow Characteristics:** Peak discharge occurs in the spring or early summer when the snow melts. Flow is typically lower in the winter when snow accumulates there is some overlap here with glacial regimes, depending on the glacial coverage of the catchment.
- **Locations:** Found in regions with substantial snowfall during winter, such as mountainous and high-latitude areas.
- **Example:** Rivers in the Coast Mountains and the Andes.

3. Pluvial Regime

- **Primary Driver:** Rainfall.
- **Flow Characteristics:** River flow is primarily influenced by rainfall patterns, with peak flows occurring during the rainy season and reduced flows during dry periods.
- **Locations:** Temperate and tropical regions where rainfall is a dominant factor.

- **Example:** The rivers of the UK, which have higher flows during the wet winters, and lower flows during the drier summers.

4. Tropical Pluvial Regime

- **Primary Driver:** Monsoon rains in tropical regions.
- **Flow Characteristics:** High flow during the monsoon season and relatively lower flow during the dry season. The variation in discharge is more intense compared to temperate pluvial regimes due to heavy tropical rainfall.
- **Locations:** Tropical and subtropical areas that experience seasonal monsoons.
- **Example:** The Ganges River and the Mekong River, which have pronounced wet and dry seasons due to the monsoon periods.

5. Nivo-pluvial Regime

- **Primary Driver:** Snowmelt followed by rainfall.
- **Flow Characteristics:** The flow initially peaks in late spring or early summer due to snowmelt, followed by another peak in the autumn caused by rainfall. Snowmelt is the dominant factor, with rainfall as a secondary influence. The main flow minimum is in the winter months.
- **Locations:** Regions that transition from snowmelt in early spring to significant rainfall later in the year.
- **Example:** Rivers in Eastern European steppe.

6. Pluvio-nival Regime

- **Primary Driver:** Rainfall followed by snowmelt.
- **Flow Characteristics:** Similar to nivo-pluvial regimes, but the with the nival peak occurring earlier (such as March/April in the norther hemisphere) and the pluvial peak in the autumn months. Here low flows occur in the summer months rather than winter months.
- **Locations:** Found in areas where the climate has both significant rainfall and seasonal snow, often in lower mountain ranges such as the Scottish Highlands depending on snow cover.
- **Example:** Rivers in regions with both significant rainfall and a moderate winter snow cover.

7. Nivo-glacial Regime

- **Primary Driver:** Combination of snowmelt and glacial melt.
- **Flow Characteristics:** The river experiences two distinct peaks: the first one during late spring due to snowmelt and the second in summer caused by glacial melt. Snowmelt has a stronger influence on flow patterns compared to glacier melt.
- **Locations:** Found in mountainous areas where both glaciers and seasonal snow contribute to the river's flow.
- **Example:** Rivers in the Himalayas, such as the Indus River, where both snow and glaciers play significant roles.

The 7 types of river regimes can be summarised as follows:

1. **Glacial Regime**: Driven by glacier melt with peak flow in summer.
2. **Nival Regime**: Dominated by snowmelt, with peak discharge in spring or early summer.
3. **Pluvial Regime**: Influenced mainly by rainfall patterns, with peaks during wet seasons.
4. **Tropical Pluvial Regime**: Controlled by monsoon rains, with sharp contrasts between wet and dry seasons.
5. **Nivo-pluvial Regime**: Peaks first with snowmelt and then with rainfall; snowmelt is the dominant factor.
6. **Pluvio-nival Regime**: Peaks first with rainfall and later with snowmelt; rainfall is the dominant factor.
7. **Nivo-glacial Regime**: Combines snowmelt and glacier melt, with snowmelt having a stronger effect.

Natural Impacts on flow:

Beneath the overarching theory of river regimes, many other factors can influence river flow. These can broadly be categorised into natural and human factors. The line between what is a natural or human is becoming increasingly blurred, such as with anthropogenic climate change, and land use changes within a catchment. Although, if we consider natural influences on river flow as not stemming from direct human interventions (such as in channel modifications or land use changes within a catchment) we can broadly categorise natural impacts on river flow as follows.

Climate

It can now be said with high confidence that climate change in recent decades has modified all components of the global water cycle (Intergovernmental Panel on Climate Change (IPCC), 2023). Climate is perhaps the most fundamentally important factor in controlling river flow. Ultimately, it dictates how much water can enter a river system. Recent research by the University of Leeds has shown a significant climate-driven shift in river flow seasonality, particularly affecting latitudes above 50°N, such as the UK (Wang et al., 2024). Analysis of historical river flow data from 10,120 gauging stations worldwide demonstrated that approximately 21% of these stations have experienced marked changes in the seasonal patterns of water levels. The study isolated the impact of climate change from other human factors such as water extraction or reservoir impoundments. Modelling showed a direct link between rising air temperatures and the observed weakening in river seasonality, suggesting that warmer climates disrupt the traditional cycles of high and low flows that are essential to ecosystems and water management.

Geology

Geology also plays a critical role in shaping river flow regimes. The permeability of the ground in a river's catchment influences how water is absorbed and released. For example, the Lambourn River, which flows through chalk-rich, permeable areas, has a more stable flow than the nearby River Ock, which flows through impermeable clay and reacts more rapidly to rainfall events (CEH, 2015). Most research has focused on topographic and soil properties, but geological features like bedrock type and hydraulic conductivity are essential to understanding river flow, especially during dry periods when groundwater largely supports streamflow (Carlier et al., 2018).

Rivers fed by chalk aquifers, or ‘chalk streams’ are of particular importance in the UK, as of the 200 known globally, 85% exist in the UK (Wildlife Trust, 2024). Chalk is a highly pure and porous type of limestone. Water filters down through the rock, creating aquifers that overflow as springs, feeding chalk streams with minimal surface runoff. The slow movement of water through chalk helps to even out fluctuations in rainfall and keeps the water temperature stable. Consequently, these streams exhibit a consistent annual flow pattern, with relatively minor differences between winter and summer levels and an absence of sudden flood conditions (Berrie, 1992)

Studies have shown that lithology can shape flow duration curves (FDC) and maintain streamflow in arid conditions. For instance, sandstone is identified as crucial in buffering streamflow in Montana and Switzerland, while permeable volcanic rock stabilizes flow in Oregon. Bedrock’s storage capacity is key, especially in alluvial and permeable deposits which can significantly impact catchment outflows (Carlier et al., 2018).

