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Environmental flows and the European Water Framework Directive

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SUMMARY

1. Environmental flows is now a widely accepted term that covers the quantity, timing, duration, frequency and quality of water flows required to sustain freshwater, estuarine and near-shore ecosystems and the human livelihoods and well-being that depend on them.
2. The Water Framework Directive (WFD) of the European Union does not use the term environmental flows explicitly, but requires member states to achieve good ecological status (GES) in all waterbodies, which is assessed by reference to aquatic biology. Nevertheless, it is accepted that ecologically appropriate hydrological regimes are necessary to meet this status. Implementing environmental flows will be a key measure for restoring and managing river ecosystems.
3. The WFD explicitly requires stakeholder involvement, but this has been interpreted as largely a dissemination exercise by national government agencies. Stakeholders are no longer involved in negotiation over ecological objectives as these are pre-set in the WFD. However, stakeholders may be more involved in reviewing standards and agreeing to measures to restore river ecosystems to the status required by the WFD.
4. The U.K. has undertaken two major projects to set environmental standards for water resources (i) to define water abstraction limits that maintain a healthy river ecosystem and (ii) to define ecologically appropriate flow releases from reservoirs.
5. Implementation of environmental flows remains a major issue, but new ideas such as time-limited licences and licence trading are being tried.

Keywords: environmental flows, European Commission, good ecological status, reservoir releases, Water Framework Directive

Introduction

The increasing recognition that ecosystems perform services to mankind, keeping the planet fit for living and providing much of our 'quality of life' (Acreman, 2001), has led to an ecological approach (Pirot, Meynell & Elder, 2000; Smith & Maltby, 2003) to natural resource management that underlies sustainable development. Freshwater ecosystems can provide economic security, e.g. fish, medicines, timber; social security, e.g. protection from natural hazards, such as floods; and ethical security, e.g. upholding the rights of people and other species to water (Acreman, 2001). It is a truism that aquatic ecosystems require water to maintain the physicochemical structure, species, communities, processes and functions that give them their specific character. Thus water allocated for the environment means indirectly supporting people by maintaining valuable ecosystem goods and services (Acreman, 1998). The Millenium Ecosystem Assessment (2005) showed that many ecosystems were being degraded or lost, with aquatic systems

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suffering particularly from the withdrawal of water for direct human needs for drinking, growing crops and supporting industry, with many impacts directly resulting from fragmentation by dams (Nilsson *et al*., 2005).

Water allocation to the environment has been recognised within frameworks such as Integrated Water Resources Management (IWRM; Moriarty, Butterworth & Batchelor, 2004) and Environmental Impact Assessment (EIA; Gilpin, 1995) for many years, but has normally been treated in terms of minimum needs, implemented as a very small constant flow in a river. Hydro-ecological analysis has shown that all elements of the flow regime influence freshwater ecosystems, including floods, average and low flows (Junk, Bayley & Sparks, 1989; Richter *et al*., 1996; Poff *et al*., 1997). This research led to the establishment of the science of environmental flows (Acreman, 2001; Dyson, Bergkamp & Scanlon, 2003). Many approaches to environmental flow assessment are therefore based on comparisons with natural hydrological regimes (Poff *et al*., 2010).

A key challenge in environmental flows is synthesising the knowledge and experience gained from individual case studies into a scientific framework that supports and guides the development of environmental flow standards at the *regional* scale (Poff *et al*., 2003; Arthington *et al*., 2006). To set standards for environmental flows at broad geographical scales, new frameworks for determining environmental flow needs of many rivers simultaneously – as opposed to detailed site-by-site studies – are required. A consensus of experiences and knowledge of a group of international scientists has been integrated into a framework called the 'Ecological Limits of Hydrologic Alteration' (ELOHA, Poff *et al*., 2010). The concept of ensuring adequate water for aquatic ecosystems is a key element in many international policies (such as the International Convention on Wetlands, signed by 132 countries) and in the water law of some countries including South Africa (Rowlston & Palmer, 2002), Tanzania (Acreman *et al*., 2006) and Costa Rica (Jiménez *et al*., 2005). The European Water Framework Directive (WFD) is a ground-breaking regional policy integrating water management and ecosystem conservation; this study considers how the concept of environmental flows fits within the WFD, with examples from its implementation in the U.K.

The EU Water Framework Directive

The European Union (EU) currently includes 27 member states; other states, such as Turkey, have intermediate status and may join over the next decade. Climate and water resources vary considerably across the continent. Southern Europe is dominated by a Mediterranean climate with hot dry summers and mild wet winters. Here, water demand is primarily for irrigated agriculture and domestic supply, with major increases in population by tourism along the coast during the summer. In northern Europe, precipitation is more evenly spread throughout the year and water use is primarily for public supply and industry. High population densities produce localised major water stress; the Thames basin in SE England, for example, receives around 650 mm of precipitation, but has a population of over 10 million, yielding less than 1000 m^3 $person^{-1}$ $year^{-1}$, which is comparable with water stress in Saudi Arabia and Ethiopia (Falkenmark & Widstrand, 1992).

