Final report **Project WFD82**

GUIDANCE ON ENVIRONMENTAL FLOW RELEASES FROM IMPOUNDMENTS TO IMPLEMENT THE WATER FRAMEWORK DIRECTIVE

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Use of the report

The development of UK-wide classification methods and environmental standards that aim to meet the requirements of the Water Framework Directive (WFD) is being sponsored by UK Technical Advisory Group (UKTAG) for WFD on behalf its member and partners.

This technical document has been developed through a collaborative project, managed and facilitated by SNIFFER and has involved the members and partners of UKTAG. It provides background information to support the ongoing development of the standards and classification methods.

Whilst this document is considered to represent the best available scientific information and expert opinion available at the stage of completion of the report, it does not necessarily represent the final or policy positions of UKTAG or any of its partner agencies.

Executive summary

Implementation of the EC Water Framework Directive (WFD) requires the development of procedures to ensure the adequate mitigation of the negative impacts created by water abstraction and impoundments. Flow regime releases from impoundments, such as reservoir dams, will be included in the licence conditions to allow the proper mitigation of negative impacts caused by their construction and operation.

This report provides general background on WFD and the potential impacts on the river ecosystem together with guidance on the setting of environmental flow release regimes from impoundments. The guidance is aimed at environmental regulators, dam operators and other stakeholders and it is equally applicable in all UK member countries.

The guidance is divided into three parts:

1. A step by step guide, supported by a flow chart, that describes the process of defining the target river ecosystem status, setting flow regime releases from impoundments and monitoring their effectiveness in achieving that status. The steps include revision of the flow release regime according to impoundment capability, purpose and designation.

2. A method for initial assessment of whether a water body is likely to fail to meet Good Ecological Status because of changes to the flow regime (indexed by simple flow regime statistics), which can be used where appropriate biological assessment tools are not adequate. Annex A provides some examples of pre and post impoundment flow regimes from the UK that illustrate the degree of alteration to the flow regime hydrographs and to key flow regime statistics.

3. A procedure for defining an environmental flow regime release based on the requirements of riverine species for basic elements (building blocks) of the natural flow regime. Three levels of assessment (desk-top flow assessment, hydraulic assessment and biological assessment) provide a risk-based approach in which greater investment in the assessment yields lower uncertainty in results. In all three levels, assessments should be carried out by a team of experts that normally includes physical scientists, such as a hydrologist, hydrogeologist and geomorphologist, and biological scientists, such as an macro-invertebrate ecologist, a freshwater botanist and a fish biologist.

All guidance is provided within the limits of current knowledge of the flow regime requirements of river ecosystems and the likely impacts of flow alterations of ecosystem status.

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Project advisor panel

As an addition to the role of the Steering Group, a key element of this project was the establishment of an independent advisory panel of river specialists. The panel members provided direction, guidance, comments and intellectual stimulation through attendance at project workshops and written technical input. The work of the panel formed a scientific peer review of the project. Panel members were very supportive of the work undertaken and this guidance was developed by consensus. However, all details of the guidance do not necessarily fully represent the scientific views of any individual member.

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1. Background

The implementation of the EC Water Framework Directive (WFD) requires the development of procedures to ensure the adequate mitigation of the negative impacts created by water abstraction and impoundments. Flow releases from impoundments, such as reservoir dams, in the form of compensation flows and freshets will be included in the licence conditions to allow the proper mitigation of negative impacts caused by their construction and operation. The SNIFFER project WFD82 was established to produce guidance on the setting of compensation flows and freshets from impoundments. The guidance is aimed at environmental regulators, dam operators and other stakeholders and it is equally applicable in all UK member countries.

2. Impacts of impoundments on the hydrological regime

Impoundments, such as dams and their reservoirs, are constructed for a range of purposes, including water supply, hydropower generation and flood control, but the overall objective is the same; namely to store water temporarily for later use or release, thus smoothing out natural variations in the hydrological regime. Consequently, river flow regimes downstream of an impoundment will be different from their natural state. Given that most reservoirs can, for short periods, store all the flow from the upstream catchment (though large floods may pass the spillway), the flow regime downstream can in many cases be totally controlled by operation of the impoundment. Active management is therefore required to generate a flow regime downstream. This contrasts with abstraction, where many of the elements of the flow regime are left broadly untouched (*e.g.* timing, variability, high flows) and the aim is to manage by restricting abstraction.

Some 70% of reservoirs in the UK release a constant discharge through the year, (Gustard *et al*., 1987) although some also release short duration higher flows (freshets). The term compensation flow is often used for this release of water; as historically it was intended protect the rights of existing mill owners downstream of new reservoirs. However, the term has become adopted for all constant low flow releases for other purposes, such as navigation and protection of the river ecosystem. The average compensation flow release of the 261 reservoirs for which data were available (Gustard *et al*., 1987) was 16% of the mean flow (18.6% if reservoirs with zero flow release are excluded). Some schemes, particularly where fishing interests were dominant, had seasonal variations in released flow usually with winter discharge being half or one third of the summer flow. For many other impoundments, such as ornamental lakes, no flow release structures exist. Freshets are released from some reservoirs for a variety of reasons, including testing the dam's release structures or triggering fish migration in the river downstream.

The situation is shown conceptually in Figure 1 for a water supply reservoir, where the flow regime downstream of the impoundment is constant for long periods with occasional high flows, either when flood water passes the spillway or when freshets are released. Clearly, the actual flow regime below any dam will vary greatly from this hypothetical situation depending on inflows to the reservoir, demands on the reservoir water and outlet operating rules. It is noteworthy that during low flow periods, a constant release may exceed the natural flow. However, for water supply reservoirs, the total volume of flow release will be less than the natural flow (by the amount of reservoir off-take and some additional evaporation and seepage). For regulating reservoirs, the river is used to transmit water from the reservoir to the point of use. On the River Dee, for example, the actual flow exceeds the natural flow most of the time as water is released from upstream reservoirs for abstraction at downstream towns. In such cases the total annual volume of release may be equal to the natural flow volume, but the timing of different flows will be different.

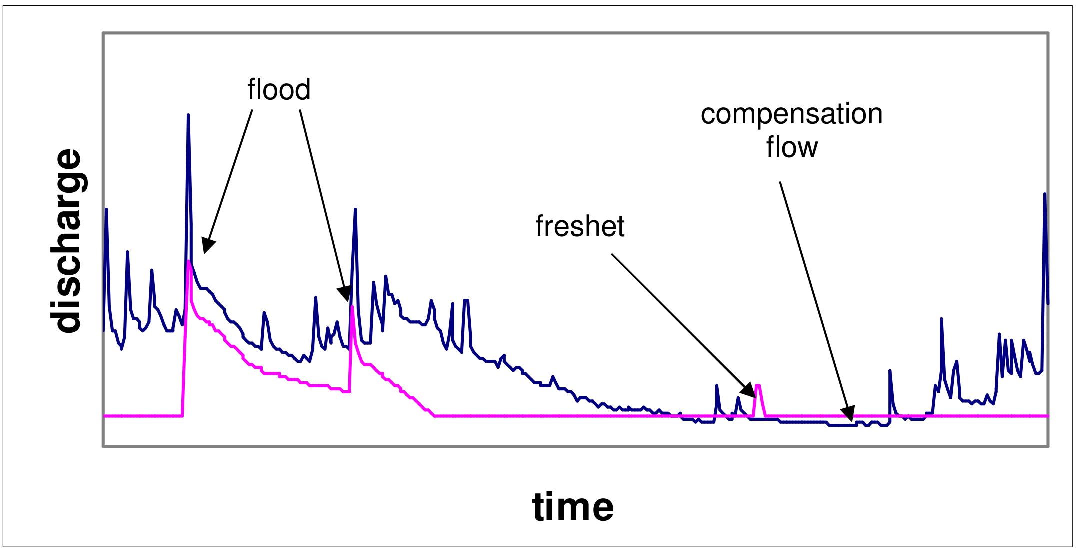

Figure 1. Natural (blue) and regulated (pink) flow regimes downstream of a hypothetical water supply reservoir.

For hydropower, if one ignores low head run of river schemes, there are broadly two possible situations. Either there is a large dam across the river with turbines in situ, or there is take-off from a dam (which could be small or large) via a penstock to turbines. In either case there may be more or less focus on hydro-peaking (meeting peak electricity demand). In the first case, assuming the flow released is largely driven by power demand, there may be large, rapid fluctuations (ramping) during the day (Figure 2). The annual volume of released water is likely to be similar to the natural flow, but flows rates will be very different. In the second case, operation may be similar, but there will be a bypassed section of river between the offtake and return of water. The regime downstream of the return will fluctuate according to demand, the regime downstream of the upstream structure will be influenced more in the manner of a water supply reservoir, with a compensation flow release to the bypassed section of river.

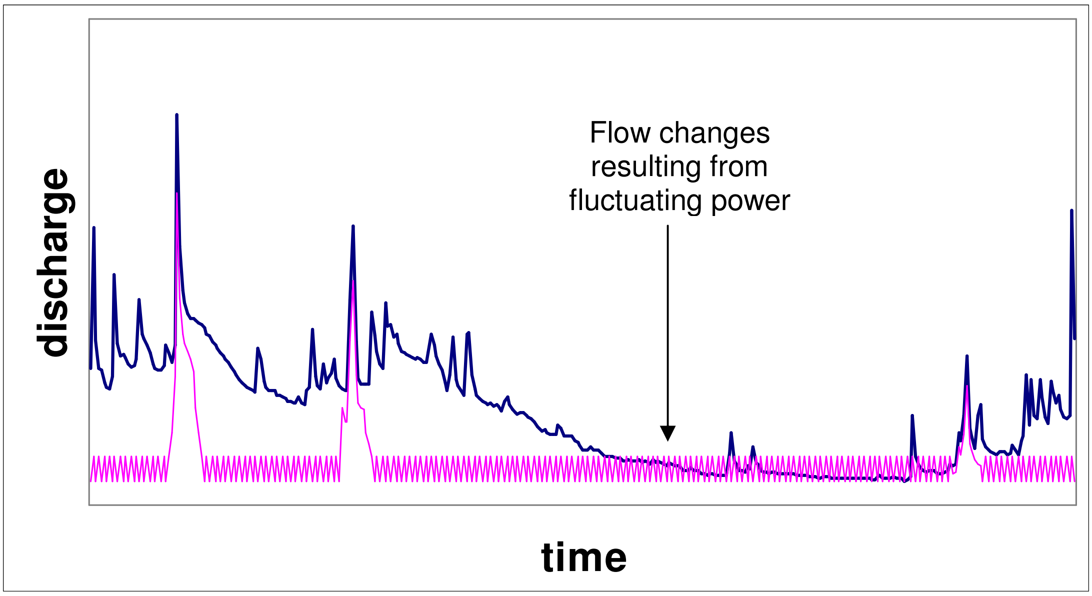

Figure 2. Natural (blue) and regulated (pink) flow regime downstream of a hypothetical hydropower dam.