Topography

The landscape patterns of a river catchment, the evolution of its topography, and changes in river networks are all strongly linked (Willett et al., 2014). Topography ultimately determines the path and residence time of water flowing both to and in a river channel, and is thus an important control on the rivers flow (Curie et al., 2007). A steep mountainous catchment, made of impermeable bedrock with thin soil cover will allow water to enter a river channel far faster than a flat lowland plain, with deeper soils and a porous aquifer after a rainfall event. In channel, depending on the topography of a riverbed or the ‘river morphology’ will determine the amount and speed of flow.

Rivers can generally be categorised into three sections: the upper, middle and lower course of the river. In the upper course are landforms such as waterfalls and rapids, formed when a river flows over hard and soft rock, and V-shaped valleys formed when vertical erosion lowers the river channel, causing the banks to fall into the water. Here as the river channel is narrow and shallow, flows and velocity will be slower as there is less water in a smaller channel than downstream. In the middle course of the river, landforms such as meanders form when lateral erosion creates wide bends in the river. If a meander grows large enough, a section of the river can become cut off, creating oxbow lakes. Landforms such as meanders can alter the speed in which water moves through the river channel, in simplistic terms, river velocity will be greater on the deeper, outside of a meander bend than the inside (Seminara, 2006). Such natural alternations of river flow are important in maintaining biodiverse habitats for in stream wildlife, particularly benthic invertebrates (Garcia et al., 2012). In the lower course, a river is generally wider, deeper and faster flowing, transporting far more water than the upper courses. Here landforms such as floodplains: flat areas of land on either side of a river channel that can be covered in flood events, deltas: formed at the mouth of a river when it deposits sediment material and estuaries: bodies of water that contain both salt and fresh water such as mudflats and salt marshes.

Sediment

Sediments are naturally occurring materials which are broken down through the process of weathering and erosion and transported by wind, water, or gravity. Sediments are most often transported by fluvial processes and can affect the flow of rivers indirectly as they are removed transported and deposited along the length of a river channel, changing its morphology. Sediments can be viewed as a sub-category of river topography controls on flow as they are closely linked. Much like how rivers can be categorised into their upper, middle and lower courses the sedimentation zones of a river can be described as follows (Fig 2):

Headwaters (Alexander et al., 2007; May, 2007):

The source zone, where headwater streams flow down steep mountain slopes, cutting deep valleys. This zone is characterized by high mountains, glaciers, permafrost, snow, steep gradients, high ridges, and deep valleys. The headwaters are also the zone of sediment production, as the steep gradients facilitate sediment movement downwards, lower temperatures inducing freeze thaw erosion processes and high winds all contributing to increased sediment production.

Transfer zone:

The lower-elevation zone where streams merge and flow down gentle slopes. This zone is characterized by lower mountains and hills, steep slopes, mixed vegetation, and human activities such as agriculture. The transfer zone is where the stream erodes less sediment but transports the sediment provided from the headwaters.

Depositional zone (Wright, 1977):

The lowest-elevation zone where the river meanders across a broad, nearly flat valley and floodplain. At the river's mouth, it may divide into separate channels as it flows across a delta or estuary extending out to sea. As the velocity and thus transport capacity of the river has decreased it will deposit most of its sediment forming these landforms which are often unique habitats for many niche species (Mclusky & Wolanski, 2012). Sediment transport from headwaters to depositional zones and the sea are also important pathways for nutrient transport, especially to the oceans (Walling et al., 2001)

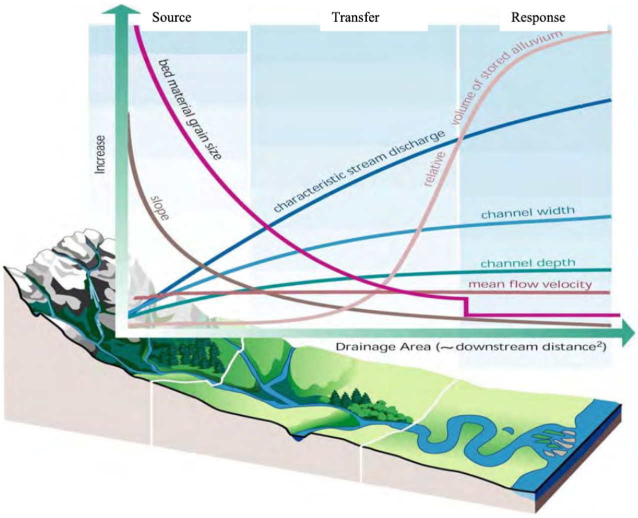

Figure 2: The different sedimentation zones of a river (Federal Interagency Stream Restoration Working Group (US), 1998).

Vegetation

Vegetation can also influence river flow, both in channel and in the wider catchment. If a catchment is heavily vegetated this can affect how long it takes water to reach a river channel. Vegetation intercepts precipitation, increasing the lag time between rainfall events and peak discharge in the river. It also removes water from the river system entirely through the processes of evaporation and transpiration from plant leaves. Vegetation also contributes to shaping the river's form by reinforcing banks and creating natural barriers that alter flow paths within the river. Vegetation can actually have quite a large effect on river morphology and flow, as studies have down that uniform riparian vegetation along river banks can have enough of a stabilising effect to reduce erosion and shift braided rivers into single channel river systems (van Dijk et al., 2013).

Animals

Whilst not having as significant effect on river flow as vegetation, animals can also play a role in shaping river morphology and flow. Species known as ecosystem engineers can modify the landscape through direct and indirect actions. The most notable and relevant examples of this are beavers, which can create large impoundments which can dramatically alter the hydrology, morphology, ecology and water quality of a river system (Brazier et al., 2021). Animals can also indirectly change river characteristics. Numerous studies have looked at the effect large predators can play on reducing riverbank erosion (Beschta & Ripple, 2012; Ripple & Beschta, 2004, 2012). The most famous example is from the reintroduction of wolves into Yellowstone National Park, which changed the grazing behaviour of prey animals, forcing them to spend less time grazing river banks allowing for increased riparian vegetation and thus greater bank stability and decreased lateral erosion of river channels (Beschta & Ripple, 2009).

These studies highlight how difficult it is to determine the controlling factors on river flow, as every aspect of a river catchment needs to be considered, from geology to flora and fauna, as well as regional and global climatic patterns. Therefore, a holistic approach to river management is needed at many different levels, and that anthropogenic modifications to river channels will have far ranging consequences by upsetting the delicate balance of natural factors controlling river flow.