The WFD came into force on 22 December 2000 (European Commission, 2000). This is a major legislative initiative, intended to resolve the piecemeal approach to European water legislation that has developed since 1975. The WFD was needed because water-related issues were handled through separate sectors, such as pollution, nature conservation and drinking water standards, some of which had become inconsistent. In addition, previous Europe-wide directives were implemented through different legislation in the various European member states.

A key turning point occurred at a 'study and reflection seminar' attended by scientists and policy makers at Lake Como in 1988. Those responsible for natural area conservation proposed an ecologically-based water directive on the basis that the ecosystem was the best indicator for sustainable development. The idea was supported by other sectors, such as abstractors who felt they were paying the price of degraded surface and ground water by funding water purification and that aquatic ecosystems should be in a state where they provided clean water. Europe has many international rivers, and although to some extent the details of WFD implementation are left to individual states, common implementation guidance has helped to harmonise objectives, monitoring and methods that support transboundary basin management.

Under WFD, all EU Member States should aim to achieve at least 'Good Status' (where biology and water quality deviate only slightly from natural conditions) in all bodies of surface water and ground water by 2015, and to prevent deterioration in the status of those waterbodies. National legislation must be put in place to achieve the WFD and competent agencies selected that can implement it. The definition of waterbodies includes rivers, lakes, canals, reservoirs, ground water and transitional water (estuaries and deltas). Wetlands are not explicitly referred to as such, since – as under the Ramsar Convention (2006) – all waterbodies are wetlands. However, wetlands associated with waterbodies are included within the definition, for example floodplains are included as part of the adjacent lake or river waterbody. Wetlands fed by aquifers are referred to as 'groundwater-dependent terrestrial ecosystems'.

Defining environmental water status

Initially, the ecological status of a surface waterbody (classification of ground waters is dealt with differently) can be bad, poor, moderate, good or high (Table 1). The status is defined as the lesser of the chemical and ecological status and assessed in terms of the extent of deviation from undisturbed reference conditions (Fig. 1). The primary means of setting reference conditions is by comparison with similar waterbodies that are undisturbed. Similarity is assessed by classifying and typing sites according to selected physical variables, from a combination of mapped (e.g. catchment area, slope, geology) and site-specific (e.g. water width, depth) data. Historical data may also be used.

It is increasingly being recognised that climate change will have a significant impact on the aquatic environment in Europe (IPCC, 2007). The WFD does not address climate change explicitly. However, there is current debate about how reference conditions will alter under climate changes that can alter the targets for management of waterbodies. Furthermore, most new research funded by the EU has to include implications of climate change and results will eventually find its way into policy. The biological aspect of the ecological status assessment of any waterbody is

Table 1 Ecological classes for waterbodies in the Water Framework Directive

Status class	Description	Actions
High	Undisturbed, pristine waterbody, with natural flow regime, water quality and biology equal to reference conditions. Healthy stands of water plants, dominated by several different underwater species. Abundant plants at the water's edge, emerging from the water. Water clear, except in flood. Diverse common and rare insects, amphibians, reptiles, fish and birds	Maintain as high
Good	Water quality and biology deviate only slightly from reference conditions. Predominantly natural species. Healthy stands of water plants, dominated by several different species that lie in the water close to the surface. Abundant plants at the water's edge, emerging from the water. Water clear, except in flood. Common and occasional rare species of insects, amphibians, reptiles, fish and birds present	Maintain as good
Moderate	Moderate deviations in biology and water quality from reference conditions. Luxuriant growth of plants, but mainly of a single species; growth may almost block the channel. Emergent plant growth at the banks is present but not very extensive. Water can be turbid with a green or brown tinge, particularly during spring. Only widespread and common species of insects, amphibians, reptiles, fish and birds present. Some wetland species showing signs of stress. Some invasion by terrestrial species	Measures needed to improve status to good
Poor	Major deviation in biology from reference conditions. Significant pollution, a few sickly looking plants covered in green slime or with long trailing fronds of blanket weed (filamentous algae). Emergent plants at the water's edge either very sparse or absent. A few sickly looking plants within a dominant single species. Very turbid, green or brown coloured water for much of the summer. Few species of fish, invertebrates present	
Bad	Heavily polluted with very few or no natural animals present. No plants visible at all. Either bare bottom sediments or a covering of green or brown slime on the bottom. Very turbid, green or brown coloured water for most of the summer	

