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Environmental flows from dams: the water framework directive

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The water framework directive (WFD) provides a template for sustainable water management across Europe. The WFD requires the development of procedures to ensure appropriate mitigation of anthropogenic impacts on river ecosystems resulting from water abstraction and impoundments. It is widely acknowledged that alterations to flow regime impact on riverine ecosystems. As a result, hydromorphology, which includes the hydrological regime, is embedded within the WFD as a supporting element to achieve good ecological status (GES). Environmental flow releases from impoundments such as reservoir dams will need to be implemented to mitigate impacts from their construction and operation. This paper outlines the process involved in the analysis of available scientific information and the development of guidance criteria for the setting of environmental flow release regimes for UK rivers. The paper describes two methods—developed by round table expert knowledge and discussions and supported by available data—for implementation of the WFD for rivers subject to impoundments. The first is a method for preliminary assessment of a water body to determine if it is likely to fail to achieve GES because of changes to the flow regime (indexed by simple flow regime statistics) in systems where appropriate biological assessment methods are limited or currently unavailable. The second is a method for defining an environmental flow regime release based on the requirements of riverine ecological communities and indicator organisms for basic elements (building blocks) of the natural flow regime.

I. BACKGROUND

The Brundtland report, *Our Common Future*,¹ and Agenda 21 of the 1992 United Nations Earth Summit in Rio² marked a turning point in modern thinking. A central principle of Agenda 21 and *Caring for the Earth*³ is that the lives of people and the environment are profoundly inter-linked. Ecosystem processes keep the planet fit for life, providing our food, air to breathe, medicines and much of what we call 'quality of life'.⁴ Successive international meetings (The Hague 2000, Johannesburg 2002,

Kyoto 2003) have highlighted the need to ensure the integrity of ecosystems through sustainable water resources management. It has been recognised that, whilst people need direct access to water to drink, grow food and support industry, providing water to the environment means using water indirectly through support ecosystem services.⁵

Sustainable water management thus requires knowledge of freshwater ecosystems and their interaction with hydrological processes. Many physical factors determine and influence the character of riverine ecosystems, including channel structure, temperature, oxygen, light, suspended sediment concentrations and river discharge/flow.⁶ Flow volume (discharge volume per unit time) is important in dilution of chemical elements and, through interactions with channel structure, in determining water depth and flow velocity.^{7,8} When combined with other factors (e.g. composition of bed material) they can collectively help define instream physical habitat.⁹ All elements of the flow regime may have a role in structuring a river ecosystem, including floods, average and low flows^{10–14} and all have a direct influence upon fish,^{15–18} macroinvertebrates^{19–21} and macrophytic plant communities^{22,23} as well as riparian and associated terrestrial ecosystems.²⁴

Impoundments such as dams are constructed for a range of purposes, including water supply management, hydropower generation and flood control. The objective of most impoundments is to divert water or store it temporarily for later use or release, thus smoothing out natural variations in flow regimes. Consequently, river flow regimes downstream of impoundments will be fundamentally different from their natural state. Given that large dams can effectively store all of the flow from the upstream catchment (though large floods may pass the spillway), the flow regime downstream may be totally controlled by operation of the impoundment. Active management is therefore required to generate an appropriate flow regime downstream in order to protect and maintain instream communities.^{25,26} This contrasts with direct abstraction from rivers, where many of the elements of the flow regime are left broadly untouched (e.g. timing, variability, high flows) and management is required to restrict the volume of water abstraction.²⁷

In the UK, 70% of reservoir dams release a constant discharge throughout the year.²⁸ The term 'compensation flow' is often used to describe this release of water as, historically, it was intended to protect the rights of existing mill owners downstream of new reservoirs. However, the term has been used for a variety of low-flow releases, including navigation and protection of river ecosystems. The average compensation flow of the 261 reservoirs for which data are available in the UK is 16% of the mean flow,²² which is similar to practice in many other countries such as France²⁹ and Brazil.³⁰ For some UK schemes, where recreational or commercial salmon fishing interests are high, flow releases are varied seasonally. For many other impoundments, ornamental lakes for example, no flow release structures have ever existed and, as a result, no water can pass them. A few UK dams release short-duration higher flows called freshets for a variety of reasons, including testing the dam's release structures or triggering fish migration (e.g. Roadford reservoir in Devon³¹).

For regulating reservoirs, the river is used to transmit water from the reservoir to the point of use. For example, on the River Dee (North Wales/Cheshire) the actual flow gauged in some places exceeds the natural flow for most of the time due to the release of water from upstream reservoirs for abstraction at downstream locations. In such cases the total annual volume of release may be equal to the natural flow volume, but the timing of flows will be different. Flow regimes downstream of other impoundments vary according to dam operation. For example, for dams containing turbines for hydroelectricity generation, flow releases may be intimately associated with peak energy demands, such as on the River Leven in Scotland.