3. Flow regimes and the Water Framework Directive

The Water Framework Directive (European Commission, 2000) requires member states to achieve at least Good Ecological Status (GES) in all water bodies, and also to prevent deterioration in the status of any water body, with High Ecological Status (HES) as the target for pristine sites. Exceptions are permitted for water bodies designated as a Heavily Modified (HMWB), where the target is Good Ecological Potential (GEP). The designation as a HMWB is undertaken through a three stage test:

(1) the water body is likely to fail to achieve GES based on biological quality elements (or an estimate of what GES may be based on current knowledge) judged against reference conditions. If it fails, the water body is termed a 'provisional' HMWB.

(2) the cause of failing to meet GES is substantial physical modification of the channel structure (not other pressures, such as water quality)

(3) the benefits of the physical modification cannot be delivered by another environmentally better option, and it would be disproportionately costly to finding other means to provide the purpose of the impoundment plus restoration or mitigation of the water body.

For test stage (1) for GES, there is currently uncertainty as to whether existing tools for assessment of biological quality elements are adequate for provisional designation purposes. Under WFD, if biological assessment is not possible, surrogates can be used. The UKTAG has agreed that alteration to the river flow regime can provide this surrogate. Appropriate flows are known to be a basic requirement to achieve a healthy river (Richter *et al.,* 1997; Poff *et al.,* 1997) and the science of environmental flows has developed to provide methods to define the water needs of river ecosystems (Dunbar and Acreman, 2001). Furthermore, most significant flow regulation also results in changes to the river ecosystem downstream of an impoundment due to changes in physical habitat and alterations in erosion and sediment supply rates.

Under these criteria, the UK interpretation of the WFD is that hydrological modification alone would not be grounds for designation as a HMWB; it only supports provisional designation and merely as a surrogate for biological alteration. Thus, although the flow regime may be significantly altered in a water body downstream of an impoundment, unless this water body contains the dam itself or the channel has been physically modified, it may not be designated as a HMWB.

Table 1 Water body designations, their target status and criteria

Designation			**target status**	
Type	**criteria**	**surrogate criteria**	**target**	**criteria**
"normal"			High Ecological Status	biology hydrology chemistry
			Good Ecological Status	biology chemistry
Heavily modified	biology morphology economics	hydrology	Good Ecological Potential	biology chemistry
Artificial				

Once the designation has been established (*e.g.* HMWB or normal water body) the water body can be fully assessed as to whether it meets its target status (*e.g.* HES, GES or GEP). The test is based on assessment of biological (fish, macro-invertebrates and macrophytic plants) and hydromorphological quality elements of the river and not river flows *per se*. Only in the case of HES is the naturalness of the river flow regime explicitly part of the status assessment. Water body designations, their target status and criteria are summarised in Table 1. If a water body fails to meet its target status, the causes need to be addressed. Alterations to the flow regime by impoundments upstream, either in the water body itself, or an upstream water body that feeds it, may well be a primary cause of target failure and thus the flow release regime would need to be altered to improve the ecological status.

The WFD 48 project (Acreman *et al*, 2006), which focused on setting environmental standards for water resources (maximum abstraction levels that would still allow achievement of GES), concluded that the conventional mode of operating dams, with constant releases (compensations flows) for long periods would not achieve GES because natural hydrological variability is an important element for maintaining healthy freshwater ecosystems. Even to achieve GEP, some basic elements of the natural regime need to be maintained; particularly floods competent to move gravel and stimulate migration are required at key times of the year and occasional larger floods to maintain channel form. Where possible, constant flow releases need to be altered so that the flow regime fluctuates, for example to maintain inundation/drying of bryophytes. Despite broad knowledge that the magnitude, timing, duration and frequency of flows are all important, there is a lack of scientific knowledge of precisely which elements of the natural flow regime are essential and which are not.

Whilst the concept of variable environmental releases, related to some natural reference catchment, may be desirable, most impoundments have very limited ability to release high flows to order or to vary flow releases easily. Thus implementing environmental flows may have major financial consequences if there is a need for refitting release structures. In addition, increased overall volumes of releases would reduce the reservoir yield, which may require developing additional water resources (at £3 million/Ml/d) that could have greater overall environmental impacts. Deep reservoirs (>10 m) tend to stratify in summer with cooler, poorer quality water at depth. Most, but not all, water supply reservoirs have multiple level draw-off points and scour valves, but many have no electrical power; relying on hand operation of valves when visited, generally once every two or three days. Pumped storage schemes may also have limited opportunity to increase flow releases.

This WFD 82 project was focused on three issues:
(1) providing an overall framework as a step-by-step guide for implementation of WFD to impoundments (secton 5)
(2) definition of a method for assessing whether a water body might not achieve Good Ecological Status (and hence becomes provisional heavily modified) on the basis of hydrological alteration, as a surrogate for biological assessment (section 6)
(3) provision of best practice guidance for identifying the elements of the flow regime needed to achieve either GES or GEP as an optimum river ecosystem under operational and other constraints (section 7).

It is important to note that all guidance is based on available knowledge and needs to be fully tested to determine whether it is precautionary or provides insufficient protection of river ecosystems. The guidance is only guidance and should be replaced by at-site analysis where data are available.

4. Principles of environment flow release regimes from impoundments

The following principles provide a basis for defining environmental flow regimes downstream of impoundments.

General and overall objectives

- Clearly identify objectives, particularly whether specific species or general river ecosystem health should be the target
- WFD objectives are related to reference conditions, hydrological management may have created artificially high diversity or numbers
- Climate change may alter reference conditions

Hydrology

- Mimic natural flow variability that would exist, except on a smaller scale and release flows to coincide with natural flow events, e.g. enhancing natural spates from side streams.
- Allow year to year variation in flows, such that the regime is optimum for different species in different years.
- Flow releases should maintain lateral connectivity between river and floodplain ecosystems
- Natural low flow regime should be maintained for proportion of time to protect from invasive species and prevent fry washout
- Elevated flows at times of natural low flows can be ecologically damaging
- Match ramping rates to pre-scheme flow regime to prevent stranding
- Release floods to maintain channel geomorphology and landscape evolution
- Accept that overall there will be less total volume of water released from an impoundment than would occur in downstream than under natural conditions, such that releases need to be optimised for where it is most beneficial
- Other impacts (such as land use) may mean that the un-impounded flow regime is not necessarily natural

Biology

- Flow releases regimes should be based on ecological requirements of different communities/species/life stages, which may vary between rivers even for the same biological communities
- Habitat modifications may be needed to work with flow release regime

Infrastructure

- Where possible build environmental flows around current release pattern procedures, such as floods, freshets and compensation flows
- Draw-off structures may be required at different levels to achieve good water quality releases

Monitoring and data

- Monitor release regimes and river ecosystem response and employ adaptive management
- Assess whether guidance is precautionary or provides insufficient protection of river ecosystems
- Make best use of existing data

Water quality and sediment

- Temperature is as important as flow and should match reference conditions
- Water from different levels within the reservoir can be different in temperature, pH and nutrient level

- Sediment-free flow releases may cause erosion downstream

<u>Reservoir levels</u>

- Consider impacts of changing reservoir levels on reservoir ecosystem when designing flow releases

<u>Expert team</u>

- Environmental flow assessments should undertaken by a multi-disciplinary team including biologists, hydrologists, hydraulic engineers, chemists and geomorphologist

5. A step-by-step guide to setting flow releases from impoundments

Setting and implementing environmental flow releases from impoundments involves many different aspects of management, including policy level objective setting, technical definition of flow needs for ecosystem support and financial considerations of the costs of mitigation measures.

The flow chart shown in Figure 3 describes the process of defining the target river ecosystem status, setting flow regime releases from impoundments and monitoring their effectiveness in achieving that status.