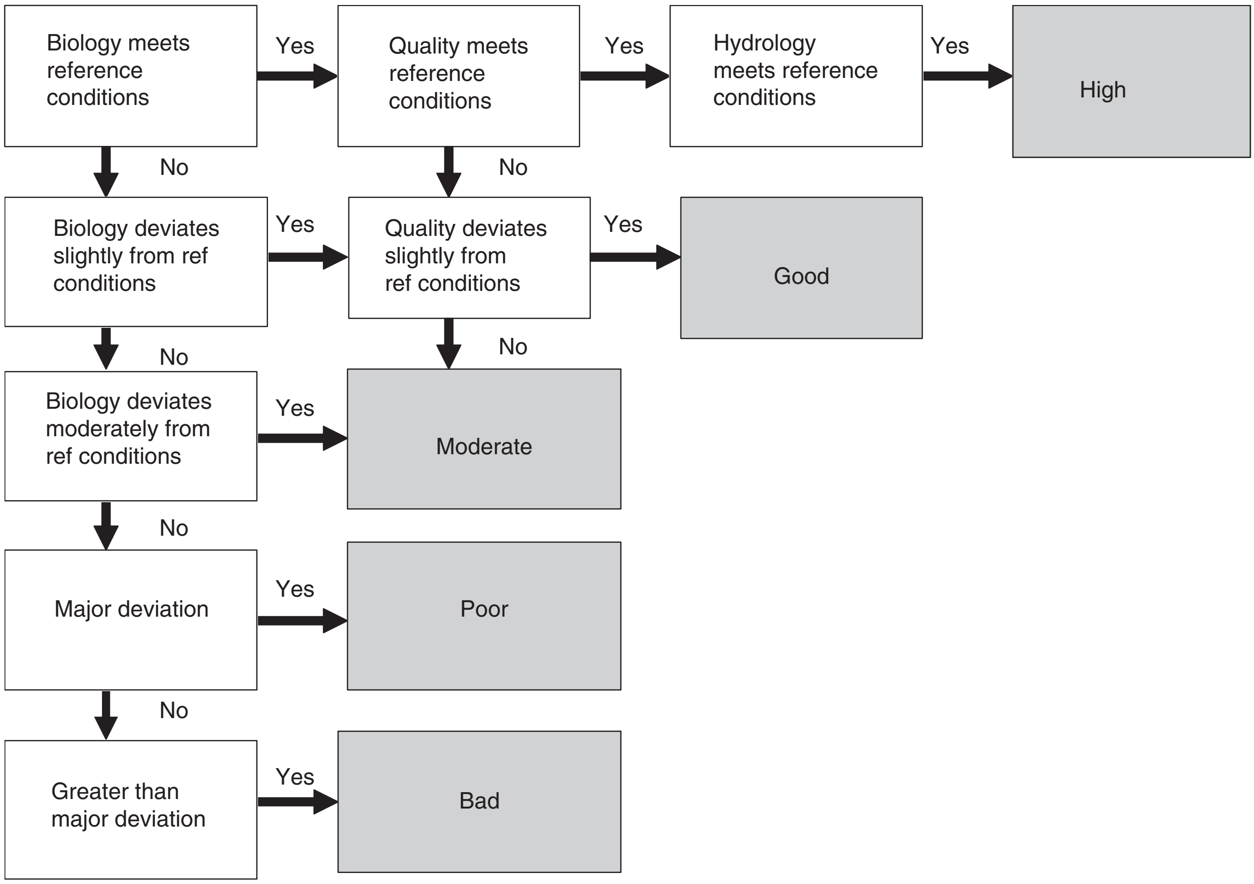

Fig. 1 The process of waterbody classification in the Water Framework Directive.

defined by the degree of deviation of the waterbody from biological reference conditions and is measured primarily through assessment of three elements of the aquatic ecosystem:

1 Fish – taxonomic composition and age structure.

2 Invertebrates – taxonomic composition and mixture of sensitive and non-sensitive taxa.

3 Macrophytes, algae – taxonomic composition and abundance.

Good ecological status (GES) is the target for most waterbodies. Pristine waterbodies are classified as high ecological status (HES) and must be maintained at this status level. Where any waterbody is moderate, poor or bad, measures must be defined to improve its status to at least good (Table 1). River Basin Management Plans must be produced showing a set of measures required to achieve at least GES by 2015. It is recognised that certain physicochemical and hydromorphological conditions are needed to maintain a healthy ecosystem, so these factors are termed supporting elements. Consequently, commonly defined measures include improving water quality or removing structures, such as weirs, that will remedy the causes of failure to meet GES. Only in the case of HES is the river flow regime a primary quality element and must be close to natural along with the biology of the river (Fig. 1).

The WFD allows limited exceptions to achieving at least GES. Waterbodies that have physical modifications, such as dams, weirs and embankments or have been straightened or deepened, can be designated as a heavily modified waterbodies (HMWB) or artificial, in the case of man-made lakes or canals. These waterbodies must achieve an alternative objective of at least 'good ecological potential' (GEP) to take account of the constraints imposed by the physical modification. GEP is defined as the best example of biological conditions in a similar waterbody with the same modifications, i.e. where reasonable mitigation measures have been implemented and best practice management is applied. In the case of a waterbody containing a dam for example, best practice could mean making appropriate environmental flow releases. A HMWB is designated if the following criteria apply:

1 The waterbody 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, public water supply, navigation).

2 The beneficial functions would be significantly compromised by restoration measures required to achieve GES and no other technically feasible and cost-effective option that is better for the environment exists for delivering the function.