This paper presents a summary of the methods developed for defining environmental flow releases from impoundments for UK rivers to support river ecosystems. The methods developed represent the output of expert workshops with the primary aim of achieving a broad consensus amongst UK river scientists regarding the most appropriate method for the definition of environmental flow releases.

2. FLOW REGIMES AND THE WATER FRAMEWORK DIRECTIVE

The water framework directive (WFD)³² provides a template for sustainable water management across Europe. It requires EU member states to achieve at least good ecological status (GES) in all natural water bodies and also to prevent deterioration in the status of any water body. Ecological status for rivers is based on biological quality elements (fisheries, macroinvertebrates and macrophytic plants) judged against reference conditions. Although hydromorphology is known to be important, it is considered as a supporting element. An alternative objective of good ecological potential (GEP) is applied where water bodies are designated as a heavily modified water body (HMWB) or artificial. HMWB designation³³ is applied if the following criteria hold.

- (a) The water body is likely to fail to achieve GES and the cause of failing to meet GES is substantial physical modification of the channel structure that is performing a function beneficial to society (e.g. flood protection, navigation).
- (b) The beneficial functions would be significantly compromised by restoration measures required to achieve GES and

if no other technically feasible and cost-effective alternative environmental option exists for delivering the function.

Water bodies downstream of impoundments may fail to achieve GES because of alterations to the flow regime. In such cases, the flow release regime would need to be altered to improve the ecological status. However, the UK interpretation of the WFD is that hydrological regime modification alone is not grounds for GES failure, because assessment of GES is based on biological criteria and HMWB designation only applies if the water body includes the dam/impoundment itself or the channel has been structurally modified. However, there is currently uncertainty as to whether existing tools for the assessment of the biological quality elements (many of which originate from the need to assess organics pollution impacts) are adequate for designation purposes at many sites.³⁴ The WFD makes provision for surrogates to be used if biological assessment methods or adequate biological data are not available. The UK Technical Advisory Committee (UKTAG) on the WFD has agreed that alteration to the river flow regime (part of the supporting hydromorphology element) can provide this surrogate at the test stage for GES. UKTAG concluded that two environmental flow methods were required to implement the WFD with regard to impoundment releases

- (a) a method to assess whether any water body is likely to fail to achieve GES (based on flow alteration as a surrogate for biological assessment)
- (b) a method to determine the environmental flow required downstream of an impoundment to meet GES or GEP (for HMWBs).

3. METHOD DEVELOPMENT

The UK has many good river scientists and, when compared with many other countries, good-quality and long-term hydrological and biological datasets. In many instances, UK scientists are therefore able to develop methods for river ecosystem assessment without the need to establish new programmes of research. However, many datasets present complex (or in some instances conflicting) messages and not all scientists agree on river ecosystem functioning or likely impacts of river flow alteration. Consequently, consensus building often involves long discussions, critical analysis of past data and methods, and ultimately a compromise of opinions.

Due to the short time available, the development of some of the methods needed to implement the WFD in the UK was defined by building consensus around expert knowledge rather than undertaking new fundamental research. For this study, expert knowledge was captured through two workshops attended by river scientists (including the authors of this paper) with a range of technical expertise including fish, macroinvertebrate and macrophyte biology, water resources management, geomorphology, hydrology and reservoir engineering. Despite broad acknowledgement by the experts that the magnitude, timing, duration and frequency of river flows were all important to river ecosystems, most felt that there was currently a lack of detailed scientific knowledge regarding the precise elements of the natural flow regime, which were viewed as essential. While it was possible to characterise the flow requirements of individual life stages of particular species at a local level, it was more difficult to reconcile the often conflicting needs of various different elements for a whole river ecosystem.

The participants of the expert knowledge workshops agreed that a method to assess whether any water body would be likely to fail to achieve GES should be based on a comparison of the post-impoundment flow regime with reference flow conditions. The reference conditions would normally be the natural flow regime, such as that recorded entering the impoundment or based on pre-impoundment conditions. In exceptional circumstances, an appropriate historical managed flow regime could be used, particularly if this has given rise to river communities or habitats designated under other legislation. An example of this is the River Kerry in northwest Scotland, which is impounded but designated under the EU habitats directive for populations of pearl mussel (*Margaritifera margaritifera*).