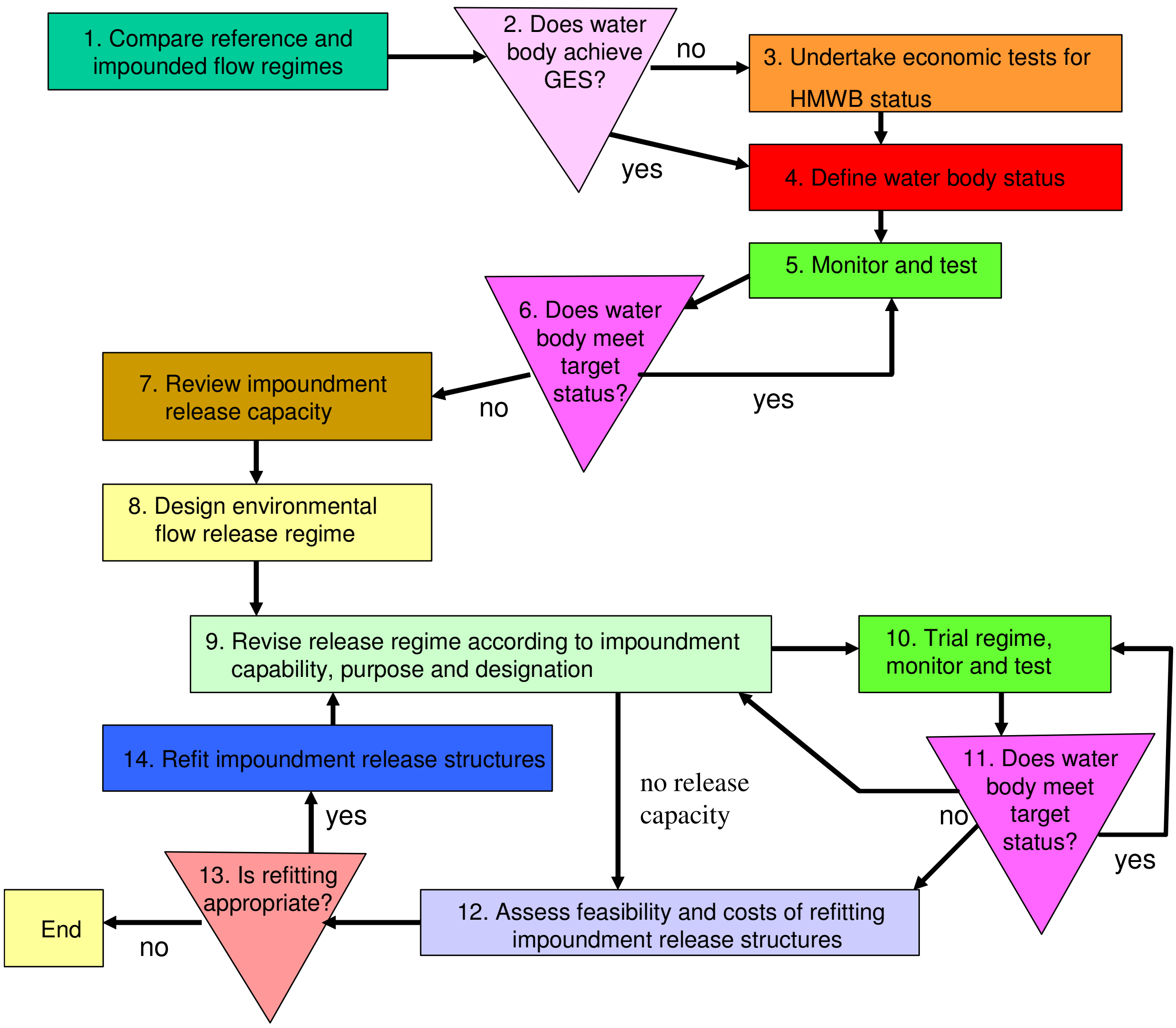

Figure 3 Flow chart for setting flow releases from impoundments

STEP 1 Compare reference and impounded flow regimes

Step 1 is an assessment of whether the water body is likely to fail to achieve GES (or an estimate of what GES may be based on current knowledge) judged against reference conditions. It involves comparing the historical (actual) biology of the river below the impoundment with reference biological conditions. Where biological data are inadequate, hydrological conditions can be used as a surrogate and the historical flow regime is compared with reference flow conditions. The reference conditions will normally be the natural flow regime, such as that entering the impounded reservoir or recorded before impoundment construction. In exceptional circumstances an appropriate historical managed flow regime may be used, particularly if this has given rise to river communities or habitats that are designated under other legislation (*e.g.* Habitats Directive). If there is a flow gauging station upstream or downstream of the impoundment, these could be used to synthesise historical and naturalised flow regimes. In many cases, both the actual and reference flow regimes will need to be estimated by modelling. This could be achieved either using a deterministic rainfall-runoff model (*e.g.* CERF) or by transposition of flows from a reference catchment to produce continuous time series of flows, or a statistical model (*e.g*. Low Flows 2000) to produce flow statistics. It should be noted that there can be considerable uncertainty whatever method is used for estimating flows, and this uncertainty should be taken into account when determining the degree of hydrological impact. The water level regime of the impounded reservoir will be assessed as part of the consideration of that water body and is not included here.

For some impoundments, the impact will only be in the water body immediate downstream, such as where modifications to the flow regime are small and a major unregulated tributary joins a short distance below. However, the downstream impact may extend to the tidal limit or estuary, especially in the case of regulating reservoirs.

STEP 2 Decision – does the water body achieve GES?

The analysis undertaken in Step 1 will provide a measure of the degree of alteration of the river ecosystem downstream of an impoundment. In Step 2, the degree of alteration is assessed to decide if the water body is likely to fail to meet GES and thus should be a provisional HMWB. In this step it must also be confirmed that the cause of failing to meet GES is physical modification of the channel structure (not other pressures such as water quality).

If the degree of alteration means that it is likely to fail to meet GES (*i.e.,* greater than the specified standard) due to physical modifications, the water body is designated provisional HMWB and step 3 is undertaken to decide on final designation.

If the degree of alteration is less than the standard, step 3 is not required and step 4 can be undertaken to decide on designation.

STEP 3 Undertake economic analysis

Biological/hydromorphological assessment (or its surrogate, hydrological alteration) of a water body against reference conditions is only a first step to designation. In Step 3, water bodies that are provisional HMWBs are subjected to economic analysis. The benefits of current modifications are compared with the costs of providing other means to achieve the purpose of the impoundment, plus restoration or mitigation of the water body, which may include decommissioning of the impoundment or changing the flow release regime. This analysis includes defining the purpose of the impoundment, such as its role in supplying water, managing floods or generating electricity.

STEP 4 Define water body status

If the analysis in Step 3 shows that restoration or mitigation would be disproportionately costly, then the water body can be designated as HMWB and is required to meet good ecological potential (GEP). GEP requires achieving an ecological status similar to the best examples of similar river ecosystems with the same modifications in place; *i.e.* with best practice applied to management of the water body.

If the analysis in Step 3 shows that the economic benefits are greater than the costs other means of achieving the purpose of the impoundment plus the costs of restoration or mitigation, then the water body will not be designated as HMWB and the water body should meet good ecological status (GES), which will require a flow regime and associated water quality that will support the river ecosystem in slight deviation from reference conditions. In some cases, this may involve decommissioning or significantly altering the impoundment.

STEP 5 Monitor and test

In this step the monitoring scheme is applied to the river water body downstream of the impoundment to assess its status.

A clear requirement of the WFD is not only to achieve the objective of GES or GEP, but also to prevent deterioration from that status. As the status is dependent upon assessing the characteristics of the water body against those of reference biological conditions, a biological monitoring programme will be required. Monitoring should define current conditions as a baseline and future change against the baseline.

The type of monitoring will depend on the characterisation of reference conditions against which the status of the water body will be assessed. The monitoring scheme will define the frequency of samples to be taken, the animal and plant communities that should be present and their expected abundance plus the hydromorphological conditions that should be met.

It is important to recall that if the test for designation of the water body is based on hydrological change, as a surrogate of biological change (step 1), it important that testing in step 5 is biological. This will test not only whether the water body itself meets it target status, but will also test the thresholds for designation employed in step 2.

STEP 6 Decision – does the water body meet the target status?

In step 6, a decision needs to be made as to whether the water body meets the target status set for it (*e.g.* GES or GEP). If it does, the water body needs to be monitored to ensure that there is no deterioration, so eventually steps 5 and 6 will be repeated.

If the status is not met and there is good reason to believe that this is due to an inadequate flow release regime from an upstream impoundment, step 7 and 8 should be implemented.

STEP 7 Review impoundment release capability

Step 7 involves assessing the ability of the impoundment to make different releases and thus to generate various elements of the natural flow regime required to meet its target status. The impoundment's ability may be limited, especially the releasing of high flows or varying flow releases frequently because of, for example, small or inflexible release values. Pumped storage schemes may also have limited opportunity to increase flow releases. Water quality should be considered along with water quantity since deep reservoirs (>10 m) tend to stratify in summer with cooler, poorer quality water at depth. Most, but not all, water supply reservoirs have multiple level draw-off points and scour valves, which can be used to mitigate these effects. If the impoundment has no current release capacity (such as, for example, with many ornamental lakes) steps 10 and 11 may by-passed initially (see step 9).

In some cases, flow releases could be linked in real-time to flows on a reference catchment, such as the inflow to the reservoir. However, many impoundments have no electrical power and rely on hand operation of valves when visited, generally once every two or three days.

Assessment of the impoundment in Step 7 will be particularly important for water bodies designated as HMWBs that are required to meet GEP. This is because the reference condition for GEP is the best practice example of a water body with the same modifications *i.e*, a similar impoundment. The assessment will help define the same modification in place within the water body.

Step 7 also involves assessing the implications of altering the current release pattern. Releases may need to be increased or reduced (or both, at different times) to meet the desired status, which may alter the reservoir yield (in the case of water supply), energy production (in the case of hydropower) or flood storage (in the case of flood management). The assessment should consider the purposes of the impoundment (determined in step 3) and the need for additional water resources development that could have greater overall environmental impacts. It should also consider potential impacts on the lake ecosystem, such as changes to level fluctuations.

STEP 8 Design environmental flow release regime to meet designation

This step involves the design of a flow regime release from the impoundment that will maintain the downstream river and upstream lake water bodies in designated status condition (GES or GEP).

Defining the extent of impact in Step 1 enables the types of habitat and likely associated fish, plant, macroinvertebrate and algal communities that might be present or should be present if the water bodies downstream were not impacted.

For GES, the key activity of this step is to determine which elements of the natural flow regime (floods, freshets, medium flows, low flows) are important for the river ecosystem downstream. The selected elements need to be specified in terms of their magnitude, duration, timing and frequency and combined to define an ecological flow release. Ideally this will be achieved from knowledge of the species that are present (or should be present) and their flow and associated habitat requirements in terms of, for example, temperature, sediment concentrations and oxygen levels. Any potential impact of releases on the reservoir ecosystem upstream should also be assessed.

For GEP, a flow regime is required that will achieving an ecological status similar to the best examples of similar reference river ecosystems with the same modifications in place; *i.e.* with best practice applied to management of the water body. Given that river ecosystem may vary even between similar rivers, it may not be appropriate simply to transfer the flow release regime from the reference site. Defining the flow release regime will involve an iterative process of determining the elements of the natural flow regime are important for the river ecosystem downstream and adapting this according to what release regime is possible at the reference impounded site.

STEP 9 Revise the flow release regime according to impoundment capability, purpose and designation

This step involves assessing the environmental flow release regime (defined in step 8) against the current ability of the impoundment to make releases (defined step 7). This will determine the feasibility of implementing the ecological flow regime with the current impoundment infrastructure and operating rules. It should be accepted that the following constraints are likely to apply:

- water supply reservoirs: overall annual volume of flow release will be less than natural
- hydropower reservoirs: outflows may fluctuate according to power demand
- regulating reservoirs: flow may be higher than natural for much of the time
- flood management reservoirs: downstream flood flows will be lower, flows after a natural flood recession will be higher

It should also be accepted that the flow regime may not be natural even without the impoundment due, for example, to land-use change. Judicial operation of the reservoir may in some cases help mitigate such impacts.

Particular attention should be given to the potential flexibility in the environmental flow release regime, for example whether it can be achieved to an acceptable degree by limited operating rules, such as constant compensation flows for long periods interrupted by occasional freshets, or whether the flow needs to vary over shorter time periods; seasonally, monthly or daily.

Some impoundments, such as many impounding ornamental lakes will may have no current release capacity. In this case, no trial can be taken in step 10 and step 12 needs to taken next to assess the feasibility of re-fitting the impoundment.

Consideration may need to given to ensuring that the reservoir ecosystem is not negatively impacted, such that it fails to meet any target status, due to changes in reservoir level cause by flow regime releases.