Human impacts on flow

Only a small fraction (fewer than 15%) of UK rivers maintains natural flow regimes (CEH, 2015). Over the centuries, humans have modified rivers extensively for various needs: land drainage, flood control, water supply, hydropower, navigation, fishing, and recreation. Such interventions have altered many rivers' physical characteristics, such as width and depth, impacting river flow, velocities, temperatures and water chemistry. Land use changes, such as urbanization and agricultural drainage, can also significantly impact flow patterns by changing the water balance in catchments. Urbanized areas, for instance, may not follow typical seasonal flow patterns due to increased runoff from impermeable surfaces. Similarly, different types of agriculture can alter evaporative demands based on the crops grown and the way in which they are planted (Shuttleworth & Wallace, 1985; Szeicz et al., 1969).

Human activities often reduce natural flow rates in the UK, particularly in drier regions, where water extraction from rivers and groundwater can cause considerable environmental stress. Conversely, flow rates can sometimes be artificially increased through reservoir outflows, groundwater supplementation, or inter-basin water transfers. Long-term river flow data often reflects human impacts more than natural and climate variations (Hannaford & Buys, 2012).

The type of human activity which takes place in a river basin can influence river flow in a multitude of ways. Outlined below are some of the most common and most impactful forms of human modifications which can affect river flow:

Barriers

A river barrier is a structure or obstacle, either natural or man-made, which prevents the movement of aquatic organisms either upstream or downstream. Barriers modify the flow and depth of water in river systems and can influence water chemistry. They can have many purposes including industrial, agricultural, infrastructure, flood defence, land reclamation, environmental management or aesthetic. The main purposes of river barriers are usually to regulate flow regimes for human benefit which otherwise often experience seasonal variations.

Barriers directly alter flow by impounding water upstream and releasing water downstream creating unnatural gradient steps in a river profile unsuitable to species which previously lived in the natural free flowing river. River barriers can significantly change the structure and morphology of a river by altering sedimentation and erosion patterns (Yu et al., 2022). Braided river systems for example, are being more tightly managed across the world for water abstractions and flood prevention and are thus contributing to the decline in water quality (Bora & Goswami, 2017). Such rivers typically have extreme high and low flows dependent on seasonality and lots of geomorphological movement and thus constructing river barriers can lead to huge changes in river morphology.

The altering of natural flow conditions by barriers can have negative impacts on aquatic organisms. Numerous scientific studies have documented significant population decline of Atlantic Salmon in rivers which have had their flow regulated by in-stream barriers (Jonsson & Jonsson, 2011; MacCrimmon & Gots, 1979; Parrish et al., 1998). The accumulation of fine sediments upstream of river barriers can also lead to habitat degradation, increased turbidity, reduced flow, and deoxygenation (Jensen et al., 2009).

Land use changes

Land use and land cover changes have a significant impact on river flow (Kayitesi et al., 2022). Changes in land use, such as deforestation, urbanization, and agricultural expansion affect how watersheds handle rainfall by modifying processes such as interception, infiltration, evapotranspiration, and groundwater recharge.

Deforestation:

Forests promote groundwater recharge through deep-rooted trees that enhance soil infiltration and base flow and consume water through evapotranspiration. Deforestation, however, reduces infiltration, leading to higher surface runoff, reduced groundwater recharge, and lower base flow, which increases flood risks and depletes dry-season flows (Farinosi et al., 2019; Naha et al., 2021; Olang et al., 2011).

Agriculture:

Agricultural land is often prone to surface runoff, especially during early rains when vegetation cover is sparse leading to more rapid conversion of rainfall to runoff (Bekele et al., 2021). The expansion of cultivated land at the expense of natural vegetation typically reduces soil and water retention, thereby lowering rainfall infiltration rates and increasing surface runoff as agricultural land is less densely vegetated and often a monoculture (Sulamo et al., 2021). This also speeds up the flow of water toward stream networks (Getu Engida et al., 2021). The lack of deep root systems found in forested areas, and dense canopy cover results in reduced evapotranspiration and groundwater recharge, which further amplifies runoff (Das et al., 2018). Use of farmland for grazing cattle will compact soil, reducing its infiltration rate (Hassaballah et al., 2017). The compacted soil increases surface runoff, with more rainfall flowing directly into streams instead of recharging groundwater (Baker & Miller, 2013).

Urbanisation:

Urban areas are covered in impervious surfaces, limiting infiltration and groundwater recharge. Soils and vegetation cover are replaced by roads, buildings and pavements, leading to greater runoff, faster conveyance, and higher flow peaks during rainfall events. In a study of 12 UK rivers over 40+ years where there has been significant urbanisation in the catchment found that for every 1 % increase in urban land cover there is an associated increase in the median of 1.9 % for low flow, 0.9 % for median flow, 0.9 % for mean flow, 1.1 % for high flow, and 0.5 % for seasonal maximum flow across seasons (Han et al., 2022). Urbanisation is most likely to be associated with increases in river flow across all seasons.

Overall, large-scale shifts from densely vegetated (forested) to less densely vegetated (non-forested) land reduces infiltration and evapotranspiration while increasing surface runoff. This intensifies discharge rates during storms, heightening flood risks, and contributes to drier conditions by reducing groundwater recharge in the dry season, which may worsen drought severity.

Channel modification

For centuries, rivers have been extensively engineered to control floods, enhance navigation, support irrigation, and supply freshwater and energy. Interventions such as building dams, installing weirs, levees, channelization, river diversion, sediment mining, and dredging, have converted naturally meandering, braided, or branching rivers into straighter, shorter, and single-thread channels with fixed paths. Notable examples include the Rhine, Thames, and Danube rivers (Hohensinner et al., 2011).

When rivers forms and widths are fixed by human intervention, engineered rivers adapt to human interventions by altering channel slope, often through bed incision or sediment buildup, and bed surface texture (the grain size distribution of sediments on the riverbed) (Ylla Arbós et al., 2021). Significant bed incision has been recorded in many engineered rivers, where narrowed channels increased flow velocity and elevate sediment transport capacity (Quick et al., 2020). This causes the channel bed to erode downstream of modifications to reach a new equilibrium slope suitable for sediment transport. However, such incision can disrupt navigation due to decreased water depth over non-erodible sections and may elevate flood risks by destabilizing in-river structures. It also impacts riparian ecosystems, causing disconnection between channels and floodplains, lowering groundwater levels and altering flow conditions where the channel is modified, as well as downstream flow conditions and in some cases (such as river barriers) upstream flow conditions as well (Buijse et al., 2002; Hiemstra et al., 2022).