The workshop experts further agreed that the tool to determine the environmental flow required downstream of an impoundment should be based on ecological requirements of different communities/species/life stages, which may vary within and between rivers even for the same biological elements or communities. Even to achieve GEP, some basic elements of the natural regime need to be maintained—particularly floods at key times of the year with sufficient competence to move bed materials and stimulate salmonid fish migration, along with occasional larger floods required to maintain channel morphology. Where possible, constant flow releases need to be altered so that the flow regime fluctuates, for example to maintain inundation/drying of bryophytes. A natural low-flow regime should be maintained for a proportion of the time to protect against invasive species and prevent unnatural fish fry washout due to increased flows at times when low flows usually occur. Rates of changes in flow conditions on the declining limb of the hydrograph should not exceed threshold limits to prevent fish stranding.

When developing an environmental flow release scheme, there should be an assessment of the ability of the impoundment to make different releases; this may be limited or even impossible (where no release structures exist), especially for the release of high flows or frequently varying flow releases, which will often be constrained by small or inflexible release values. Pumped storage schemes in particular may also have limited opportunity to increase flow releases. However, water quality must also be considered along with water quantity since deep reservoirs (>10 m) tend to become thermally stratified in the summer with cooler, poorer quality water at depth.³⁵ Some water supply reservoirs have multiple level draw-off points and scour valves that can be used to mitigate the effects of water quality issues.

4. METHOD 1: GES ASSESSMENT THROUGH COMPARISON OF REFERENCE AND IMPOUNDED FLOW REGIMES

4.1. Theoretical background

Comparison of flow regimes is usually achieved by assessing differences in key parameters that characterise the regimes. However, flow regimes are complex (particularly from rivers on impermeable substrates that hold the majority of impoundments) and require a large number of parameters to describe them accurately. To act as a surrogate for biological assessment, any regime parameters adopted should be meaningful for the river ecosystem. Many river scientists consider that all elements of a flow regime, including magnitude, timing, frequency and

duration of floods, average and low flows are important for maintaining river ecosystems.⁹ The indicators of hydrologic alteration (IHA) scheme⁷ employs 32 hydrological parameters to characterise all aspects of flow regime. The parameters include magnitude of monthly flow conditions, magnitude and timing of annual extremes, frequency and duration of high- and low-flow pulses, plus the rate and frequency of changes in conditions. Whilst this detailed hydrological characterisation may represent the best approach currently available, it is only recently that the IHA parameters have been directly related to biological elements of ecosystems.¹⁷

The IHA approach was developed into the Dundee hydrological regime assessment method (DHRAM)³⁶ for assessing altered flow regimes in Scotland. This research demonstrated that one of the main limitations of the IHA approach is the long time series (>20 years) of flow data required to define individual parameters. In addition, it is frequently not possible to derive parameters for pre- and post-impoundment situations. Consequently, data need to be synthesised for one or other or both situations. Any method of synthesising data—such as naturalisation of post-impoundment data, hydrological modelling or transferring data from a ‘reference’ catchment with a natural flow regime—carries considerable uncertainty. Any parameter that measures significant differences between pre- and post-impoundment flow regimes will need to have large confidence bands to account for this uncertainty. An additional issue is that threshold levels of ‘ecologically significant change’ would need to be defined for all 32 IHA parameters, for which there is currently insufficient knowledge. However, many of the IHA parameters are correlated. For example, rivers draining large catchments will have large flows and small catchments will have small flows. Even when standardised (e.g. by division by long-term mean flow), if a high proportion of flow occurs in the winter, January and February flows will be highly positively correlated and January and August flows will be highly negatively correlated. Redundancy in the parameters³⁷ suggests that most flow regimes can be represented by just nine indices. The ecological validity of the redundancy method has been tested using 201 hydrological parameters from previous hydroecological studies for rivers in England in association with macroinvertebrate data.¹⁷ The results clearly demonstrated that a small number of indices (less than five) describe the dominant variation in the elements of a hydrological regime that influence macroinvertebrate communities.^{17,38}

4.2. Development

Flow regimes from 290 primarily upland catchments with a base flow index (ratio of surface to groundwater flow) less than 0.5 in England, Wales and Scotland were analysed. A high degree of correlation (redundancy) was apparent between the 32 IHA parameters, which suggested that UK flow regimes may be characterised adequately by ten parameters based on the original IHA parameters (Table 1). Given that the eventual assessment method would need to be applied rapidly to all water bodies in the UK, flow parameters would, in addition, need to be restricted to those that could be readily generated. Flow duration curves can be defined for all UK water bodies regardless of available flow data using Low Flows 2000³⁹ and its equivalent in Northern Ireland.⁴⁰ Further analysis of flow data from the 290 catchments showed strong correlations between all but one of the ten IHA parameters and the parameters generated by Low