STEP 10 Trial regime, monitor and test

Once an environmental flow release regime has been defined that is feasible to implement and that is likely to achieve the desired ecological status, it can be trialled and its impact monitored and tested using the scheme designed in step 2. This testing should include water quality and sediment associated with the releases as well as there volumetric quantity.

STEP 11 Decision – does the water body meet the target status?

In step 11 a decision needs to be made as to whether the water body meets the target status (*e.g.* GES or GEP) with the flow release regime that the impoundment can currently deliver. If it does, the water body needs to be monitored to ensure that no deterioration occurs, so

eventually steps 10 and 11 will be repeated. If the status is not met and there is good reason to believe that this is due to an inadequate flow release regime, changes to the regime need to be made. Two courses of action are possible.
(i) if failure is caused by limitations of the impoundment infrastructure precluding the release regime from being implemented effectively, step 12 should be followed.
(ii) if failure is caused by inadequacies in the release regime itself, step 9 can be repeated.

STEP 12 Assess feasibility and costs of refitting impoundment release structures

Most impoundment structures have a limited ability to make variable releases, especially high flows. Thus it is likely many impoundments will not be able to make suitable releases to achieve the desired status (GES or GEP), particularly if the required release regime involves generating high flows and frequent changes to outlet structure setting.

In step 12, designs need to be made for refitting the impoundment with suitable structures to make the required releases. In the case of HMWBs, particular attention should be given to mimicking the release structures on reference impoundments that meet GEP *i.e.* those considered to be best management practice. If the water body downstream is not a HMWB, decommissioning of the impoundment should be considered.

Refitting or decommissioning an impoundment may be extremely expensive and the WFD provides the potential for derogation on grounds of disproportionate cost (Article 4(5)), this is separate from the HMWB designation process.

STEP 13 Decision – is refitting appropriate?

In step 13 a decision needs to be made as to whether refitting the impoundment to meet the status criteria (GES or GEP) is feasible and is not disproportionately costly. If it is feasible and not disproportionately costly the re-fitting can go ahead and step 14 can be implemented.

If it is not feasible to refit the impoundment or it is disproportionately costly the status may be derogated and no further action is taken at this stage.

STEP 14 Refit impoundment release structures

If the proposals to refit the impoundment with appropriate release structures (defined in step 12) are feasible and not disproportionately costly (decided in step 13), the re-fitting can go ahead. If re-fitting is too costly, a further derogation can be sought from the European Commission and the process ends.

Once the impoundment has been refitted, step 9 needs to be undertaken again to revise the release regime according to the new capability, with subsequent monitoring and testing in step 10.

6. Ecological assessment through comparison of reference and impounded flow regimes

6.1 Introduction

In step 1 of the flow chart (Figure 3), an assessment of a water body is required to determine if it is likely to fail to achieve GES. This will determine whether the water body should be considered provisionally as a HMWB. The determination is based on whether the hydrological flow regime has been altered significantly from its reference conditions (often the natural flow regime). This is a surrogate for comparison of current biological elements against reference conditions for which suitable tools do not exist at present.

The flow regime of any river system is complex (particularly flow regimes on impermeable substrates which hold the majority of impoundments) and requires a large number of parameters to describe it accurately. To act as a surrogate for biological assessment, any regime parameters adopted should be meaningful for the river ecosystem. However, many ecologists consider that all elements of a flow regime, including magnitude, timing, frequency and duration of floods, average and low flows (Poff *et al*, 1997; Junk *et al.*, 1989) are important, thus obviating the need to justify selection of specific elements ecologically. Richter *et al.* (1996) proposed a suite of 'Indicators of Hydrologic Alteration' (IHA), which are designed to assess the degree of artificial influence on river flow regimes. The IHA employs 32 hydrological parameters to characterise statistical attributes of the flow regime relevant to the biological functioning of a river. 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.

A quantitative appraisal of the hydrological alteration caused by an impoundment can be achieved by comparing the post-impounded (impounded) flow regime time-series with the pre-impounded (un-impounded) flow regime time-series. Here pre-impoundment situation could be characterised by flow data from upstream of the impoundment. Black *et al.* (2000; 2005) used the IHA approach to develop the Dundee Hydrological Regime Assessment Method (DHRAM). The main drawback with this approach is the long time series (>10 years) of flow data required to define the IHA parameters are not available for the pre- and post-situations for most impoundments. 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 or transferring data from a 'reference' catchment with a natural flow regime, will have considerable uncertainty. Any statistic that measures significant difference between pre- and post-impoundment flow regimes will need to have large confidence bands to account for this uncertainty; perhaps why DHRAM has not been widely implemented.

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 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 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. Olden and Poff (2003) undertook a redundancy analysis and suggested that most flow regimes can be represented by just 9 indices. The ecological validity of the redundancy method was tested for rivers in England using ecological data (Monk *et al.* 2006, 2007) and it was shown that a small number of indices can be used to describe dominant statistical variation in the ecologically relevant elements of the hydrological regime.

Other measures of the flow regime, such as flow duration curves, can be defined with relatively low uncertainty using Low Flows 2000. However, the flow duration curve does not capture all elements of the flow regime, especially sequencing of flows or rates of hydrograph rise and fall. Nevertheless, this provides a potential means of defining a screening tool to assessment the degree of modification of flow regimes to determine if GES is likely to be achieved.

6.2 Measures of hydrological alteration

Studies of flow regimes from 290 upland catchments (BFI <0.5) in England, Wales and Scotland have shown high degrees of correlation between the 32 IHA parameters (Booker and Acreman, 2006). These suggest that UK flow regimes may be characterised adequately by 10 parameters (Table 2).

Table 2 Relationship between IHA parameters and Low Flows 2000 statistics

Group	IHA full list	IHA short list	Low Flows 2000 list
1	December flow (m^{3}s^{-1})	mean January flow (m^{3}s^{-1})	mean January flow (m^{3}s^{-1})
1	January flow(m^{3}s^{-1})		
1	February flow (m^{3}s^{-1})		
1	March flow (m^{3}s^{-1})	mean April flow (m^{3}s^{-1})	mean April flow (m^{3}s^{-1})
1	April flow (m^{3}s^{-1})		
1	May flow (m^{3}s^{-1})		
1	June flow (m^{3}s^{-1})	mean July flow (m^{3}s^{-1})	mean July flow (m^{3}s^{-1})
1	July flow (m^{3}s^{-1})		
1	August flow (m^{3}s^{-1})		
1	September flow (m^{3}s^{-1})	mean October flow (m^{3}s^{-1})	mean October flow (m^{3}s^{-1})
1	October flow (m^{3}s^{-1})		
1	November flow (m^{3}s^{-1})		
2	1 day minimum flow	mean of annual minimum 7 day flow (m^{3}s^{-1})	Q_{95} (m^{3}s^{-1})
2	3 day minimum flow		
2	7 day minimum flow		
2	30 day minimum flow		
2	90 day minimum flow		
2	1 day maximum flow	mean of annual maximum 7 day flow (m^{3}s^{-1})	Q_5 (m^{3}s^{-1})
2	3 day maximum flow		
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}	BFI
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 between falling flows (m^{3}s^{-1}d^{-1})	BFI
5	mean fall rate		

These studies also showed strong correlations between all but one of these parameters and statistics generated by Low Flows 2000 (Table 2). Given that Low Flows 2000 statistics can be generated for all sites in the UK, regardless of available flow data, these should be used as the base set on which to compare pre- and post-impoundment flow regimes. Where flow time series are available, they should be used to calculate the statistics.

6.3 Defining impounded and un-impounded flow regime statistics

The method for defining impounded and un-impoundment flow regime statistics can be undertaken in a range of ways, summarised in Table 3. In most cases daily flow data would be appropriate. Finer resolution data would be required to assess the impact of flows that fluctuating rapidly, *i.e.* within day.

Table 3 Summary of methods to produce flow regime statistics

	method of calculating statistics	
	impounded situation	un-impounded situation
Impoundment and un-impounded flow data available	• use recorded impounded flow data	• use recorded un-impounded flow data
Only impoundment flow data available	• use recorded impounded flow data	• use Low Flows 2000
Only un-impounded data available	• use impoundment model and un-impounded flow data or • use impoundment model within Low Flows 2000	• use recorded un-impounded flow data
No data available	• use impoundment model within Low Flows 2000	• use Low Flows 2000

Using recorded flow data to generate statistics

Where a river flow gauging station exists downstream of an impoundment, the historical daily flow data series can be used to define the impounded regime. In some cases this record may extend back before the river was impounded; in which case the pre-impoundment record period can be used as the pre-impoundment condition.

Where a flow gauging station exists upstream of the impoundment, data from this can be used as the un-impounded flow regime and the impounded regime can be defined by routing the flows through a model of the impoundment[1] (*e.g.* ref?).

It is noteworthy, that the historical and upstream flow regimes may not necessarily represent natural conditions if, for example, the catchment contains major urban areas or the river is subject to abstraction pressures, in which case the flow data may need to be naturalised (Goodwin *et al.,* 2005).

[1] Work undertake by CEH and Wallingford Hydrosolutions for the Environment Agency to support initial characterisation within England and Wales under the Water Framework Directive

Using Low Flows 2000 to generate un-impounded flow statistics

Low Flows 2000 can be used to generate natural flow regime statistics for any location on the river network in the UK (Young *et al.,* 2002). These can be used to characterise the pre-impoundment situation.

Using Low Flows 2000 to generating impounded flow statistics

Where no data exist for the impounded conditions, Low Flows 2000 can be used with data on the reservoir characteristics to generate flow statistics for the impounded situation.

Using other reservoir models to generate impounded flow statistics

For many impoundments, models exist that are able to transform upstream flow regime data into a flow regime downstream of the impounded. Where both the model and data are available, this approach should be used.

6.4 Thresholds of alteration

The aim of the assessment is to determine if the impounded flow regime is significantly different from un-impounded conditions. To implement this, some threshold change in the flow statistics must be specified that defines a biologically significant change in the overall flow regime. Flow statistics will be subject to considerable sampling uncertainty due to natural variability in the flow regime, especially when generated from short records (<10 years). If the flow statistics 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 a trade-off between the thresholds being sufficiently low to capture any altered flow regimes that are unlikely to achieve GES and sufficiently high to allow for natural hydrological variability and uncertainty in the estimated statistics. Clearly, setting the threshold very low would lead to the conclusion that all impoundments have a significant impact, which would not identify those having low risk of failing GES.