Designation of HMWBs is thus ultimately an economic issue. If the modification has a high economic value (e.g. valuable hydropower generated by the dam), it can remain, the waterbody is designated as HMWB and the objectives of GEP are attained by good management. If the dam is not economic, it should be removed or operated in a way that will achieve GES in the waterbody. The concept of status relating to reference conditions that are broadly natural is controversial. For example, some rivers protected under the Habitats Directive (such as the River Itchen, U.K.) are not natural, but result from many centuries of management (including weed cutting, dredging and operation of weirs and sluice gates), yet they are highly prized ecosystems. Unless designated as HMWB, the WFD states that these should be returned to more natural conditions, which may be less diverse biologically and less acceptable to local people. The WFD is thus a specific approach to setting objectives for river restoration in which the focus is on ecological outcomes rather than social objectives, that may be less acceptable to local stakeholders.

WFD and environmental flows

In the WFD, the flow regime is not considered a primary quality element and thus hydrological modification is not used to assess waterbody status (except for HES, Fig. 1) or to designate a HMWB. Thus, although the flow regime of a waterbody may be significantly altered downstream of an impoundment or an abstraction, unless the biology is impacted, it could meet GES. Furthermore, unless the waterbody contains the dam itself or the channel has been physically modified, it may not be designated as a HMWB. Nevertheless, alterations to the flow regime degrade river ecosystems through modification of physical habitat and of erosion and sediment supply rates. Thus, GES is unlikely to be met where significant flow regime alteration occurs. Implementation of environmental flows is therefore one of the measures needed to restore or to maintain GES and can be included in the River Basin Management Planning process. The WFD does not specify the measures needed to restore or maintain GES; each country is left to define environmental standards, such as maximum abstraction rates or flow releases from dams, since these are related to river type and will vary according to reference conditions in different countries. Furthermore, the WFD does not specify how water for environmental flows may be retrieved where its over-use has been licensed. A common implementation strategy was established to produce guidance to achieve some consistency of approach and Water Directors (representatives of implementing agencies) meet every 6 months as a coordinating mechanism for sharing best practice across Europe at government level, and pan-European research projects allow scientists to work together. A programme of cross-checking and inter-calibration of different approaches across the EU has been established and is helping to ensure consistent biological standards in different EU states.

Setting environmental flows for the WFD

Each member state has its own existing tools and data for water management, and in many cases differences at provincial level within states. For example, some European countries such as the U.K. (Elliott *et al.*, 1996), Germany (Jorde, 1996), France (Ginot, 1995) and Norway (Killingtveit & Harby, 1994) have used detailed physical habitat models. These models use hydraulic equations to relate river flow to water depth and velocity that directly determine the physical habitat for different species. Such models are quantitative and replicable, but are labour-intensive and not feasible for assessment of large numbers of waterbodies. Other countries have employed rules of thumb, such as in France, where the environmental flows from dams must be at least 1/40 th of the mean flow for existing projects and 1/10 th of the mean flow for new projects (Souchon & Keith, 2001). Such rules allow dam operators to release a constant flow which may not be ecologically appropriate. South Africa (King, Tharme & de Villiers, 2000) and Australia (Arthington & Lloyd, 1998) have made use of structured expert knowledge. Although expert knowledge may be considered subjective, the structured methodical approach, in which a multi-disciplinary group of experts considers available data, is widely recognised as a robust method (Tharme, 2003; Moore, 2004). The European Commission funded a network of experts working on hydroecological issues (COST 626 Harby *et al*., 2004), which enabled coordination of activities in member states, including cross-comparison of models used in different countries. However, no specific project has been undertaken to develop consistent environmental flow procedures across Europe.

Monitoring varies in the type of organisms recorded, the monitoring techniques and frequency of observations. The WFD presented a major challenge in its goal to harmonise water management across Europe. The European Commission has funded various research projects to support implementation of the WFD; many of these projects have cost Euro 3–4 million each. They have been focused primarily on methods for predicting reference conditions in waterbodies. The Fish-based Assessment Method for European rivers (FAME) (Schmutz, 2004) is a good example. FAME supported development of the European Fish Index (EFI), in which environmental variables (altitude, distance from source, catchment area, slope, wetted width, air temperature, presence⁄absence of lake upstream) are used to predict which fish communities would be present in reference conditions. Rivers are then classified into five levels of degradation based on deviation of observed numbers of species and abundance from that predicted by the model. The STream And River typologies project (STAR) developed a similar procedure for predicting macroinvertebrate community reference conditions (Sandin & Verdonschot, 2006). For some of these methods, the comparison of the observed and reference condition communities reveals the causes of the differences and suggests measures that can be implemented, such as certain macroinvertebrate communities which are known to prefer slow- or fast-flowing conditions. In other cases, separate studies are required to identify causes of failure to achieve GES.