Group	IHA full list ¹¹	IHA short list for UK WFD	Low Flows 2000 list ³⁹
1	December flow (m/s)	Mean January flow (m/s)	Mean January flow (m/s)
1	January flow(m/s)		
1	February flow (m/s)		
1	March flow (m/s)	Mean April flow (m/s)	Mean April flow (m/s)
1	April flow (m/s)		
1	May flow (m/s)		
1	June flow (m/s)	Mean July flow (m/s)	Mean July flow (m/s)
1	July flow (m/s)		
1	August flow (m/s)		
1	September flow (m/s)	Mean October flow (m/s)	Mean October flow (m/s)
1	October flow (m/s)		
1	November flow (m/s)		
2	1-day minimum flow	Mean of annual minimum	Q ₉₅ (m/s)
2	3-day minimum flow	7-day flow (m/s)	
2	7-day minimum flow		
2	30-day minimum flow		
2	90-day minimum flow		
2	1-day maximum flow	Mean of annual maximum	Q ₅ (m/s)
2	3-day maximum flow	7-day flow (m/s)	
2	7-day maximum flow		
2	30-day maximum flow		
2	90-day maximum flow		
3	Mean Julian day of minimum flow		
3	Mean Julian day of maximum flow		
4	Number of times flow rate rises above 25th flow percentile	Mean number of times per year flow exceeds Q ₂₅	Base flow index
4	Number of times flow rate drops below 75th flow percentile	Mean number of times per year flow is less than Q ₇₅	
4	Mean duration of high pulses	Mean number of flow rises	
4	Mean duration of low pulses		
5	Number of flow rises		
5	Number of flow falls		
5	Mean rise rate	Mean fall rate—mean different	Base flow index
5	Mean fall rate	between falling flows (m/s per day)	

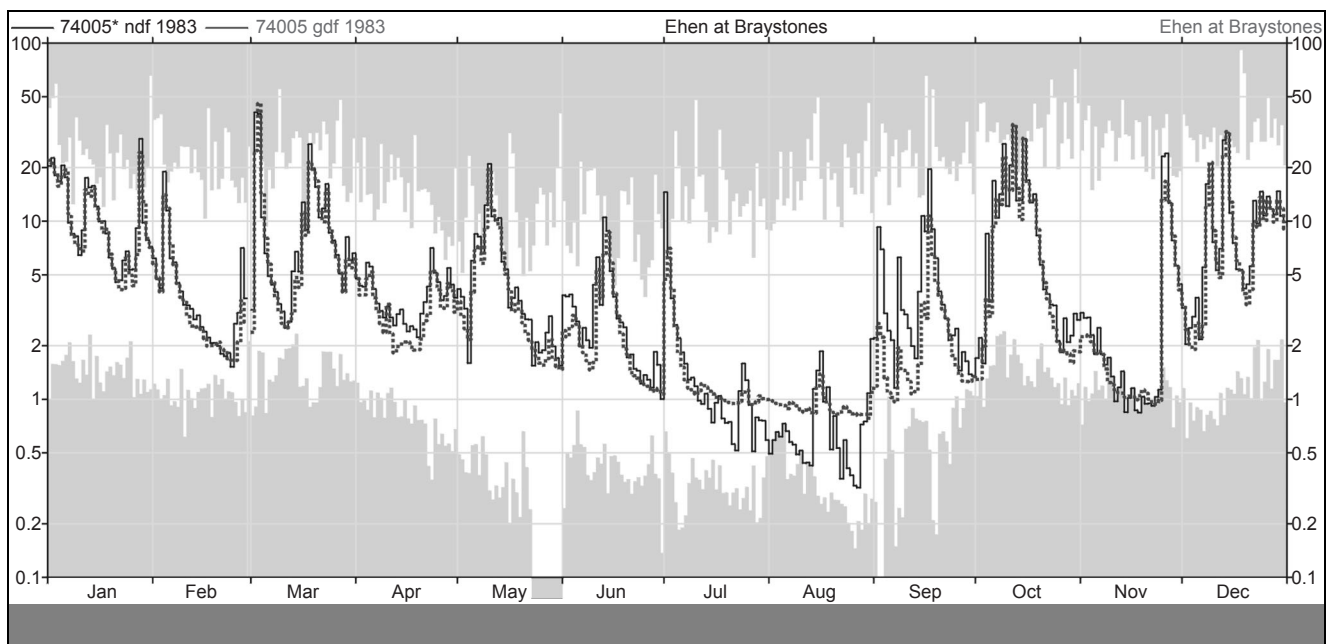
Table 1. Relationship between indicators of hydrologic alteration (IHA) and Low Flows 2000 statistics

Flows 2000 (Table 1). However, this analysis highlighted the fact that flow duration curves generated by Low Flows 2000 do not capture the sequencing of flows or rates of hydrograph change (rise and fall). Nevertheless, the seven parameters identified from Low Flows 2000 (Table 1)—mean January flow (m/s), mean April flow (m/s), mean July flow (m/s), mean October flow (m/s), Q₉₅ (m/s), Q₅ (m/s) and base flow index—provide the basis of a screening tool with which to assess the degree of modification of flow regimes to determine if GES is likely to be achieved. It was concluded that these Low Flows 2000 parameters would be used as the basic set on which to compare pre- and post-impoundment flow regimes. However, where observed flow time series are available, these should be used in preference to Low Flows 2000 to derive the statistics.