Hydrological regime indices were calculated for nine sites in England and Scotland where pre and post impoundment flow regime data were available (Hannaford and Acreman, 2007). These indices were used to guide the development of thresholds indicating the likelihood that the flow regime would fail GES. The flow hydrographs are presented in Annex A; they show that impoundments can have widely different impacts on the flow regime. The impoundment on the River Ehen has a minor impact with less than a 30% change in key statistics (Table A2). In contrast, the Shell Brook impoundment has a significant impact, reducing Q_{95} by 75% and increasing mean July flow by 118%. In general, the Low Flows 200 statistics reflect the wider set, apart from the rapid changes in flow of the Leven caused by the impoundment, which are indexed only by the Richter statistics.

In theory, different thresholds may be appropriate for different statistics and for positive or negative differences (*e.g.* reductions in Q_{95} may have a smaller threshold than increases in Q_{95}). However, such variation cannot be justified without considerably more analysis.

Table 4 provides initial thresholds for the flow regime statistics. If the different between any statistics for the pre- and post-impounded flow regimes is outside of the threshold, the impounded flow regime falls into the stated category.

Table 4 Thresholds of hydrological alteration to meet GES

Low Flows 2000 statistics mean January flow (m^3s^{-1}) mean April flow (m^3s^{-1}) mean July flow (m^3s^{-1}) mean October flow (m^3s^{-1}) Q_{95} (m^3s^{-1}) Q_5 (m^3s^{-1}) BFI	**Low risk of failing GES if alteration less than 40% in all statistics**	**Medium risk of failing GES if alteration greater than 40 but less than 80% in any statistic**	**High risk of failing GES if alteration greater than 80% in any statistic**

7. Designing an environmental flow release regime

7.1 Introduction

The comparison of flow regimes approach described in Section 4 enables flow regimes that are unlikely to achieve GES to be identified based on past flow records. However, the same approach cannot be used directly to design a future operational environmental flow release regime. This is because the comparison is based on statistical analysis of a long (>10 year) historical time series of flows, whereas the future environmental flow regime releases will needs to be made in real time.

This section of the guidance is aimed at designing environmental flow releases to meet GES (Step 7 in the flow chart on page 5; Figure 3). GEP is considered as a compromise between GES and the practicalities of impoundment operation. GEP is the ecological status achieved in the best examples of water bodies with the same modifications in place; *i.e.* with best practice applied to management of the impoundment. Achieving GEP (Step 9 in Figure 3) is addressed in sub-section 5.5.

Perhaps the best known approach to setting environmental flow releases from impoundments is the Building Block Methodology (BBM) developed in South Africa (Tharme and King, 1998; King *et al.* 2000). Its basic premise is that riverine species are reliant on basic elements (building blocks) of the flow regime (Table 5).

Table 5 Building block check-list

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

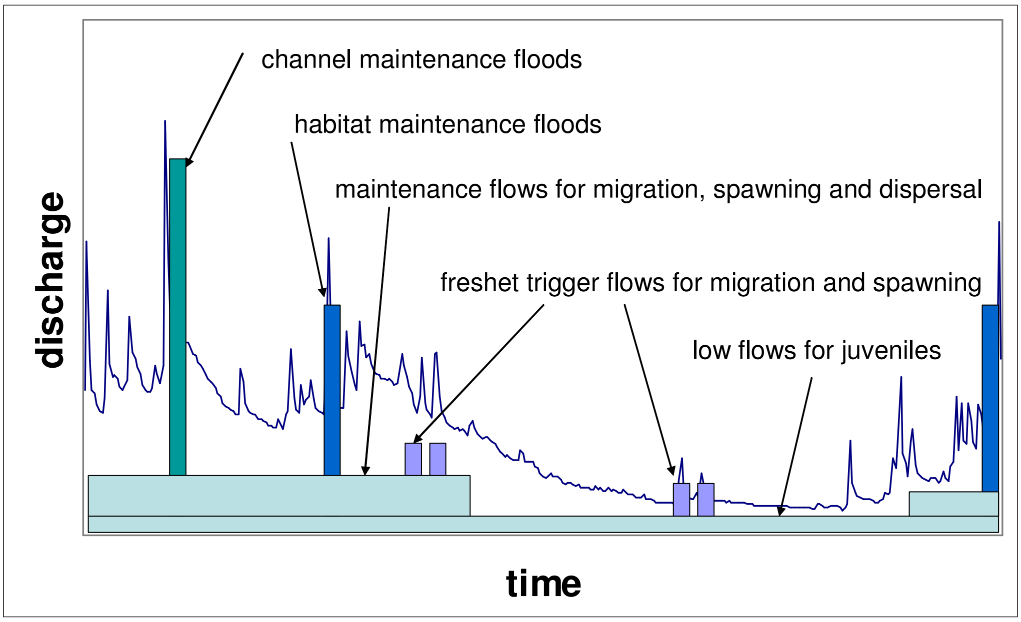

Figure 4 Building block Methodology – conceptual approach

A flow regime for ecosystem maintenance can, thus, be constructed by combining these building blocks (Figure 4). The BBM revolves around a team of experts that normally includes physical scientists, such as a hydrologist, hydrogeologist and geomorphologist, and biological scientists, such as an aquatic entomologist, a botanist and a fish biologist. They 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 (King *et al.* 2000), is presently used routinely in South Africa to comply with the 1998 Water Act (DWAF, 1999) and has been applied in Australia (Arthington and Long 1997, 1998).

7.2 Key ecologically relevant flow regime elements for UK rivers

Table 6 provides some example information available from published sources. The information comes primarily from individual studies, in which the results vary from site to site. Consequently, this information is not necessarily appropriate for all river water bodies. The companion volume to this guidance note is the literature review undertaken for WFD 82 (Old and Acreman, 2006); this contains a summary of information from many scientific studies.

Table 6 Example summary information on flow needs

	Timing and related conditions	Flow needs
salmonids: river entry	Flood/High tide Night time Water temperature between 5° and 17°C (measured at 09h00). Sufficiently well oxygenated river flow	Elevated river flows
Salmonids: 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 baseflow 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 migrations. Increased migration is likely to occur in most rivers during periods of elevated flow.
Salmonids: spawning	In upland and northern rivers spawning 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
Salmonids: downstream adult migration	Migration November to May	Elevated flows may help
Salmonids: post emergence	March – May	Low, stable flow is necessary with no rapid increases/decreases
Salmonids: dispersal of parr	April – July	Periods of elevated flow

Coarse fish: migration and spawning	February-March	Rheophilic cyprinids need good flows to migrate and spawn
Coarse fish: 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 coarse fish (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 *Ranunculus*. Preferred water depths depend on species but have been observed to range from 0 to 150cm. 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 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.

Some generic points gleaned from the literature are:

- 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 program is implemented
- information to define building blocks of an environmental flow regime is available for many UK river ecosystems from literature
- differences between rivers means that building blocks cannot be easily transferred
- spring flows from some impoundments may be adequate for fish migration.
- freshets are particularly important in summer in rivers with low baseflow or in dry years. In other rivers they may also enhance migration.
- entry of fish into headwater tributaries is particularly flow dependent (October-November).
- during the spawning period elevated flows are required to ensure redds are well oxygenated and fine sediment is not deposited. During and subsequent to spawning elevated flows also aid adult salmon in migrating downstream.
- immediately after emergence rapid increases in flows should not occur as newly emerged fry are vulnerable.

- after emergence elevated flows are needed to distribute parr downstream. This helps to ensure that sufficient habitat is available.
- variable flows throughout the year (without extremes) will ensure a healthy riverine environment, and natural invertebrate fauna and macrophyte assemblage.
- Ecologically effective elevated flows may be achieved in some cases by reducing compensation flow gradually and then rapidly increasing releases back to normal compensation flow level
- flood flows are required to maintain channel geometry and to remove undesirable species

7.3 Hierarchical approach

For application to UK river water bodies, three levels of BBM can be envisaged (Table 7). This provides a risk-based approach (Faulkner *et al*., 2002) in which greater investment in the assessment yields lower uncertainty in results. In all three approaches, assessments should be carried out by a team of experts that normally includes physical scientists, such as a hydrologist, hydrogeologist and geomorphologist, and biological scientists, such as an macro-invertebrate ecologist, a freshwater botanist and a fish biologist.

Table 7 Three levels of assessment for BBM application

Approach	Advantages	Disadvantages
desk-top flow assessment	Rapid, does not require field visit, low investment	gives only indicative results, high uncertainty
hydraulic assessment	works with physical habitat, medium investment	requires hydraulic measurements, medium uncertainty
biological assessment	works with biological data from the water body, low uncertainty	requires biological monitoring, high investment

Desk-top flow assessment

This is an approach in which environmental flow releases from impoundments are considered from available data. The literature on ecological response to flow regimes provides some examples of flow requirements for different river species (Old and Acreman, 2006). However, many of these are specific to the river in question, due to, for example, genetic differences in salmon populations. Nevertheless, if used with these caveats in mind, literature sources can be used as a first approximation to the types of flow regime that would be most appropriate to different rivers. Where possible the literature should be used conjunction with flow data and biological data from fish, invertebrate and macrophyte surveys that characterise the river hydrologically and biologically in its reference (natural) condition. In the absence of biological surveys, expected biota can be estimated from RIVPACS (Wright et al, 2000) for macro-invertebrates, Cowx *et al* (2004) and FAME for fish and Holmes *et al* (1998) for macrophytes.

The steps required to define an environmental flow regime are provided in Table 8. Most steps are generic, but some vary according to the assessment approach followed.

Hydraulic assessment

This approach recognises that flow itself is not directly driving the usability of a river for different species and biotic communities. Rather it is the hydraulic properties of the river, such as depth, velocity and wetted bed area. Furthermore, many of the species/community requirements are defined in terms of depth and velocity. Although full hydraulic model simulation of river reaches requires considerable site data collection, estimates of the distributions of depth and velocity can be derived from catchment variables or simple site measurements: see for example results of the RAPHSA project

Biological assessment

This approach recognises that all river ecosystems are unique and that there is considerable uncertainty in transferring flow requirements of species and communities from one river to another. This may result, for example, from genetic differences between rivers. This assessment level required biological research but yields results with lowest uncertainty.