WFD and environmental flows in the U.K.

The U.K. was the first European country to address environmental flow needs through two key projects to achieve GES; WFD 48 (SNIFFER, 2006; Acreman *et al*., 2008) and WFD 82 (SNIFFER, 2007; Acreman *et al*., in press). Both projects were of short duration, initially 6 months each, and work was limited to defining the environmental flow requirements using existing science and data, such as the Resource Assessment and Management (RAM) framework (Environment Agency, 2001a) of the Catchment Abstraction Management Strategies (Environment Agency, 2001b), which includes abstraction limits to achieve healthy river ecosystems.

Setting abstraction limits

The WFD 48 set standards for water resources, i.e. restricting abstraction to levels that would leave an environmental flow appropriate to maintain GES; termed restrictive management (Acreman & Dunbar, 2003). The project had two main outputs; a means of classifying river ecosystem types, based on the characteristics of the river basin draining to them, and a set of look-up tables for each river type specifying the maximum abstraction allowable at different flows. To undertake the WFD 48 project, a panel of leading U.K. river scientists specialising in fisheries, macroinvertebrate ecology, macrophyte ecology, hydrology and water resource management was created from universities, research institutes, consultancies and environment protection agencies. The main forum of interaction for the panel was a series of workshops. The experts also provided information and references for a literature review and commented by E-mail on drafts of the various documents produced, including workshop and project reports. They were asked to define:

1 The ecological basis for environmental flow standards, in terms of the state of knowledge.

2 A river ecosystem classification (of around 10 types).

3 Aspects of the flow regime that are important ecologically.

4 The form of standards, e.g. whether threshold values of abstraction are related to actual volume of flow or percentages of reference flow, such as natural flow.

For WFD purposes, the classification needed to differentiate river waterbodies on the basis of ecological sensitivity to changes in the flow regime. Consequently, existing U.K. hydrological classifications of rivers, developed for studies of flood response (Institute of Hydrology, 2000) or low flows (Young, Grew & Holmes, 2003) were not considered to be appropriate. Several models that link physical characteristics to river ecosystems were explored. For example, the River Invertebrate Prediction And Classification System (RIVPACS; Wright *et al.*, 1988) predicts the expected invertebrate communities in U.K. rivers based on catchment variables. However, the large number of RIVPACS groups (35; Wright, 2000) was not considered appropriate for the current classification. Holmes, Boon & Rowell (1998) classified U.K. rivers on the basis of macrophytes found during surveys at over 1500 sites. The classification yielded 10 river community types (RCTs), varying from lowland, eutrophic rivers to torrential, oligotrophic streams. By excluding impacted rivers, the classification was reduced to eight types. The utility of this classification was discussed by the expert panel and thought to be relevant to macrophytic plants and macroinvertebrates, although less appropriate for differentiating fish communities.

To classify river waterbodies for fish communities, the expert panel reviewed the typology devised by Cowx *et al*. (2004) and reduced their original eight fish types to four that have different flow regime requirements:

1 High base flow (Chalk geology) rivers – groundwater-fed rivers with smoothly varying flow regimes.

2. Eurytopic/limnophylic cyprinids, e.g. common bream *Abramis brama* Linnaeus 1758 – lowland slow-flowing water.

3 Rheophlic cyprinids, e.g. barbel *Barbus barbus* Linnaeus 1758 – mid-reach, fast flowing water.

4 Salmonid (juvenile salmon and trout spawning and nursery areas) – headwater streams.

When setting the standards for these river types (see below), it was found that only in the case of salmonid spawning and nursery areas did standards exceed those required for macroinvertebrates and macrophytes. In other words, use of the macroinvertebrate/macrophyte standards would ensure adequate protection of flows for fish community types 1–3. Consequently, only the salmonid spawning/nursery area type was added to the eight types appropriate for macrophytes and macroinvertebrates. Habitat modelling of Chalk rivers, such as the Itchen (Booker *et al.*, 2004) and Wylye (Dunbar, Gowing & Linstead, 2000), found differential ecological impacts of changes in flow in headwaters and downstream reaches, with headwaters being more sensitive to abstraction, thus requiring different environmental standards, i.e. a different percentage of the flow can be abstracted. The Chalk river type was thus sub-divided into headwater and downstream reaches, producing 10 types overall: the eight RCTs (A1, A2, B1, B2, C1, C2, D1, D2), with a sub-division of A2 into headwater, A2(hw), and downstream river reaches, A2(ds), plus salmonid spawning and nursery areas (Table 2).

During the project workshops, working groups with the expert panel focused on the flow needs of macrophytes, macroinvertebrates and fish. Each group reviewed available information, discussed the ecological basis for setting flow thresholds and defined abstraction standards for different flows. The following paragraphs summarise some of the issues discussed.