Climate forcing

The impact of anthropogenic climate change on river flow is much the same as how natural climate and climate change influences river flow. The main difference being that it is human activity releasing greenhouse gasses into the atmosphere which changes the water cycle, rather than natural shifts in climate observed from proxy records from pre-history. Global studies or river systems response to climate change show that low flow conditions (during drier seasons) will be the most significantly affected by future anthropogenic climate forcing (Thompson et al., 2021). Academics have also demonstrated that past changes in river flow (such as increased flooding events) can now be attributed to historical climate warming. A study of 22 flooding events on major rivers across the globe between 2010-2013, found that 64% could be attributed to anthropogenic climate change (Hirabayashi et al., 2021). The mechanisms of how anthropogenic climate change affects river flow are no different to natural climate influences, but it is the accelerated rate at which climate changes are happening because of human activity which is most concerning, as river, and the organisms which relay on them have less time to adapt to these changes.

Abstraction

Water abstraction in the process of taking water from a natural resource such as a river, lake, spring or groundwater aquifer for human usage (EPA, 2024). Water is generally piped, pumped or diverted for uses in agriculture, industry or drinking water supply. Large water abstractions pose significant environmental risks from reducing river flows, and thus need to be carefully regulated. Abstraction can alter the natural flow regime either directly changing surface water flows or indirectly by lowering groundwater levels and consequently affecting flows to springs, wetlands, lakes and rivers .The Scottish Environment Protection Agency (SEPA, 2024), outline the following risks of reduced river flow from water abstractions in the UK:

- Drying out of rivers and wetlands
- High variable flows of water below hydropower stations and water supply reservoirs, resulting in bare banks and potential stranding of fish
- Changing water levels in reservoirs, leading to regular drying out of the shoreline and preventing growth of plants and spawning fish
- Interference to the flow of sediment downstream of dams, which reduces the amount of gravel available (needed by fish to spawn).
- Interference with other users of the water environment (e.g. loss of dilution capacity and resulting deterioration of water quality, or loss of abstraction capacity).

Abstraction in the UK

Periods of naturally low flow occur during extended dry spells (such as droughts) and play a key role in supporting biodiversity. However, these low flows can be extended or worsened by unsustainable water abstraction for public supply, industry, agriculture, or domestic use. Excessive groundwater abstraction lowers groundwater levels, impacting river flows and may also lead to the intrusion of lower-quality water from the sea or deeper aquifers.

Other artificial abstractions which impact flow include treated sewage discharge, water transfers between catchments, and water storage and release from reservoirs. These activities can sometimes counterbalance raw abstraction impacts or cause flow levels to vary significantly from their natural state.

For surface water bodies, flow is a critical factor in ecological assessments, with high-status classification in the Water Framework Directive (WFD) requiring natural flow conditions. Outflow from groundwater also supports surface water flows needed for biological health. Unsustainable abstraction rates reduce surface water flows, leading to lower flow velocities, shallower depths, and decreased flow continuity, all of which can negatively affect ecological conditions. Additionally, groundwater pumping can reduce local spring flows and water levels essential for the ecological health of groundwater-dependent wetlands, especially during dry periods, as seen especially in parts of eastern England.

The most recent abstraction figures for England stand at 10.4 billion cubic meters of water taken from non-tidal surface waters and groundwater sources in 2017 (Defra, 2023). This is a 27% increase from the 8.2 billion cubic meters abstracted in 2011. 13% of total abstractions were from groundwater whilst the rest came from non-tidal surface waters. Groundwater abstraction has decreased from 2.4 billion cubic metres in 2000 to 2.1 billion cubic metres in 2018 (Fig 3).

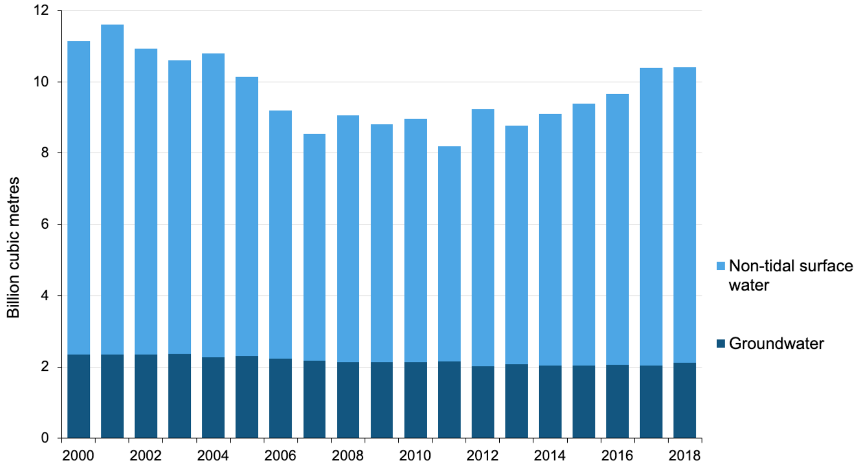

Figure 3: Water abstraction in England between 2000 and 2018 from non-tidal surface water and groundwater sources in billion cubic meters (Defra, 2023).

According to Defra (2023) the increase in water abstraction from 2011 to 2017 is primarily due to water used for electricity generation, which rose significantly from 1.4 billion cubic meters in 2011 to 3.3 billion cubic meters in 2017. Abstraction for public water supply, comprising 51% of total abstraction from non-tidal waters, has remained steady, with a 3% increase over this period to an estimated 5.3 billion cubic meters in 2017. Water abstraction for fish farming, watercress production, and amenity ponds declined from 1.7 billion cubic meters in 2000 to 0.9 billion cubic meters in 2017, with a similar reduction in abstraction for other uses, down by approximately 0.7 billion cubic meters since 2000.

In 2018, overall abstraction estimates from non-tidal surface waters and groundwater remained stable. Increases in water abstraction for spray irrigation and electricity generation were balanced by decreases in abstraction for other industrial activities, as well as for fish farming, watercress cultivation, and amenity ponds.

Water supply in England is fully dependent on naturally occurring supplies of water from lakes, rivers, reservoirs and ground water sources. The problem is that these natural sources cannot supply enough water to meet the UK's demands and provide enough left over to maintain adequate flow for our rivers and lakes to thrive. This is true in normal conditions. In periods of drought, UK water bodies are under even more intense pressure

There are three principal drivers behind the projected increase in in the UK's water supply deficit which is driving unsustainable levels of water abstraction and reducing river flow:

Population change: Average water consumption per person, per day, in England is 142 litres (Sulamo et al., 2021). The UK's population is set to increase by approximately 4 million people by 2045 (Office for National Statistics, 2020). The majority of that increase will occur in England – mostly in the already severely water-stressed southeast. This population change represents an increase in demand of 570 million litres of water per day.