Table 8 Steps required to define an environmental flow release regime for different assessment levels

	assessment level		
step	**desk top**	**hydraulic**	**biological**
1	Define a natural flow regime for the water body in terms of daily discharge time series for a representative 10 year 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		Quantify relationships between flow and hydraulic parameters using hydraulic models	
5	Determine flow regime requirements for each species/community and life stage using published literature	Determine physical habitat requirements of each species/community and life stage using published literature	Undertake biological research including fish tagging to determine flow regime and physical habitat requirements of each species/community and life stage
6	Verify the requirements by identifying elements of the flow regime in the historical record		
7	Check that flow release elements will deliver other important variables such as water quality, including temperature and sediment load.		
8	Define the Building Blocks		
9	Record the results in the environmental flow release regime table (Annex B)		
10	Add up the individual flow needs to assess overall implications for water resources		
11	Repeat the analysis for each water body ensuring that environmental flow upstream are sufficient to meet needs downstream		

7.4 Defining a long-term environmental flow release regime

The assessment approaches specified in Section 7.3 produce a flow regime through a year based on a set of Building Blocks as depicted in Figure 4. However, Figure 4 only shows one year and the implication is that the same releases are made each year. In natural systems, the flow regime varies considerably over different time periods including days, months, years and decades. It is evident that some flow requirements may be contradictory, such that high flows are required for river-floodplain connectivity that benefits some species at the same time that flows need to be limited for protection of juveniles of another species. This is consistent with the biological records for natural systems, which show that some years are good for some species and poor for others, *e.g.* one year may be good for salmon another is good for coarse fish. Consequently, it may be necessary to design several flow release regimes that are used on a rotating basis.

A further issue is that inflows to the impoundment may be insufficient to make the required releases in any year. Implementation can involve defining one flow release regime for 'normal' rainfall years, when the suite of river ecosystem functions and processes can be expected (termed a maintenance flow), and a different one for drought years when all flow needs cannot be met, which is designed for species survival such that some species may not breed (a drought flow).

An alternative strategy is to define environmental flow release regimes in terms of proportions of the natural flow regime. The release regime is then implemented by real-time determination of the natural regime by monitoring of a reference catchment, which could be upstream of the reservoir. Clearly this is a hi-tech solution requiring telemetry and automated operation of release structures. However, it incorporates natural variability and hydrological signals from a natural regime. Partial use of this idea could involve setting releases according to past rainfall or reservoir levels.

7.5 Implementation

Once an environmental flow release regime aimed at GES has been agreed by the river scientists, Step 7 in the flow chart (Figure 3, page 5), it needs to be revised or adapted where appropriate (step 9). Revision may be necessary for three reasons:

- the water body is designated as HMWB and only needs to meet GEP
- the impoundment cannot make the releases as currently specified
- monitoring and testing (Steps 10 and 11) have shown that the release regime is failing to achieve the required status even when modifications to the impoundment release structures have been made (Step 14).

Achieving Good Ecological Potential

GEP requires achieving an ecological status similar to the best examples of similar river ecosystems with the same modifications in place; *i.e.* with best practice applied to management of the water body. This involves assessing similar impoundments on other rivers, how they are operated and how they impact on 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 the other impoundments. Some elements of the release regime may be dropped if the target species are maintained in the best examples without these elements.

Best practice will involve a compromise between achieving the original objectives of the impoundment (hydropower generation, water supply, flood management), whilst releasing a flow regime appropriate to supporting key aspects of the river ecosystem. The release regime may therefore include rapid rises and falls in flow (hydropower dams) or flows higher than natural (regulating reservoirs).

Impoundment release limitations

The current ability of the impoundment to make environmental flow releases is assessed in step 8 of the flow chart (Figure 3). Limitations may include operational requirements of the impoundment, flood storage, water supply provision or hydropower generation, releases for subsequent abstraction downstream. Release structures may be very small or non-existent. 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 may not be appropriate; including lower temperatures.

In adapting the environmental release regime to over come the limitations of the impoundment, particular attention should be given to the potential flexibility in the regime, for example whether it can be implemented to an acceptable degree by limited operating rules that can be practically achieved, such as constant compensation flows for long periods interrupted by occasional freshets, or whether the flow needs to vary over shorted time periods; seasonally, monthly or daily?

Failure to achieve the required status

A third reason for adapting the environmental flow regime is when monitoring and testing shows that even when the regime is implemented, the water body is failing to achieve the required status even when modifications to the impoundment release structures have been made. This may be due to uncertain scientific knowledge when the release regime was defined in step 8.

8. References

Acreman, M.C., Dunbar, M.J., Hannaford, J., Bragg, O.M., Black, A.R., Rowan, J.S. and King, J. 2006. *Development of environmental standards (Water Resources) Stage 3: Environmental Standards*, Project WFD 48, Scotland and Northern Ireland Forum for Environmental Research, 146 pp.

Arthington, A.H. and Long, G.C. (Eds.), 1997 *Logan River Trial of the Building Block Methods for assessing environmental flow requirement: background papers*. Centre for Catchment and Instream Research and Department of Natural Resources, Queensland, Australia.

Black, A.R., Bragg, O.M., Duck, R.W., Jones, A.M., Rowan, J.S. and Werritty, A. 2000 *Anthropogenic impacts upon hydrology of rivers and lochs: Phase 1. A user manual introducing the Dundee Hydrological Regime Assessment Method.* Report to Scotland and Northern Ireland Forum for Environmental Research, SR(00)01/2F. SNIFFER, Edinburgh 32pp.

Black, A.R., Bragg, O.M., Duck, R.W. and Rowan, J.S. 2003 DHRAM: a method for assessing the severity of anthropogenic change in river flow regimes. *Hydrological Sciences Journal*

Booker, D. and Acreman, M.C. 2006 Redundancy analysis of hydrological regime indices for rivers in Great Britain. *Technical report 1. WFD 82* Compensation flows and freshets. Centre for Ecology Scotland and Northern Ireland Forum for Environmental Research, SR(00)01/2F. SNIFFER, Edinburgh 6pp.

Hannaford, J. and Acreman, M.C. 2007 Assessment of hydrological regime indices for comparing pre and post impoundment flow regimes of rivers in Great Britain. *Technical report 2. WFD 82* Compensation flows and freshets. Centre for Ecology Scotland and Northern Ireland Forum for Environmental Research, SR(00)01/2F. SNIFFER, Edinburgh 6pp.

Cowx, I.G., Noble, R.A., Nunn, A.D., Harvey, J.P. 2004 *Flow and level criteria for coarse fish and conservation species*. Report to Environment Agency W6-096, University of Hull.

Department of Water Affairs and Forestry., 1999. *Resource directed measures for protection of water resources.* Department of Water Affairs and Forestry, Pretoria, South Africa.

European Commission 2000. *Directive 2000/60/EC of 20 December 2000 establishing a framework for community action in the field of water policy.* European Parliament and Council, Luxembourg.

Faulkner

Goodwin, T. H., Young, A., Maxted, R., Marks, S. 2005 *Flow Naturalisation Handbook* - Guidance for the EA. R & D Project W6-075

Gustard, A., Cole, G., Marshall, D. and Bayliss, A. 1987 *A study of compensation flows in the UK*. Institute of Hydrology, Report No 99. Institute of Hydrology Wallingford, UK.

Holmes, N. T. H., Boon, P. J. and Rowell, T. A. 1998. "A revised classification system for British Rivers based on their aquatic plant communities." *Aquatic Conservation-Marine and Freshwater Ecosystems* **8,** 4, 555-578

Hughes, D.A. and Smakhtin, V.U. 1996 Daily flow time series patching or extension. A spatial interpolation approach based on flow duration curves. *Hydrological Sciences Journal* 41, 6, 851-871.

King, J.M., Tharme, R.E. and de Villiers M.S. (eds.) 2000 *Environmental flow assessments for rivers: manual for the Building Block Methodology.* Water Research Commission Report TT 131/00, Pretoria, South Africa.339 pp.

Junk, W.J., Bayley, P.B., Sparks R.E. 1989 The flood pulse concept in river-floodplain systems. *Canadian Journal of Fisheries and Aquatic Science* 106, 110-127.

Monk, W.A., Wood, P.J., Hannah, D.M., Wilson, D.A., Extence, C.A. and Chadd, R.P. 2006 River flow variability and macroinvertebrate response within riverine systems. *Rivers Research and Applications*, 22, 595-615.

Monk, W.A., Wood, P.J., Hannah, D.M. and Wilson, D.A. 2007 Selection of hydrological indices for the assessment of hydro-ecological change. *Rivers Research and Applications*, 23, 113-122.

Old, G. and Acreman, M.C. 2006 *Guidance on compensation flows and freshets. Task 3: a review of literature on environmental flow requirements of UK river ecosystems*. Project WFD 82, Scotland and Northern Ireland Forum for Environmental Research, 26 pp.

Olden, J.D., Poff, N.L. 2003 Redundancy and choice of hydrologic indices for characterizing streamflow regimes. *Rivers Research and Applications*, 19, 101-121.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C. 1997 The natural flow regime. *Bioscience* 47, 769-784.

Richter, B.D., Baumgartner, J.V., Wigington, R., Braun, D.P. 1997. How much water does a river need? Freshwater Biology 37(1) 231-249

Tharme R. E. and King J. M., 1998. *Development of the building block methodology for instream flow assessments and supporting research on the effects of different magnitude flows on riverine ecosystems.* Report to Water Research Commission, 576/1/98. Cape Town, South Africa.

Wright, J. F., Sutcliffe, D. W. and Furse, M. T., Eds. (2000). *Assessing the Biological Quality of Fresh Waters: RIVPACS and other techniques,* Freshwater Biological Association, Ambleside.