The primary aim of the method was to determine if an impounded flow regime is significantly different from pre- or un-impounded conditions. To implement this, threshold changes in flow parameters that define ecologically significant changes in the overall regime must be specified. Flow parameters will be subject to considerable sampling uncertainty due to natural variability in the flow regime, especially when generated from short time series (<10 yr). If the flow parameters have been generated by Low Flows 2000, particularly for impounded conditions, there will be further uncertainty as a result of model limitations. Setting the

thresholds is therefore a trade-off between being sufficiently low to capture altered flow regimes unlikely to achieve GES and sufficiently high to allow for natural hydrological variability and uncertainty in the estimated statistics. Clearly, setting the threshold at a very low level would lead to the conclusion that all impoundments have significant impacts, which would not identify those truly having a high risk of failing to meet GES.

To test the approach, Low Flows 2000 parameters were calculated for nine sites in the UK for which pre- and post-impoundment flow regime data were available. These sites were used to guide the development of thresholds indicating the likelihood that the flow regime would fail to achieve GES. Two example flow hydrographs are given in Figures 1 and 2. On the River Ehen (Cumbria, UK) (Figure 1) the impact from impoundment is clearly restricted to periods of low flow, with less than a 30% change in key parameters. In contrast, the River Derwent (Yorkshire, UK) (Figure 2) impoundment has an impact on all parts of the flow regime, with changes to most statistics of 40–60%. Given the paucity of relevant ecological data, it was decided that changes greater than 40% in any parameter represented a significant risk of failing to achieve GES. In theory, different thresholds may be appropriate for different parameters and for positive or negative differences (e.g. reductions in Q₉₅ may have a smaller threshold than increases in



Q_{95}). However, such variation could not be justified without considerably more detailed analysis of further sites.