Climate change: In addition to an overall rise in temperature, England will experience changes to annual rainfall distribution culminating in shorter, wetter spells either side of longer, drier periods. As part of this, England can expect an increase in the frequency of extreme weather events. Both drought and flash floods will have negative impacts on our water resources.

Abstraction licence change: It is estimated that 700 million litres of water is currently unsustainably abstracted by water companies every day (Environment Agency, 2020). This figure could be set to increase to 2 billion by 2050. The National Framework for Water Resources has set the target for all unsustainable abstraction to be replaced between 2025 and 2050.

Currently, only 16% of rivers are classified as healthy according to the WFD, and freshwater species are declining quicker than any other (UK Gov, 2022). Wild fish populations continue to decline, with salmon populations failing to meet even the most basic conservation limits and now listed as endangered on the IUCN Red List. Our rivers and the species which depend on them are already severely stressed and not resilient to change. This means low flows and drought, exacerbated by abstraction during these naturally vulnerable times, will have even greater impacts on them.

If England were to experience an extreme drought, demand would outstrip supply even now in 2025. If this were to occur, water companies would be forced to take extra water from rivers, lakes, and groundwater sources to ensure public water supply didn't fail. Many rivers already suffer from over-abstraction and low flows, and adding drought conditions and extra abstraction would devastate freshwater ecosystems.

UK water supply would fail to meet demand in a drought because water companies have failed to invest, over many years, in alternative water supply sources. Additional abstraction, through drought permits, continues to remain the cheapest solution for water companies, leading to increasing periods of low flows unsuitable for maintaining aquatic biodiversity. The last reservoir built in England was constructed over 30 years ago. The next reservoir's (Havant Thicket in Hampshire) completion date keeps getting pushed back and now looks unlikely to be completed before 2034. Currently in the UK rivers are the only source of additional water to maintain our water supply in times of extreme drought.

Effects of abstraction on the River Kennet (WWF, 2009):

A report by the WWF-UK highlighted the ecological impact of over-abstraction on the River Kennet, a chalk stream tributary of the River Thames which flows through Wiltshire and Berkshire in Southern England. The River Kennet being a chalk stream provides unique habitats and species yet has been classified as "unfavourable" in terms of its ecological status, primarily due to reduced flows and falling groundwater levels. These issues are partly due to water abstraction by Thames Water for the Swindon-Oxford area, where a significant portion of abstracted water does not return to the river, causing a net depletion of river flow. Studies show that abstraction has led to reduced summer river flows, with reductions reaching 35–40% during droughts, which affects species such as water crowfoot, dependent on fast-moving, clear water.

The Axford abstraction point saw regulatory adjustments to reduce its environmental impact, and further reductions are planned. However, Thames Water forecasts increased demand in the region by 2030, largely from population growth and household demand, which may continue to pressure river flows.

Climate change adds to these pressures, with predictions of increased winter precipitation but uncertain summer rainfall patterns, which would lead to reduced flows and water quality issues. Future river management strategies for the Kennet emphasize “low-regret” actions that can adapt to various climate scenarios. Overall, the River Kennet case study underscores the importance of sustainable abstraction levels to protect ecological integrity in the face of rising demand and climate uncertainties and the difficult challenges of achieving this.

The effects of flow on aquatic wildlife:

Invertebrates

Almost all rivers undergo discharge increases; these can stem from natural events (such as increased rainfall) or anthropogenic modifications. In an ecological sense, the term ‘flood’ embodies any increase in discharge. During periods of flooding, invertebrates are affected directly and indirectly through habitat changes caused by water velocity and physical scouring from the initiation of bed movement (Bunn & Arthington, 2002). Scouring can cause damage to them and their food source. During extreme high flows, river invertebrates may be swept downstream in large numbers. This so-called "catastrophic drift" leads to a major redistribution of animals, as well as reduced fitness and increased mortality among drifters. The term catastrophic drift is used to distinguish between the normal daily and seasonal rhythms in drift and the large-scale loss of animals observed during floods; thus, it is synonymous with disturbance. Gibbins et al. (2007) used portable flumes to recreate the conditions of small frequent floods within a gravel bed river. They found that the total number of individuals lost from the bed and the taxonomic composition of the drift were influenced strongly by shear stress and bedload. At the highest bedload transport rates taxonomic composition of the drift was closer to that of the benthic community than it was when the bed material was stable. The authors concluded from this work that discharge events not considered as disturbances in geomorphic terms may initiate frequent episodes of catastrophic drift from patches of streambed. Bruno et al. (2010) also found a relationship between high flow events and considerable loss of benthic invertebrate populations to drift. Drifting invertebrates were collected during a planned water release that increased the discharge 7-fold. Peaks in drifting invertebrates occurred within 5–10 min and the number of invertebrates lost from the riverbed per minute to the drift increased 9-fold at the first downstream station with same effects occurring 8 km downstream.

Natural seasonal inundation of floodplains at peak flood times is critical for channel migration, an important phenomenon for maintaining high levels of habitat diversity across floodplains. However, river regulation can shift seasonal timing and change magnitude with major ramifications for aquatic and terrestrial biota (Ward & Stanford, 1995). Although numerous studies have shown the negative response floods have on invertebrates (through reduced abundance and diversity), invertebrates do persist even in very flood-prone streams and recovery from most flooding events is relatively rapid (Death, 2008). A meta-analysis by McMullen & Lytle, (2012) found a significant reduction in overall invertebrate abundance and a reduction in abundance of major groups of invertebrates immediately after flood events in rivers on a global scale. The declines were evident despite large differences in river type (parent geology, gradient, catchment size), regional climate, and continental setting. It was also found that invertebrate abundance was generally lowered by at least one-half after flood events and although sample sizes were not sufficient to examine all taxonomic groups, floods had a significant, negative effect on densities of Coleoptera, Eumalacostraca, Annelida, Ephemeroptera, Diptera, Plecoptera, and Trichoptera. However, despite the observed large effects of flood events on invertebrate communities, they appear to be relatively short-lived, reflecting the high resilience of many invertebrate taxa. Robinson & Uehlinger (2008) evaluated the long-term effects of floods on a regulated river. Although floods reduced invertebrate richness and biomass after the first year the density of organisms recovered quickly between floods. However, these were mostly smaller short-lived taxa like baetid mayflies and protonemurid stoneflies. It was found that later floods had ∼30% less of an effect on macroinvertebrates than the earlier floods of similar magnitude, indicating that the new assemblage structure is more resilient to flood disturbance. The authors hypothesised that regular flooding caused an ecosystem regime shift that took three years to unfold.