Annex A Examples of pre and post impoundment flow regimes

Pre-impoundment typical year – black line (historical range - pale blue and red shading)
Post-impoundment typical year – blue line

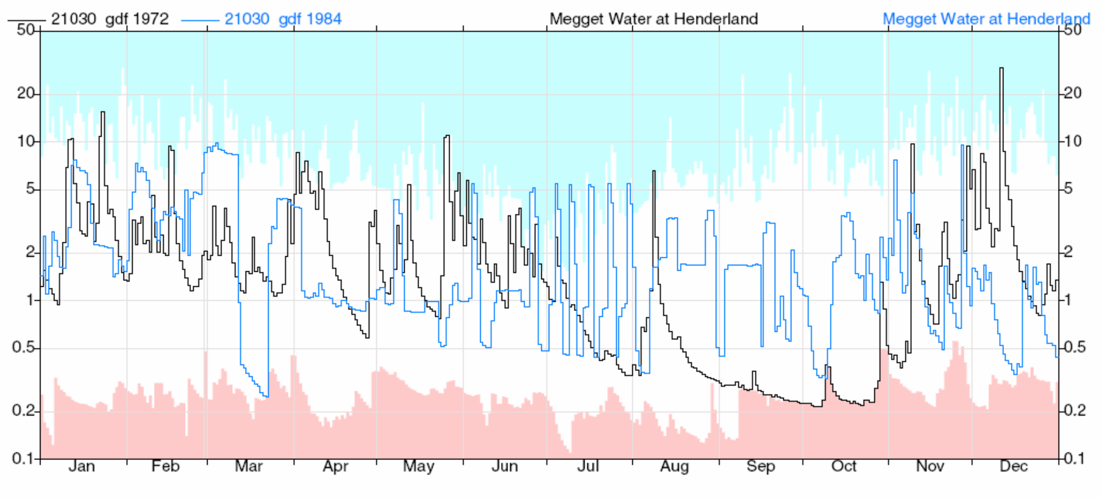

Figure A1 Megget Water at Henderland

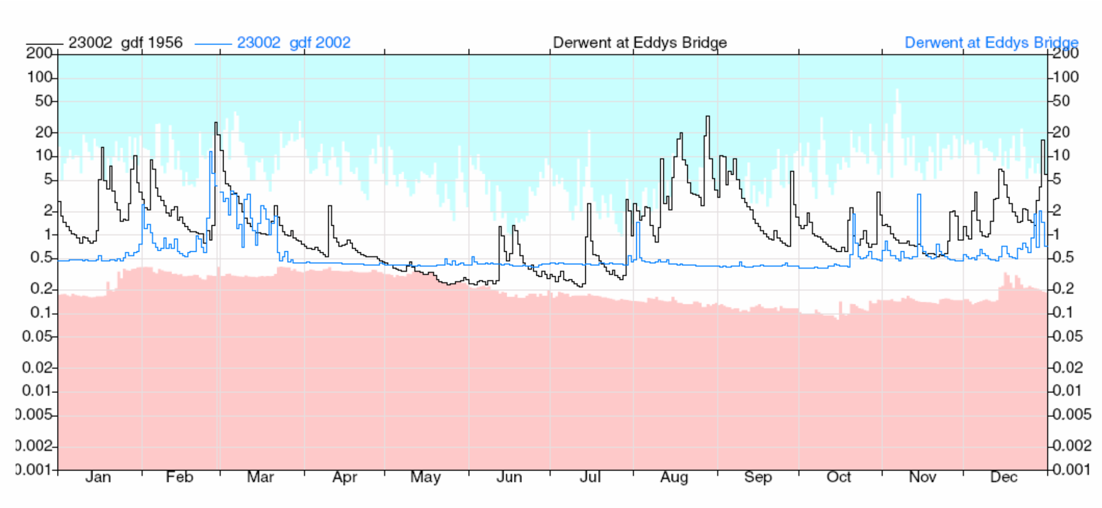

Figure A2 Derwent at Eddys Bridge

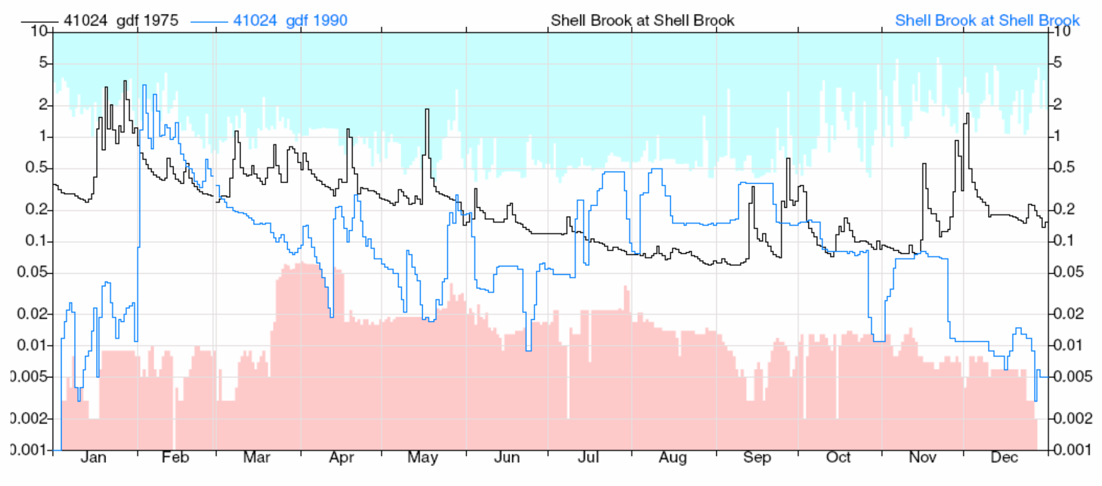

Figure A3 Shell Brook at Shell Brook

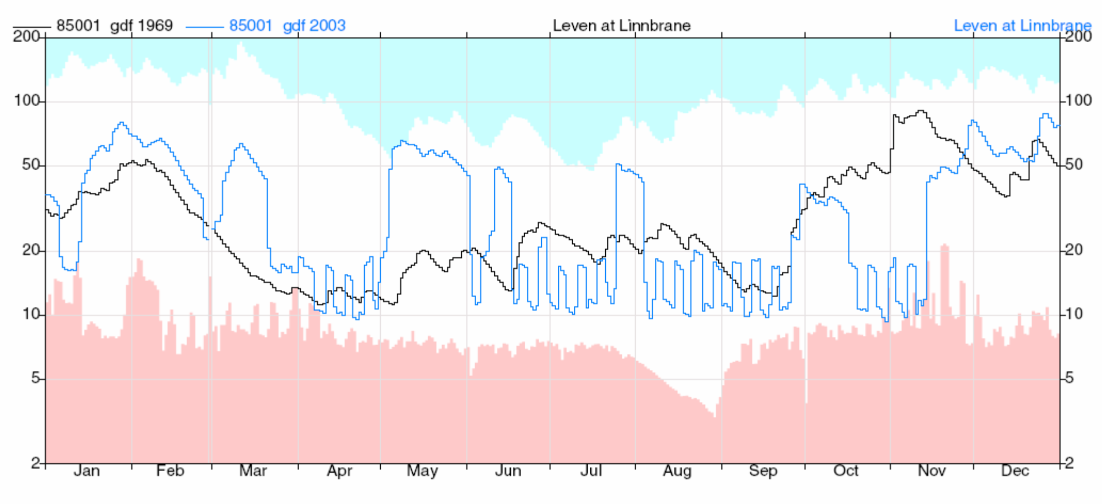

Figure A4 Leven at Linnbrane

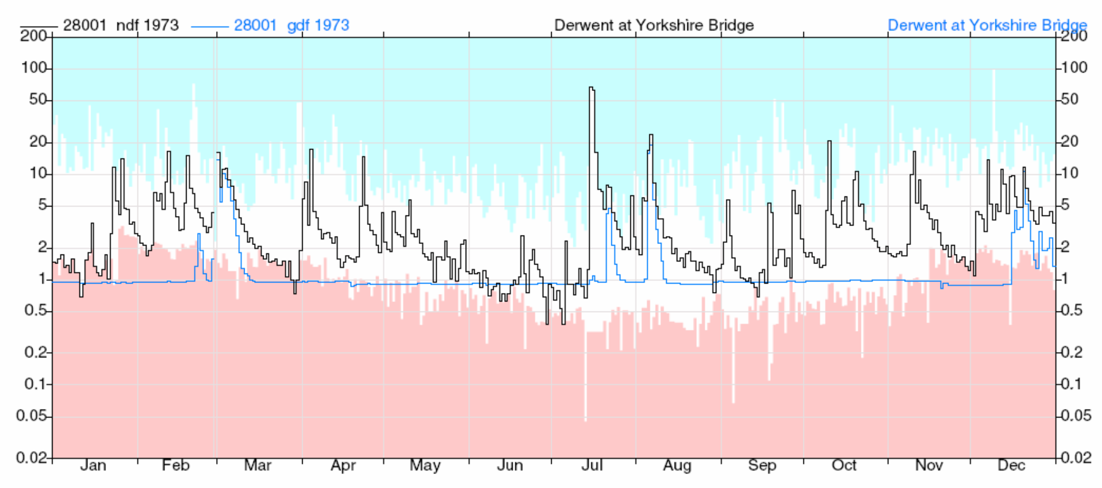

Figure A5 Derwent at Yorkshire Bridge

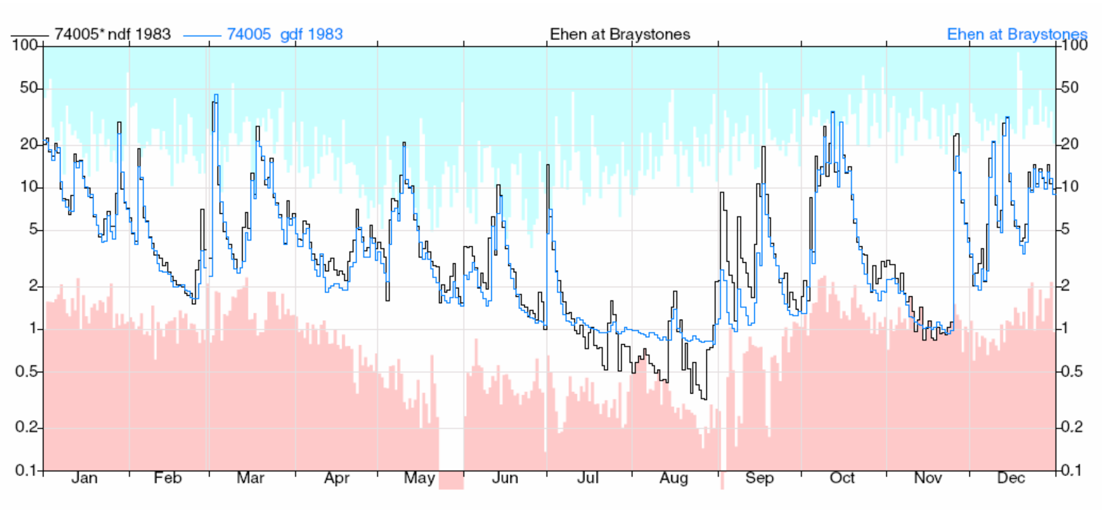

Figure A6 Ehen at Braystones

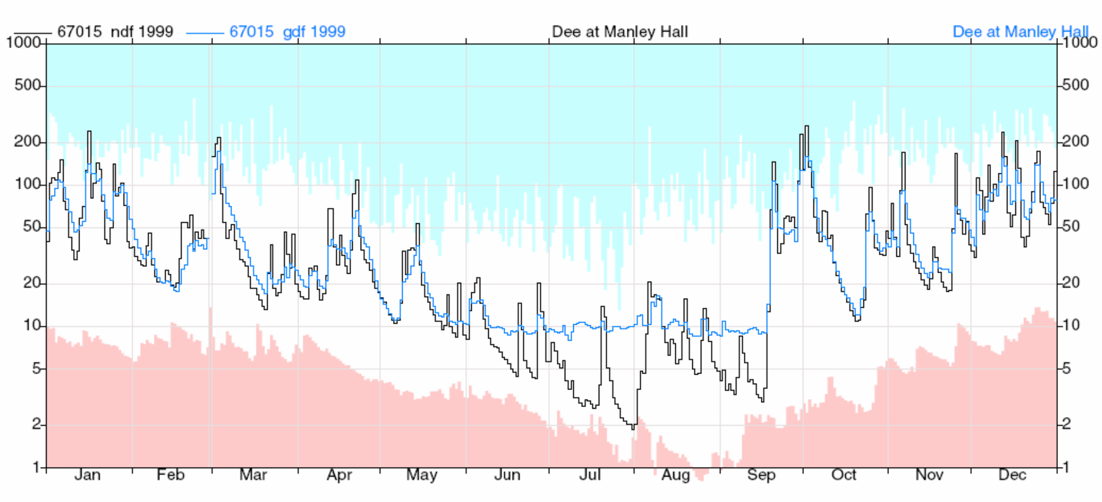

Figure A7 Dee at Manley Hall

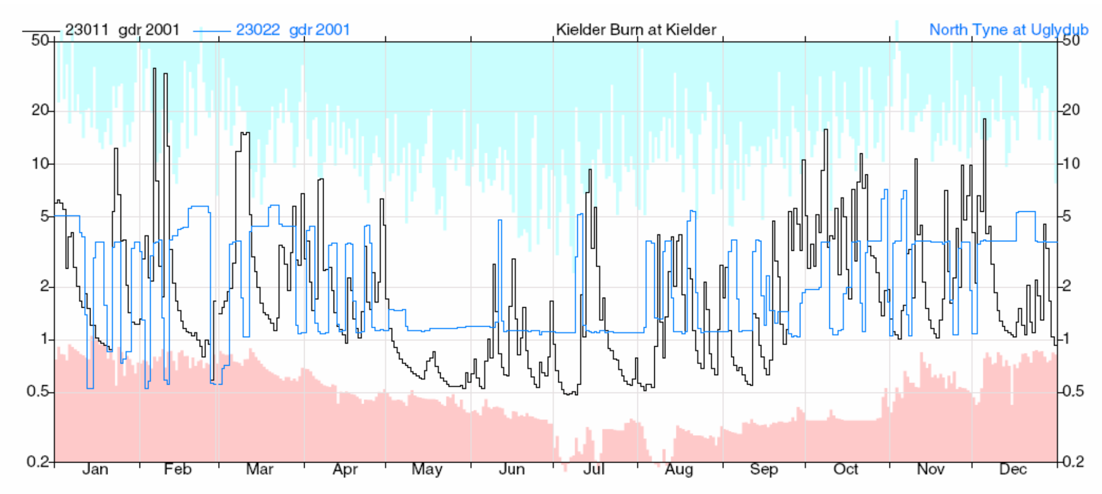

Figure A8 Pre= Kielder Burn at Kielder; post= North Tyne at Uglydub

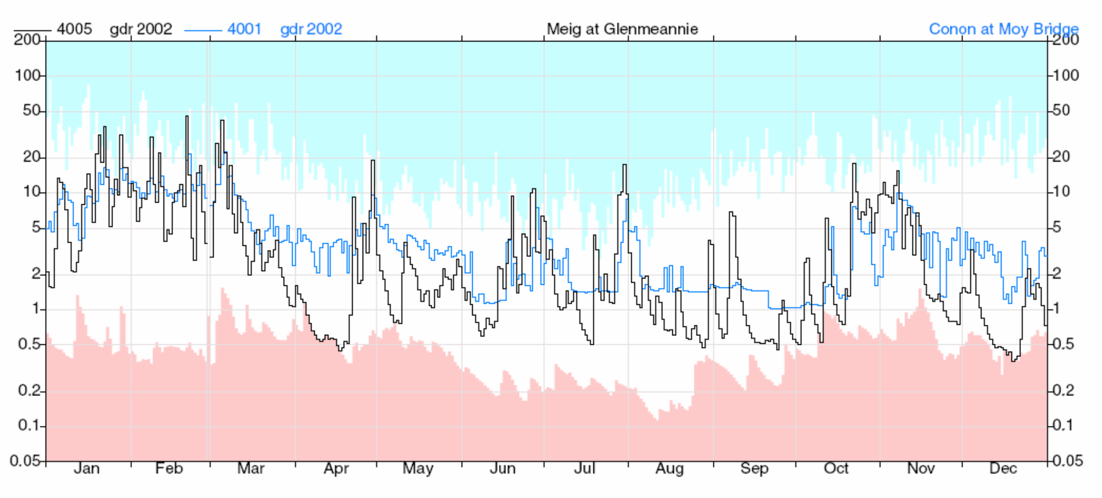

Figure A9 Pre= Meig at Glenmeannie; post = Conon at Moy Bridge

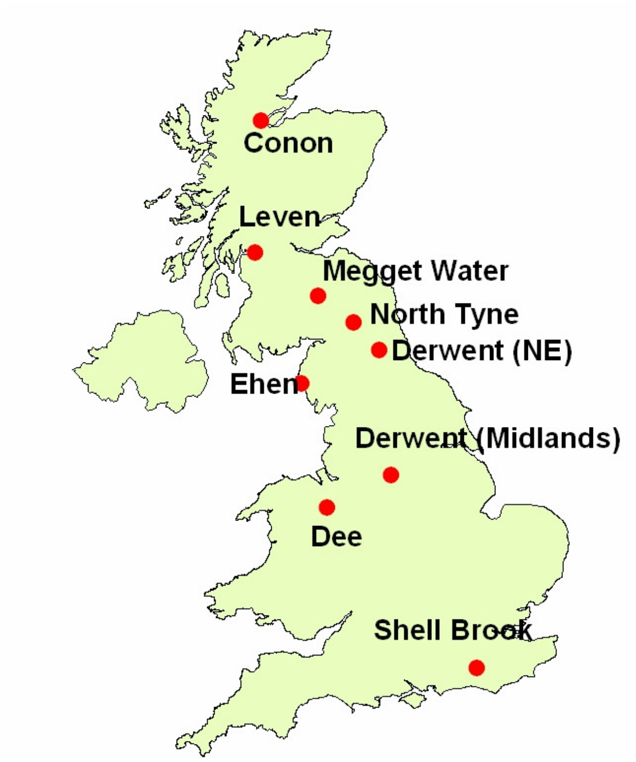

Figure A10 Location of sites with pre and post impoundment flow regime data

Table A1 Impoundment types

Impoundment	**purpose**
Conon at Moy Bridge	Hydropower
North Tyne at Uglydub	Water supply
Dee at Manley Hall	Water supply
Ehen at Braystones	Water supply
Derwent at Yorkshire Bridge	Water supply
Leven at Linnbrane	Hydropower
Shell Brook at Shell Brook	Water supply
Derwent at Eddys Bridge	Water supply
Megget Water at Henderland	Water supply

Table A2 Pre and post impoundment flow regime statistics for nine example rivers

All changes shown as % deviations from the natural condition

difference less than 40% (+ or -)	low risk of failing GES
difference between 40 and 80 % (+	medium risk of failing GES
difference greater than 80% (+ or -)	high risk of failing GES

				Low Flow 2000 statistics							other Richter stats					
	Method	pre-impact years*	post impact years	Q95	Q5	BFI	Jan	Apr	Jul	Oct	Min7d	Max7d	HiPulses	LoPulses	Mn-veDiff	Rises
Megget Water	Obs	1969 - 1981	1982 - 2004	35	-23	31	-25	-12	26	-41	46	-18	-22	59	-39	10
Derwent (NE)	Obs	1955 - 1964	1966 - 2005	61	-68	41	-74	-37	-53	-66	31	-50	-20	67	-72	7
Shell Brook	Obs	1972 -1977	1978 - 2005	-75	2	-2	-10	35	118	-3	-69	-2	-14	-32	-4	-4
Leven	Obs	1964 - 1971	1972 -2005	-38	22	-9	48	14	-22	-7	-29	22	21	509	92	17