5. METHOD 2: DESIGNING AN ENVIRONMENTAL FLOW RELEASE REGIME

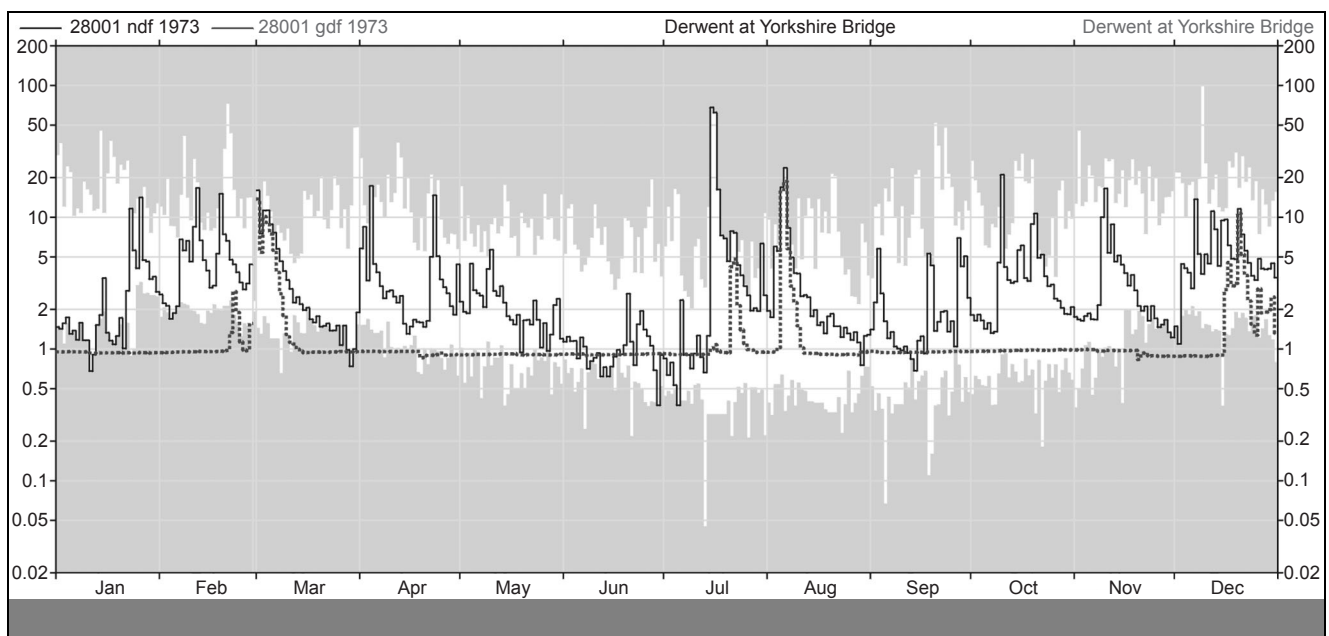
5.1. Theoretical background

Given that the method outlined in Section 4 to assess GES by comparison between reference and impounded flow regimes cannot be used directly to design a future operational environmental flow release regime, a second method was developed to design environmental flow releases to meet GES. A second method was required because the comparisons (outlined in method 1) are based on analysis of a long historical time series of flows whereas future environmental flow regime releases will need to be set in real time, i.e. according to current meteorological or hydrological conditions.

Perhaps the best known approach to setting environmental flow releases from impoundments is the building block methodology

(BBM) developed in South Africa.⁴¹ Its basic premise is that riverine communities and species are reliant on basic elements (building blocks) of the flow regime (Table 2). This suggests that a flow regime that would achieve GES could be constructed by combining building blocks following the ten steps in Table 3. The BBM revolves around expert opinion/knowledge, normally from physical scientists (such as hydrologists, hydrogeologists and geomorphologists) and biological scientists such as aquatic ecologists (e.g. macroinvertebrate, macrophyte and fish biologists). Such scientists follow a series of structured stages, assess available data and model outputs, and use their combined professional experience to come to a consensus on the building blocks of the flow regime. The BBM has a detailed manual for implementation,⁴² is presently used routinely in South Africa to comply with the 1998 Water Act⁴³ and has been applied to rivers with impoundments in Australia.⁴⁴

The natural flow paradigm⁸ assumes that the natural flow regime will provide the best possible conditions for ecosystem



Building block	Purpose
Low flows	Habitat for juveniles and prevention of invasive species
Maintenance flows	Stimulate species migration, spawning and dispersal
Freshets	Stimulate species migration, spawning and dispersal
Small floods	Sort river sediments, connect river and floodplain habitats
Large floods	Remove un-desired species, maintain channel structure and evolution

Table 2. Building block checklist

functioning. However, this may not be appropriate where channel geometry has been altered by historical anthropogenic activities. In the UK, many rivers have been subject to past engineering activities such as widening, deepening or straightening.⁴⁵ In such instances, hydraulic models can be used to set environmental flow releases in terms of depth and velocity needs of target species (as in the physical habitat simulation (Phabsim) approach.⁴⁶ In the BBM, scientific experts view the river (or photos of it) at different flows as a qualitative consideration of hydraulics.

GEP is an alternative objective to GES where the aforementioned HMWB conditions are met; hence, in the context of impoundments, it must take into account impoundment operation. Under current proposals from UKTAG, GEP would be achieved by applying best practice to the management of the impoundment (i.e. the practice that is applied to the best example of an ecologically similar water body with the same modifications in place). The drawback with this approach is that there is no consistency in ecological targets for GEP. Applying this would involve assessing similar impoundments on other rivers, how they are operated and how they influence the river ecosystem downstream. The process starts with consideration of the environmental flow release regime that will meet GES and assessing which elements are delivered by the best examples of other impoundments. Some elements of the release regime may not be required if the target species are maintained in the best examples without these elements. In addition, the release regime may therefore include rapid rises and falls in flow (hydropower dams) or flows higher than would naturally occur (regulating reservoirs).

5.2. Development

A literature search was undertaken to find information that could be used to construct a flow regime using the BBM

(Table 4⁴⁷). It is noteworthy that flow requirements varied considerably from site to site even for the same species, so these data are not necessarily appropriate for all river water bodies, which suggests that impoundments would need to be assessed on a structure-by-structure basis making the most of locally available information and expertise. Furthermore, suitable conditions are often given as required depth or velocity that results from the interaction of flow channel geometry and plant growth. However, some generic points gleaned from the literature were as follows.