At the opposite end of the spectrum, hydrological connectivity is disrupted when rivers experience drought conditions. These disruptions range from flow reduction to complete loss of surface water. Longitudinal patterns as to where flow ceases and where drying up occurs differ between streams (Lake, 2003). Defining drought hydrologically is problematic because the return times, intensity, duration and long-term trends in low-flow periods are specific to regions and times. Droughts may instead be referred to as ‘significant low-flow periods’ (Humphries & Baldwin, 2003). Generally, as flows decrease habitat space is reduced and invertebrate richness commonly decreases; invertebrate taxa differ in their environmental tolerances and needs, so any loss of habitat area or alteration of food resources from decreased flow can influence organism behaviour and biotic interactions (Dewson et al., 2007). Natural low flows and artificially reduced flows have similar effects on invertebrates, but the severity (duration and magnitude) of the flow decrease can influence invertebrate responses (Dewson et al., 2007).

A significant proportion of studies examining the effects of low flows on invertebrates have involved monitoring changes in the invertebrate community composition upstream and downstream of artificial flow decreases, specifically water abstractions. Miller et al. (2007) found that in an intensively managed agricultural catchment high-intensity, relatively short-duration irrigation water withdrawals (<2 months) and the associated alterations to the physicochemical environment changed the relative abundance of macroinvertebrate communities, while macroinvertebrate indices and proportional abundances of functional feeding groups remained unchanged. However, discharge reductions exceeding 90% of ambient levels and temperatures above 30 °C were associated with shifts in community composition from a dominance of collector-gatherer and filterer Ephemeroptera, Plecoptera and Trichoptera taxa to predatory insects and scraping elmid beetles. Studies investigating the effects of human-induced flow reductions on aquatic biota upstream and downstream of abstraction points are often tainted by the potential for synergistic interaction of multiple environmental variables such as temperature and oxygen. Therefore, determining the effects caused by reduced flow alone is not usually possible. James et al. (2009) overcame this problem using experimental channels, as flows could be closely manipulated without causing large alterations to other variables. They found that invertebrates were actually exhibiting resistance to the experimental flow reduction, with the effects of increased magnitude and duration of flow reduction being restricted to changes in the relative abundances of just a few taxa. Prolonged low flows did not result in predictable changes and if invertebrates can persist at flows much lower than their supposed optima, using hydraulic-habitat models to set minimum flows could be unsuitable. Walters (2011) also created an experimental low-flow stream set up, but this work looked at community trait composition of aquatic insects in response to reduced flow disturbance. Desiccation resistance was not found to be a favoured trait; high crawling rate and armouring were found to be the trait states that conferred increased resistance. As these traits provide improved protection from predators, the author hypothesised that biotic interactions could also be a key driver in shaping invertebrate communities during low-flow disturbance conditions.

Many historically perennial streams have already become intermittent as a result of excessive abstraction and impoundment (Belmar et al., 2010). Arscott et al. (2010) examined the community structure and life history traits of benthic invertebrates along an intermittence gradient. The following intermittence metrics were used: flow permanence (average % time that flowing water is present), flow duration, frequency of drying, and distance to the nearest perennial site. Overall, community structure in perennial river sections was richer and denser than intermittent river sections. The strongest relationships between taxon-richness and density metrics related to flow duration, flow permanence and a combination of the two. The results indicated that 0.5 taxa/m^2 would be added with every 10-day increase in flow duration and 1.9 taxa/m^2 would be added with every 10% increase in flow permanence. Communities at river sections with intermittent flow were a nested subset of the perennial communities with desiccation sensitive taxa being progressively removed with increasing intermittence. Proportions of taxa with plurivoltine reproduction and small sizes decreased with increasing flow permanence and flow duration. Bogan et al. (2013) also found that invertebrate richness was lower in intermittent river reaches when compared to consistent reaches despite the two often being connected. However, in this study stoneflies, midges and blackflies with intermittency adaptations such as larval/egg diapause dominated the assemblages, rather than being a nested subset of the species in the consistent reaches. The authors highlighted that intermittent flow river sections support a multitude of unique and locally rare species so need special consideration in conservation planning.

A number of studies have demonstrated that high faunal diversity can still be achieved irrespective of flow manipulation as long as habitat heterogeneity is maintained (Armitage, 1995). Suren & Jowett, (2006) compared the relative importance of floods and low flows in structuring invertebrate communities. They found that after low flow events the densities of most invertebrates either remained unchanged or increased. Four taxa did show a density decline but this was in response to a very long period (up to 9 months) of low flow and was attributed to loss of available habitat. The authors concluded that invertebrate communities were more susceptible to changes due to floods and these changes were greater than even extended periods of extreme low flow. It was also found that the degree of change was proportional to flood magnitude. Dunbar et al. (2010) also compared the effects of high and low flows on invertebrate communities, by looking at LIFE scores. However, in this study their responses in highly modified/resectioned river channels versus less modified channels were explored. Morphological structure did influence the response of the biota during high and low flows. Habitat modification, specifically extent of resectioning, influenced not only the overall magnitude of the LIFE score but also the slope of response of LIFE score to flow. The less modified channels were able to maintain greater habitat diversity and stability of substratum, thus providing more refuges for invertebrates at extreme high and low flows. Because of these refuges at the least modified sites, taxa preferring faster velocity discharge, including caseless caddis species (notably from the genera *Hydropsyche* and *Rhyacophila*), numerous mayfly species and *Gammarus pulex* were able to continue to exist in reduced numbers during low flows, whereas at the highly modified sites these taxa generally disappeared during low flows. Work by Lake (2003) emphasised that restoration of streams must include the provision of drought refugia for invertebrates and the inclusion of drought in the long-term flow regime, stating that invertebrate survival in refugia strongly influences the capacity of biota to recover from droughts once they break. A review by Garcia et al. (2012) also corroborates the concept of flow refugia enabling the persistence of species that would otherwise be unable to resist hydraulic stress, leading to increases in faunal diversity. However, as re-meandering is one of the most favoured mechanisms to restore natural flow regimes, the authors identify the need for studies on whether meanders have any specific physical or hydraulic features that lead to the origin of flow refuges for benthic invertebrates.

