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Effects of flow variation on invertebrates and fish in riverine systems

Literature Review

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I. 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).

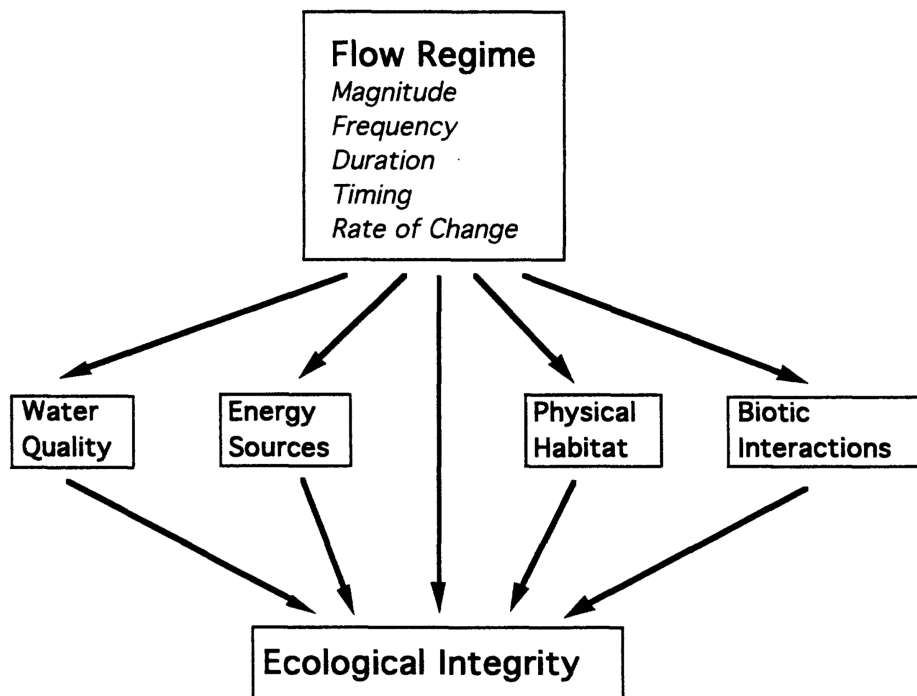


Figure 1: Five main components of flow regime. Modification of these has cascading effects on ecological integrity of rivers (Poff *et al.* 1997).

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 (Ward and Stanford, 1983, 1995; Poff *et al.*, 1997). 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 60% of the world's rivers have been diverted (Naiman *et al.*, 2002). In England and Wales, the latest available statistics for water abstraction indicate that in 2014 an estimated 13.2 billion cubic metres was abstracted from non-tidal surface and ground waters (DEFRA, 2016). 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.

II. Effects on 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. Cristina 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 elmids 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/m² would be added with every 10-day increase in flow duration and 1.9 taxa/m² 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.

III. Effects on 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 (Dunkley & Shearer, 1982; Baglinière *et al.*, 1990; Smith, 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. Hembre *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 m³ 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 m³ 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.* (2007) 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.* (2003) 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).

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. Páez *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).

IV. Current Policy

Abstraction

The UK Government is currently in process of reforming the system of water abstraction management in England and Wales. The proposals are in response to the consultation, 'making the most of every drop' (DEFRA, 2013). DEFRA have stated that the current system is not flexible or modern enough to respond to pressures on the environment given a growing population and climate change (DEFRA, 2016). The current system stems from the 1963 Water Resources Act, where abstractors were given licenses to take fixed

volumes of water. This had a greater focus on managing competing human demand rather than protecting the environment. Further amendments to this legislation were made in the 2003 Water Act, with more modern abstraction licenses requiring abstraction to be reduced when rivers are under pressure (hands off flows) (Environment Agency & Ofwat, 2011). This management has been proven ecologically inefficient as 13% of river water bodies in England and 4% in Wales are failing to support WFD Good Ecological Status (GES) due to abstraction. About 42% of groundwater bodies (pretty much every groundwater body in the south and east of England) and 6% in Wales have also been identified as failing Good Groundwater Quantitative Status (Environment Agency, 2013a). There is only a certain amount of recharge into a groundwater each year, and of this recharge, some is needed to support connected ecosystems. For good management, only that portion of the overall recharge not needed by the ecology can be abstracted - this is the sustainable resource, and the Directive limits abstraction to that quantity. Therefore, currently relevant environmental objectives of the Water Framework Directive are not being met in England and Wales.

The Coalition Government committed to reform of the water abstraction management system in England in the Natural Environment White Paper, published in June 2011, and then set out the proposed direction, principles and process for reform in the Water White Paper, Water for Life, in December 2011 with an aim to implement the new regime fully by the mid to late 2020's.

"We will introduce a reformed water abstraction regime resilient to the challenges of climate change and population growth and which will better protect the environment..." (DEFRA, 2011)

A large part of the reform is introducing 'permits' to replace the current license system. Permitted volumes will not be the same as current licensed volumes and will be based on abstractors past peak usage, meaning 'unused headroom' will be removed. The Environment Agency (EA) has also committed to a programme of measures, including completion of the Restoring Sustainable Abstraction (RSA) programme by 2020 as well as a list of actions to be prioritised over the next six years. These actions have two main themes:

- Ensuring new licenses do not pose a risk to the environment and evaluating/taking necessary action on existing licenses.
- Promoting efficient water use and reducing the amount of water taken from rivers and the ground.

The 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 one of the routes employed to deliver River Basin Management Planning Objectives, which are a required element of the European Water Framework Directive (WFD). These plans must be produced for each of the 11 River Basin Districts in England and Wales. They set out the actions necessary to ensure that inland and coastal waters achieve WFD 'good ecological status or potential' status and that deterioration from their current status does not occur (Environment Agency, 2013b). Since 2008, 200 licences in England have been changed and around 250 licences are still being investigated (DEFRA, 2016). There is also an aim to revoke licences that have been unused for more than four years by 2021.

V. Concluding Remarks

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. The abstraction reform has the potential to be a key driver in ensuring future removal of water from ecosystems is sustainable. However, time is of the essence with such a magnitude of water bodies in England and Wales currently failing WFD standards. It is essential that the RSA programme is completed as soon as possible to address existing damaging abstractions, only then can additional environmental damage be prevented and restoration initiated.

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VI. References

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