- The requirements of salmonids, coarse fish, macrophytes and invertebrates can all be met in a regulated river system provided a suitably designed environmental flow release programme is implemented.
- Information to define building blocks of an environmental flow regime is available for many UK river ecosystems from the literature.
- Building blocks cannot be easily transferred between sites due to differences between rivers.
- Spring flows from some impoundments may be currently adequate to facilitate fish migration.
- Freshets are particularly important in summer in rivers with low base flow or in dry years; in some rivers they may also enhance fish migration.
- Entry of salmonid fish into headwater tributaries is particularly flow dependent (October–November).
- During the salmonid spawning period, elevated flows are required to permit upstream migration of fish, distribute spawning fish throughout the river system, ensure reeds are well oxygenated and prevent excessive fine sediment deposition. During and subsequent to spawning, elevated flows also aid adult salmon migrating downstream.
- Immediately after emergence from eggs, rapid increases in

1	Define a natural flow regime for the water body in terms of daily discharge time series for a representative 10-yr period
2	Analyse the flow regime in terms of the magnitude, frequency and duration of high, medium and low flows
3	Assemble biological survey data or use models for the water body to determine the expected biological communities and life stages for the river in reference condition
4	Determine flow regime requirements for each species/community and life stage using published literature
5	Verify the requirements by identifying elements of the flow regime in the historical record
6	Check that flow release elements will deliver other important variables such as water quality, including temperature and sediment load
7	Define the building blocks
8	Record results in an environmental flow release regime table
9	Add up individual flow needs to assess overall implications for water resources
10	Repeat the analysis for each water body ensuring that environmental flow upstream are sufficient to meet needs downstream

Table 3. Ten steps required to define an environmental flow release regime using the BBM

Timing and related conditions		Flow preferences
Salmonids River entry	Flood/high tide Night time Water temperature 5–17°C (measured at 09h00) Sufficiently well oxygenated river flow	Elevated river flows
Upstream migration	Spring run, Feb–May Summer run, Jun–Aug Autumn run, Sept–Nov Exact timings may vary between rivers and sub-catchments due to genetic differences	Required flows for salmon migration vary annually and seasonally Adequate base flows may occur during spring In high base flow, rivers a high background migration may occur during summer that is unrelated to river flow In rivers with a flashy flow regime or in a dry year, summer flow increases are likely to initiate migration Increased migration is likely to occur in most rivers during periods of elevated flow
Spawning	In upland and northern rivers spawning typically occurs between October and December In lowland or southern rivers spawning may take place anytime between November and March	During this period extreme flow events capable of mobilising gravel must not occur or eggs will be damaged or washed away Flows need to be sufficiently high to ensure a wide distribution of spawning and connectivity between various habitats during spawning to allow dispersal
Downstream adult migration	November to May	Elevated flows may help
Post-emergence	March–May	Low, stable flow is desirable, with no rapid increases/decreases
Dispersal of smolts	April–July	Periods of elevated flow
Coarse fish Migration and spawning	February–March	Rheophilic cyprinids need good flows to migrate and spawn
Pike, stickleback and dace	February–April	No extreme high or low flows. Extreme high flows may wash out/displace or damage eggs and larval fish. Extreme low flows may result in stranding of fish in backwaters/marginal areas or drying out of eggs Pike and sticklebacks spawn in flooded backwaters during late winter/early spring floods Sustained and elevated flows are needed to ensure connectivity of backwaters/marginal areas and to avoid fish stranding during flow recessions
Late-spawning (e.g. chub, barbel and sea lamprey)	May – July	No extreme high or low flows. Extreme high flows may wash out/displace or damage eggs and larval fish. Extreme low flows may result in stranding of fish in backwaters/marginal areas or drying out of eggs
Macrophytes	March – June	A velocity of 0.1 m/s is often quoted as being critical for the growth of <i>Ranunculus</i> . Preferred water depths depend on species but have been observed to range from 0–150 cm. At velocities in excess of 1m/s, macrophytes are rare Periods of elevated flow are likely to clean macrophyte stands of old growth
Invertebrates	Invertebrates tend to recover quickly after floods and droughts if refuges are available in channel substrate or marginal habitats Invertebrates are less sensitive to hydrological extremes in natural channels owing to the greater abundance of refugia	A seasonally variable flow regime Density may increase with the frequency of floods greater than 3 times median flow. Invertebrates may be displaced or killed by unnaturally rapid changes in flow and temperature

Table 4. Example summary information on ecosystem flow needs⁴⁷

flows are thought to be detrimental to emerging salmonid fry.

- (i) Variable flows throughout the year (without extremes) will ensure a healthy riverine environment and diverse macro-invertebrate and macrophyte assemblages.
- (j) Ecologically effective flow increases may be achieved by reducing compensation flow gradually and then rapidly increasing releases back to normal compensation flow level.
- (k) Periodic high flows (greater than 2 yr return period) are required to maintain channel geometry and, with it, habitat diversity.