Fish

Migration:

There is a clear consensus that modified flow regimes in regulated rivers affects fish and fish habitat, but the severity and direction of the response varies widely. Anadromous fish species feed and grow at sea but migrate into freshwater to spawn. To maintain natural anadromous salmonid populations both adult upstream and juvenile downstream migrations are essential (Rivinoja, 2005). Studies have shown that water discharge appears to be an important factor stimulating adult Atlantic salmon (*Salmo salar*) to enter rivers from the sea and it is elevated flows that stimulate their upstream migration (Baglinière et al., 1990; Dunkley & Shearer, 1982; Smith et al., 1994). At very low flows salmon are inactive and do not attempt to migrate upstream (Cragg-Hine, 1985). Stewart (1973) found in northwest England that at flows of 2.4 ml/d per m of width or less no upstream salmonid movement occurred, this was named 'absolute survival flow'. Migration reached a peak of intensity at a mean flow of 17.3 ml/d per m, with migration reducing at flows higher than this value. Hembrel et al. (2001) found evidence supporting that high water discharge and temperature triggered the brown trout (*Salmo trutta*) smolt run in a Norwegian river. When the discharge was lower than 50 m^3 per second few smolts descended. Similar results were found by Aldvén et al. (2015) for brown trout and Atlantic salmon in a Swedish river. Peak migration occurred at discharges above 1 m^3 per second. Discharge had the greatest effect on downstream migration, but temperature was also important when there was no increase in discharge.

Often diverse bypasses are built to preserve or renew migration possibilities for fish in regulated rivers (Calles & Greenberg, 2005). To control water discharge, artificial freshets may be used to encourage the upstream and downstream migrations of Atlantic salmon. A section of the river Mandal, Norway was manipulated in 2004 to provide artificial freshets in order to encourage Atlantic salmon smolt migration past hydropower intakes. Testing and modelling indicated that increasing water discharge into the bypass resulted in a large increase in smolt migration through the bypass section (Fjeldstad et al., 2012). The developed migration route choice model showed that bypass migration generally decreased with increasing total discharge but increased with increasing proportional diversion of the total flow to the bypass. The authors recommended that power production planning for low discharges during spring, and spill of water into the bypass during smolt migration times could increase smolt survival significantly. Lundqvist et al. (2008) demonstrated that larger artificial freshets may have more successful effects on salmon passing a power-station but the general consensus is that relatively short and small artificial freshets in large regulated rivers may not work. Results in Thorstad et al. (2005) indicated that artificial freshets did not seem to stimulate upstream salmon migration in residual flow stretches to a large extent, although small effects were found during one of the sample years. They speculated that the effects of water discharge on upstream salmon migration are being exaggerated, particularly in large rivers with a generally high water discharge.

Reduced flows can also present a physical barrier, preventing anadromous fish from completing their life cycles. Lack of availability of one or more habitats or poor connectivity between habitats is likely to act as a bottleneck and lead to population decline (Lucas et al., 2009). The accessibility of many tributaries to fish is dependent on water discharge. Gosset et al.(2006) found in their study that physical obstacles for migrating adult brown trout usually corresponded to water abstraction (for hydropower plants, water supply and irrigation). They hypothesised that loss of water discharge increases fragmentation at the entrance of tributaries. In most cases, migrating fish will have to await an increase in discharge to enter the tributary and the loss of time and energy caused by waiting will compromise their reproductive success as well as their survival probability. Work by Lucas et al. (2009) demonstrated that the combination of small-scale obstructions and low river discharge can affect the distribution of key habitats, especially access to habitats required by relatively mobile megafauna. Despite there being over 98% of suitable spawning habitat for river lamprey (*Lampetra fluviatilis*) more than 51 km upstream, an annual average of just 1.8% of the combined site-specific maximum daily counts of spawning river lamprey occurred there. The results showed that passage at obstructions, including those with fishways, was almost always associated with strongly elevated river discharge. Areas subject to unnaturally low water flows can also experience greater peaks in water temperature, especially in summer months, which many fish are unable to tolerate (Hendry et al., 2003).

The passability (percentage of fish which can successfully navigate past an obstacle) of 'passable' manmade barriers must also be considered when considering fish passages past river obstacles. No barrier will be 100% passable and reducing the passability only slightly can have compounding consequences (Buddendorf et al., 2019). This can have escalating knock-on consequences for habitat connectivity upstream and has been shown to reduce Dendric Connectivity Index (DCI) even when fish pass efficiency is as high as 95% (Fig 4). Fish barrier efficiency must also account for the downstream movement of fish. While most passages are focused on the upstream movement of fish, diadromous fish must also migrate downstream either as smolts in the case of salmonids or, silver eels in the case of eels. This means that some fish ladders may actually only serve as one-way route for migrating fish, only partially mitigating the environmental impacts they were intended to reduce (Agostinho et al., 2007). A comprehensive literature review of 65 articles from 1960 to 2011 looking at fish passage efficiency found that downstream passage efficiency was 68.5%, and upstream passage efficiency was 41.7% (Noonan et al., 2012). Salmonids were more successful than non-salmonids in passing upstream (61.7 vs. 21.1%) and downstream (74.6 vs. 39.6%) through fish passage facilities. The type of fish passage present also significantly affected barrier passability, with pool/weir ladders and vertical slot passages having the highest efficiency and baffle and fish elevators having the lowest (Noonan et al., 2012).

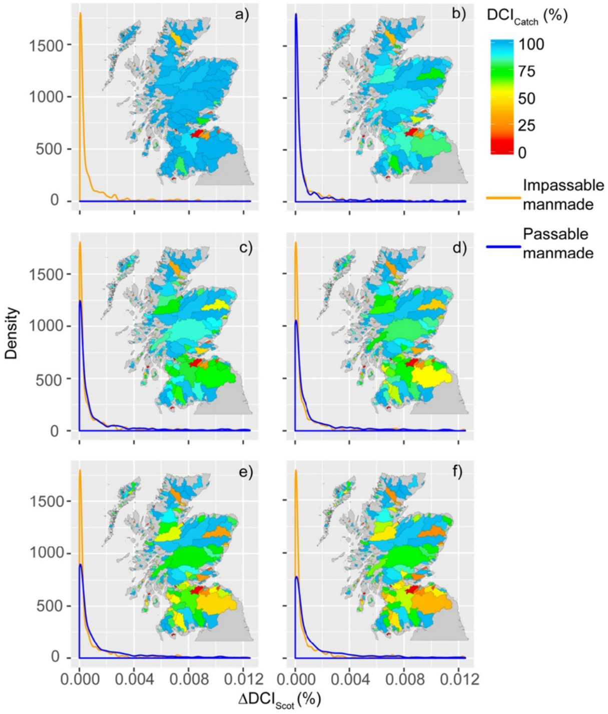

Figure 4: Density plots of DCI for impassable manmade barriers (yellow) and passable manmade barriers (blue) where the passability of Passable Manmade Barriers is 100%, 95%, 90%, 85%, 80%, and 75% in subplots a–f, respectively (Buddendorf et al., 2019).