Derwent (Midlands	Nat	1933 - 1981	-	-16	-30	41	-44	-44	-60	-51	15	-27	-56	-52	-46	-10
Ehen	Nat	1977 - 1997	-	17	-9	12	-4	-8	-21	-11	26	-8	-22	-33	-34	-13
Dee	Nat	1969 - 2001	-	151	-15	31	-2	14	31	-6	155	-9	-65	-58	-77	-30
Conon	Donor	1986 -2005	-	174	-36	132	-6	22	14	-6	269	-34	-44	19	-58	29
North Tyne	Donor	1983 - 2005	-	20	-43	44	-13	-8	43	-22	26	-29	-49	66	-50	40

Notes

Obs Pre-impoundment compared with post-impoundment

Nat Naturalised compared with observed impacted

Donor Synthetic natural series derived using scaling (by catchment area) of flows from site upstream of impoundment and compared with data downstream of impoundment

pre- and post-impact years show the ranges over which analyses were carried out where there is observed data

*For Naturalised and Donor cases, the same range of years were used for analysis; this range is also shown in the table.

North Tyne synthetic 'natural' data is based on 23011, which is 58.8 km2; the downstream catchment is 241.5 km^2.

Conon 'natural' synthetic data is based on transposing 4005 (upstream natural catchment, the Bran) which has an area of 120 km2 to the downstream catchment (4001) of 961 km^2

The data from these catchments can only be used for indicative purposes, particularly in the case of the Conon where the size difference is so great.

Annex B Environmental flow release regime table

Normal year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total	%MAR
Flow (m^3s^{-1})														
Depth, velocity or wetted area														
% natural flow														
Volume million m^3														

Dry year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total	%MAR
Flow peak (m^3s^{-1})														
Duration (days)														
Depth, velocity or wetted area														
% natural flow														
Volume million m^3														

Wet year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total	%MAR
Flow (m^3s^{-1})														
Depth, velocity or wetted area														
% natural flow														
Volume million m^3														

Drought year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total	%MAR
Flow peak (m^3s^{-1})														
Duration (days)														
Depth, velocity or wetted area														
% natural flow														
Volume million m^3														