The expert panel agreed that aquatic, littoral, riparian and floodplain vegetation may vary in their flow requirements or tolerances, but noted that limited specific analysis had been undertaken to define thresholds. They noted, for example, that *Ranunculus penicillatus* ssp. *pseudofluitans* (Dumort) Bab, the dominant macrophyte of Chalk rivers, has adapted a physiological response in shape to thrive in higher currents and can suffer smothering by epiphytes in low currents. Consequently, 0.1 m s^{-1} is often quoted as a minimum velocity to maintain the growth of *Ranunculus* (Cranston & Darby, 2004). This species prefers depths of between 50 and 150 cm (Newbold & Mountford, 1997). The macrophyte experts concluded that 10% abstraction would have negligible impact, whilst 30% abstraction or above would be significant ecologically. It was thought that some river macrophytes were more sensitive to flow change during spring and early summer (March–May), so no abstraction below Q_{95} would be preferable during this season for all rivers.

The panel agreed that flow, temperature and substratum type are three of the dominant variables

Table 2 River water reach types based on Holmes *et al.* (1998)

Holmes *et al.* type	Holmes *et al.* sub-type	Final WFD48 type
A. Low altitude; low slope; eutrophic; silt/clay-gravel bed; smooth flow	A1 lowest gradients (0.8 ± 0.4 m km^{-1}) and altitudes (36 ± 25 m), predominantly clay	A1 as sub-type
	A2 slightly steeper (1.7 ± 0.8 m km^{-1}), low altitude (55 ± 38 m)	A2 (hw) headwaters as sub-type with catchment area <100 km^2
	Chalk catchments; predominantly gravel beds, base-rich	A2 (ds) downstream as sub-type with catchment area >100 km^2
B. Hard limestone and sandstone, low-medium altitude, low-medium slope; mesotrophic; gravel-boulder (mainly pebble-cobble), mostly smooth flow, small turbulent areas	B1 gradient (4.1 ± 9.9 m km^{-1}), altitude 93 ± 69 m Hard sandstone, calcareous shales	B1 as sub-type
	B2 shallower than B1 (2.7 ± 10.7 m km^{-1}); altitude 71 ± 58 m	B2 as sub-type
C. Non-calcareous shales, hard limestone and sandstone, medium altitude, medium slope, oligo-meso-trophic; pebble, cobble, boulder bed, smooth flow with abundant riffles and rapids	C1 gradient 5.4 ± 6.5 m km^{-1}; altitude 101 ± 84 m; hard limestone; more silt and sand than C2; mesotrophic	C1 as sub-type
	C2 steeper than C1 (7.3 ± 10.8 m km^{-1}); altitude 130 ± 90 m; non-calcareous shales; pebble-bedrock; oligo-mesotrophic	C2 as sub-type
D. Granites and other hard rocks; low and high altitudes; gentle and steep slopes; ultraoligo – oligotrophic; cobble, boulder, bedrock, pebble; smooth with turbulent areas – torrential	D1 medium gradient (11.3 ± 15.6 m km^{-1}); low altitude (93 ± 92 m), oligotrophic, substrate finer than D2 (incl silt & sand); more slow flow areas than D2. Includes acid heaths	D1 as sub-type
	D2 high gradient (25.5 ± 33 m km^{-1}); high altitude (178 ± 131 m); stream orders 1 & 2, bed rock and boulder; ultra-oligotrophic, torrential.	D2 as sub-type
		Salmonid (juvenile salmon and trout spawning and nursery areas) – headwater streams

controlling macroinvertebrate distribution and survival (Boon, 1988; Cortes *et al.*, 2002; Lytle & Poff, 2004). Previous U.K. research demonstrated that high winter–spring discharge may be one of the most important variables influencing late summer communities in groundwater-dominated rivers (Wood *et al.*, 2001). Communities may also change in response to the deposition of fine sediment on the channel bed caused by flow alteration (Armitage & Ladle, 1991). Periodic high, flushing flows are therefore desirable to prevent settling of fines clogging interstitial spaces in the substratum (Wood & Armitage, 1997). Regional studies of macroinvertebrate communities in U.K. rivers (Extence, Balbi & Chadd, 1999) suggested that upland rivers are more sensitive to changes in flow than those in lowland rivers, thus they need more stringent standards of protection. The macroinvertebrate experts concluded that types A2, B1, C2 and D2 were probably more sensitive to abstraction and thus require the highest levels of protection with 10% permissible abstraction. Type A1 rivers are the least sensitive and require the lowest level of protection, with 30% abstraction allowable. For all other types the critical level is 20%.