Habitat:

In regulated rivers, canalisation and reduced water discharge may lead to loss or impairment of salmonid spawning areas, thereby having negative effects on stock recruitment (Barlaup et al., 2008). Flow velocity of water through salmonid redds is considered a key factor controlling the survival of incubating eggs as it brings dissolved oxygen and removes metabolic waste (Zimmermann & Lapointe, 2005). Adequate flows are necessary for salmonid eggs to ensure oxygen needs are met and excessive fine sediment deposition is prevented. Additionally, under high flow events capable of mobilising gravel, salmonid eggs may be damaged or washed out of redds causing them to die (Acreman & Ferguson, 2010). As a result, it is essential for spawning salmon to select redd sites that meet the flow requirements of the eggs. A meta-analysis of various literature on Atlantic salmon and brown trout spawning habitat criteria by Louhi et al. (2008) showed that Atlantic salmon spawning sites are characterised by water depth of between 20 and 50 cm and flow velocity between 35 and 65 cm s^{-1}. When different sized rivers were independently analysed, local variability was evident. Salmon in larger rivers used deeper water (30–55 cm), whereas in smaller rivers they preferred shallower areas of around 10–30 cm. When all sizes of rivers were analysed in combination, trout redds were mainly located in depths of 15–45 cm and velocities of 20–55 cm s^{-1}. Interactions between discharge and microhabitat factors for trout were not as clear as for salmon, although in large streams, spawning sites were in deeper water (20–55 cm) and lower velocities (20–40 cm s^{-1}). Local variability in spawning discharge preference had previously been identified by Gibbins et al. (2002). The locations used by spawning Atlantic salmon in a reach of the Girnock Burn, Scotland, were monitored over three successive years. Spawning fish used relatively high discharges, with the highest electivity value being for a discharge approximately three times the reach median flow. However, fish spawning in the upper parts of the catchment selected higher relative discharges compared to those in lower parts. The minimum discharge used for spawning also increased significantly with distance up the catchment (Gibbins et al., 2008). The explanation for these different localised preferences is speculated to relate to the interactions between discharge, channel geomorphology and point hydraulic conditions, as spawning locations function and respond to changes in discharge quite differently (Malcolm et al., 2012). Spawning fish will also avoid periods of rapidly varying discharge so rates of flow change are also an important part of redd habitat selection (Moir et al., 2006).

Throughout their different life stages salmonids actively select habitats with particular combinations of water depth, velocity, and substrate (Armstrong et al., 2003). Water velocity has been categorised as the most important environmental feature characterising the habitat of stream-living fishes (Heggenes, 1996). An experimental study by Pakkasmaa & Piironen (2000) showed that both juvenile Atlantic salmon and brown trout were able to adapt to different flow velocity environments through morphological differentiation. In fast flows salmon became more robust, whereas brown trout became slightly more streamlined. These morphological changes occurred very rapidly, within a month of exposure to the different water flows. As it was previously demonstrated that brown trout prefer deep stream areas with moderate to low water velocities and rocky substrates, whereas young Atlantic salmon choose faster flowing and shallower areas (Heggenes, 1996), the different morphological responses observed may be a reflection of their different habitat preferences. Paez et al. (2008) found that mature Atlantic salmon parr captured in higher velocity rapids are significantly smaller than fish found in slow-current habitats. They proposed that water current velocity contributes to the size difference through the extra energetic demands experienced as body shape enlarges and movement is further limited in faster currents. However, despite the extra energy expenditure associated with higher velocity environments, no difference in the gonadal somatic index between habitats was found. If water velocity is proven to have a causal effect on body size, water velocity will have a direct impact on the reproductive success of mature parr (given the importance of salmon size during spawning). Flow regime may have its strongest influence via effects on streambed composition-associated changes in shelter availability. The availability of shelter in salmonid habitats has been shown to be a key factor in parr growth and survival. When flow regulation is large enough to prevent the occurrence of bed-mobilising flows, streambeds can become armoured because of increasing embeddedness and packing of substrate. These effects will in turn reduce the availability of interstitial shelter space to salmon parr (Nislow & Armstrong, 2012)

Conclusions

River flow and abstraction are crucial factors influencing water quality and aquatic biodiversity, particularly here in the UK where naturally river regimes are predominantly only pluvial, and can be more heavily influenced by anthropogenic activities. Flow is often regarded as the "master variable" for riverine ecosystems, dictating the physical conditions that support diverse biological communities. Variability in river flow, derived from natural processes like rainfall and snowmelt, is essential for sustaining habitat diversity, which is vital for different life stages of aquatic species. Anthropogenic activities significantly disrupt natural flow regimes through water abstraction and the construction of barriers, affecting approximately 63% of the world's rivers. In the UK, only about 1% of rivers remain free from artificial barriers, leading to severe alterations in flow dynamics. This disruption can concentrate pollutants due to reduced water volume, degrading water quality. As abstraction decreases river flow, pollutants become more concentrated, or water is returned in worse quality, or in a different location, exacerbating ecological stress.

The ecological consequences of altered flow regimes are profound. Riverine species, especially migratory fish, rely on specific flow conditions for migration, spawning, and overall survival. Reduced flows can hinder the natural migration of fish, such as Atlantic salmon, which require adequate discharge to navigate upstream for spawning. Low-flow conditions can lead to increased sedimentation and higher water temperatures, both detrimental to aquatic organisms.

Abstraction also impacts groundwater levels, which can reduce base flows in rivers and affect wetland ecosystems. In regions like Eastern England, excessive groundwater abstraction lowers water levels and disrupts the ecological integrity of groundwater-dependent wetlands and chalk streams, further reducing aquatic biodiversity.

Climate change adds another layer of complexity, as it alters precipitation patterns and river flow regimes at local, regional and global scales. Although the UK has experienced increased rainfall in the past decades, climate models predict that river flows will likely decline in the future, making low-flow events more common and severe. This shift poses additional risks to aquatic habitats and species that are already under pressure from abstraction, and compounded by population growth and urban expansion, could have disastrous consequences for freshwater species, which are already declining faster than marine and land animals globally, and in the UK.

Maintaining natural flow regimes and managing abstraction rates are critical for protecting water quality and supporting aquatic biodiversity in the UK. Sustainable water management practices must consider both the ecological needs of species and the hydrological impacts of human interventions to ensure the health of riverine ecosystems. Current water policy in the UK, and the actions of private water companies are exuberating the threat posed to aquatic wildlife from changing river flow conditions due to climate change. How we plan to manage UK freshwater in the future must account for the threats posed by climate change and human activities, and inform our current understanding of the natural flow regimes which control UK rivers.

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