The BBM flow regime shown in Figure 2 shows only one year and the implication is that the same releases are made each year. In natural riverine systems, the flow regime varies considerably, temporally varying from days, months, years to decades. It is evident that some flow requirements may be contradictory, for example high flows are required for river-floodplain connectivity to benefit the spawning of some species while at the same time flows need to be limited to protect juveniles of other species from potential washout from the system. This is consistent with biological records for natural systems that show that, due to variations in rainfall, some years are good for some species and poor for others, e.g. one year may be good for salmonids while another is good for coarse fisheries.

Consequently, it may be necessary to design several BBM flow release regimes that are used on a rotating basis. For example, one flow release regime for 'normal' rainfall years, when a suite of river ecosystem functions and processes can be expected (termed a maintenance flow in the BBM), and a different regime for drought years when all flow needs cannot be met (designed for species survival, although some may not be able to reproduce successfully (e.g. during low flows associated with droughts)). With increasingly powerful opportunities of forecasting meteorological and hydrological conditions, it may be possible to predict which flow release regime should be applied in real time.

An alternative strategy is to define environmental flow release regimes in relation to the natural flow regime. The release regime is then implemented by real-time determination of the natural regime by monitoring of a reference catchment that could be upstream of the impoundment or on a similar nearby tributary. Clearly this requires telemetry and automated operation of release structures. However, it incorporates natural variability and hydrological signals from a natural regime. Partial use of these ideas could involve setting releases according to past rainfall or reservoir levels combined with hydrological models.

Application of method 2 has thus far assumed that the impoundment has the ability to make any environmental flow releases specified by BBM. However, limitations may include operational requirements of the impoundment, flood storage, water supply provision or hydropower generation and releases for subsequent abstraction downstream. In some instances, release structures are small or non-existent and as a result it may not be possible to implement a new flow regime. In addition, release structures may take water from only one level in the reservoir; thus, although the environmental flow release regime may be deliverable volumetrically, its quality (particu-

larly dissolved oxygen and water temperature) may not be appropriate.

6. CONCLUSION

The methods for the design of environmental flow release from dams described in this paper are based on approaches developed in the USA (IHA) and South Africa (BBM) in the late 1990s and thus have undergone significant trialling and testing over the past ten years. Although our scientific understanding of links between river flow and river ecosystems has improved,^{38,48} the concepts used still underpin the latest thinking on environmental flows. For example, the new framework for developing regional environmental flow standards developed by a world-wide group of experts⁴⁹ incorporates the use of baseline flow regimes and flow alteration-ecological response relationships that are key elements in IHA and BBM.

The development of both methods employed up-to-date knowledge of the flow regime requirements of river ecosystems and the likely impacts of flow alterations upon aquatic ecosystems. Nevertheless, it also highlighted that our knowledge is currently limited. In particular, the threshold levels of flow changes that are likely to have significant ecosystem impacts are uncertain and the compound ecosystem impacts of flow and water quality are poorly understood.

An adaptive management approach to environmental flows is recommended in which monitoring, testing and modification of the flow regime are undertaken to ensure that a water body is achieving its target status. The science of environmental flows is still in its infancy and further research is required, particularly on the use of pilot environmental flow releases to analyse ecosystem response and assess the appropriateness of the parameters and thresholds used in the two methods.

Implementation of the WFD involves application of sustainable water management, which requires methods to ensure adequate mitigation of the negative impacts on river ecosystems created by impoundments. A multi-disciplinary team was able to develop methods for

- (a) initial assessments of whether a water body is likely to fail to meet GES because of changes to the flow regime (indexed by simple flow regime statistics); such an can be used where appropriate biological assessment tools or biological data are not available
- (b) defining an environmental flow release regime based on the requirements of riverine species for basic elements (building blocks) of the natural flow regime.

While the hydromorphological requirements of different species and life stages cannot always be quantified, it is widely acknowledged that flow regime is important and cannot be ignored. In the absence of adequate ecological data and understanding, the BBM offers a preliminary opportunity to consider and improve hydrological conditions below impoundments for the benefit of various aspects of freshwater ecosystems.

Many UK dams currently release little flow. This has had significant negative impacts on downstream ecosystems that would not now meet the ecological status required under the

WFD or more general aspirations of sustainable water management. The methods described in this paper provide support to water managers on the allocation of water resources between direct use (for water supply, agriculture, power generation and industry) and indirect use through the provision of ecosystem services. However, some significant barriers exist to implementation of more sustainable and ecologically appropriate flow regimes. For example

- (a) some dams do not have appropriate structures to make flow releases and necessary installations would be expensive
- (b) the operating rules of many major UK dams are governed by acts of parliament; these would need to be repealed
- (c) major infrastructure, industry and communities have evolved based on direct use of water from reservoirs; the development of new resources to compensate for loss of available water would be expensive.

Achieving sustainable water management is thus likely to cause high short-term costs and disruption to people's lives.

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