The panel felt that the flow requirements of salmonid fish are relatively well understood. Critical flows for migration on the River Exe (southwest England) increased upstream both as percentage of Q_{95} and actual flow, suggesting greater protection of flows may be required to stimulate and enable fish migration in upstream than downstream reaches (Sambrook & Cowx, 2000). Spawning salmonids require a minimum area of suitable habitat and flows sufficient to keep gravel free from fines; thus salmonids have threshold levels of depth and velocity (Armstrong *et al.*, 2003). During incubation salmon eggs must be

Table 3 Standards for U.K. river types/sub-types for achieving GES given as % allowable abstraction of natural flow (thresholds are for annual flow statistics)

Type or sub type	Season	Flow $> Qn_{60}$	Flow $> Qn_{70}$	Flow $> Qn_{95}$	Flow $< Qn_{95}$
A1	Apr.–Oct.	30	25	20	15
	Nov.–Mar.	35	30	25	20
A2 (ds), B1, B2, C1, D1	Apr.–Oct.	25	20	15	10
	Nov.–Mar.	30	25	20	15
A2 (hw),	Apr.–Oct.	20	15	10	7.5
C2, D2	Nov.–Mar.	25	20	15	10
Salmonid spawning &	June–Sep.	25	20	15	10
nursery areas	Oct.–May	20	15	Flow $> Q_{80}$	Flow $< Q_{80}$
(not chalk rivers)				10	7.5

submerged and well oxygenated by water percolating through the gravels and parr survival rates are density dependent so sufficient flow is required to maintain adequate habitat (Crisp, 1996). Coarse fishes exhibit greater plasticity towards modified flows, but many also depend on flow, particularly rheophilic cyprinids, such as dace, barbel and chub (Mann, 1996). Others require high flows at certain times of the year, especially spring, to access floodplain or backwater habitats for breeding and refuge (Cowx, 2001). The fish experts focused particularly on protection of low flows, i.e. very limited or no abstraction when the flow was less than natural Q_{95}.

The working group analyses of threshold flow needs resulted in four broad types with different permitted abstraction levels. The maximum levels of abstraction ranged from 7.5% to 35% of the natural flow depending on river type and flow rate (Table 3). No other countries have yet produced new methods or look-up tables explicitly for WFD implementation, although several countries, including Norway, Sweden and Slovenia are starting the process and have invited U.K. experts to present their experiences in start-up workshops.

Setting flow releases from reservoirs

In the WFD 48 project, it was recognised that releasing water from a reservoir to achieve environmental flows involves active management (Acreman & Dunbar, 2003) and is a very different issue from limiting abstraction. Consequently a second project was set up, called WFD 82 (SNIFFER, 2007; Acreman *et al.*, in press), to provide best practice guidance for setting flow releases from impoundments. The WFD 82 study used broadly the same panel of experts as WFD 48, but with the addition of expertise in dam engineering and geomorphology. This study concluded that no simple generic rules could be set that would apply to all rivers of the U.K. Instead it was recommended that each waterbody below a dam required individual analysis of its natural flow regime and identification of key elements of the regime needed to conserve different parts of the river ecosystem.

The panel agreed that the tool to determine the environmental flow required downstream of an impoundment should be based on ecological requirements of different communities or species or life stages, which may vary within and between rivers even for the same biological elements or communities. However, 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 and 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.

The panel assessed functional analysis approaches (Acreman & Dunbar, 2003) including the building

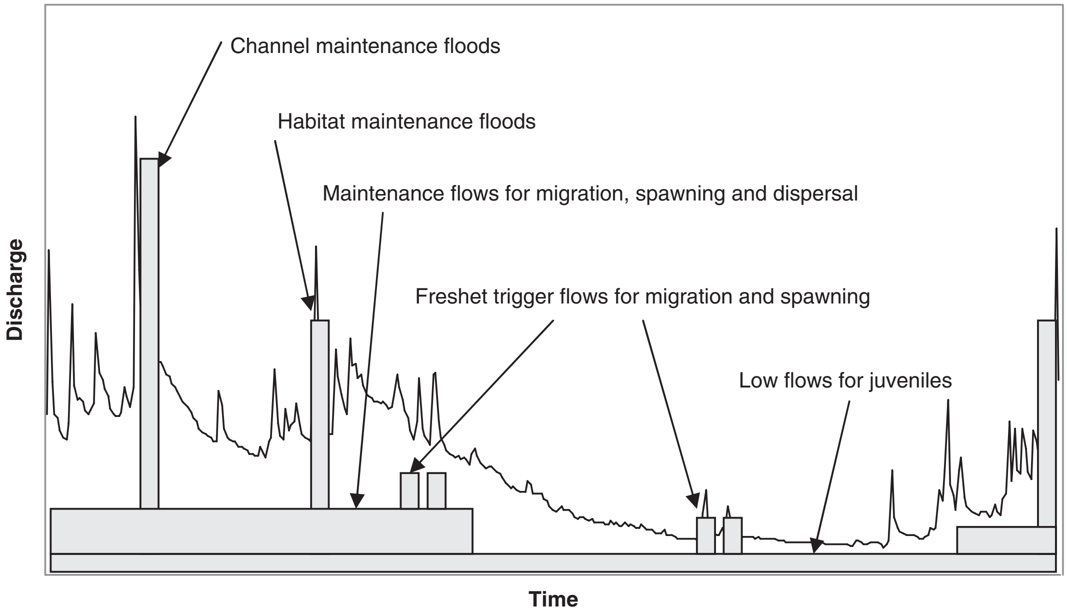

Fig. 2 Building an environmental flow release regime: a conceptual approach. The continuous line represents the natural flow hydrograph for 1 year; the blocks represent the flow regime required to maintain a healthy ecosystem.

block methodology (BBM; Tharme & King, 1998), as having the best potential for defining the elements of the flow regime needed to achieve either GES or GEP in river ecosystems under operational and other constraints. The basic premise of BBM is that riverine species rely on basic elements (building blocks) of the flow regime (Fig. 2). A flow regime for ecosystem maintenance can, thus, be constructed by combining these building blocks. Full application of BBM requires site-specific data. The utility of BBM needs to be tested in the U.K., but it was recommended as potentially the best way forward. In making its decision the panel agreed on the following points.

1 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.

2 Information to define an environmental flow release regime is available for many U.K. river ecosystems from the literature (an example of available information for U.K. rivers is given in Table 4); for others site studies would be needed.

3 Differences between rivers mean that environmental flow requirements cannot be easily transferred between sites.

4 Spring flows from some impoundments may be currently adequate to facilitate fish migration.

5 Freshets are particularly important in summer in rivers with low base flow or in dry years, and in some rivers they may also enhance fish migration.

6 Entry of salmonid fish into headwater tributaries is particularly flow dependent (October–November).

7 During the salmonid spawning period elevated flows are required to permit upstream migration of fish, to distribute spawning fish throughout the river system, to ensure redds are well oxygenated and excessive fine sediment deposition prevented. During and subsequent to spawning elevated flows also aid adult salmon in migrating downstream.

8 Immediately after emergence from eggs, rapid increases in flows are thought to be detrimental to emerging salmonid fry.

9 Variable flows throughout the year (without extremes) will ensure a healthy riverine environment and diverse macroinvertebrate and macrophyte assemblages.

10 Ecologically effective flow increases may be achieved by reducing compensation flow gradually and then rapidly increasing releases back to normal compensation flow level.

11 Periodic high flows (>2 year return period) are required to maintain channel geometry and with it habitat diversity.

The panel noted that the flow regime shown in Fig. 2 shows only 1 year and the implication is that

Table 4 Examples of summary information on flow needs of U.K. river ecosystems

	Timing and related conditions	Flow preferences
Salmonids: river entry	Flood/high tide Night time Water temperature between 5 and 17 °C (measured at 09:00 hours). Sufficiently well oxygenated river flow	Elevated river flows
Salmonids: upstream migration	Spring run Feb.–May Summer run June–Aug. Autumn run Sep.–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 that is unrelated to river flow may occur during summer 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 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
Salmonids: downstream adult migration	Migration Nov.–May	Elevated flows may help
Salmonids: post-emergence	Mar.–May	Low, stable flow is desirable, with no rapid increases/decreases
Salmonids: dispersal of smolts	Apr.–July	Periods of elevated flow
Coarse fish: migration and spawning	Feb.–Mar.	Rheophilic cyprinids need good flows to migrate and spawn
Coarse fish: pike, stickleback and dace	Feb.–Apr.	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	Mar.–June	A velocity of 0.1 m s^{-1} 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 150 cm. At velocities in excess of 1 m s^{-1} 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 because of 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

the same releases should be made each year. In natural riverine systems, the flow regime varies considerably over different time periods 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 another species from potential washout from the system. This is consistent with the biological records for natural systems, which show that due to hydrological variations, some years are good for some species and poor for others, e.g. one year may be good for salmon and another for coarse fish. Consequently, it may be necessary to design a series of flow release regimes that are used on a rotating basis. For example, one flow release regime could be designed for 'normal' rainfall years, when the suite of river ecosystem functions and processes can be expected, and a different regime, designed for species survival, could be used for drought years when all flow needs cannot be met, although some fish may not be able to successfully reproduce (e.g. during low flows associated with droughts).

It was further noted that when developing environmental flow releases these should include an assessment of the ability of the impoundment to make different releases, which may be limited or even impossible (where no release structures exist), especially for release of high flows or frequently varying flow releases, which will often be constrained by small or inflexible release values. Retrofitting of release structures is possible but very expensive. 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 at depth (Petts, 1984). Some water supply reservoirs have multiple level draw-off points and scour valves, which can be used to mitigate the effects of water quality issues.

In lieu of a full method for setting environmental flow releases from reservoirs, the WFD 82 project produced a screening tool for initial assessment of where waterbodies downstream of reservoirs are likely to fail to achieve GES because of alteration of the flow regime. Natural (pre-dam) and current (post-dam) flow regimes were examined for six rivers. A range of variables that characterise the elements of the flow regime, based on Richter *et al.* (1996), were calculated for the pre- and post-dam situations (using recorded data and models) and their differences examined. Differences were due to the impact of the reservoir and the uncertainties in modelling. Where all post-dam flow parameters were within 40% of the pre-dam parameters, it was considered that there was low risk of failing GES due to flow regime modification (Acreman *et al.*, in press). Additional research was undertaken to test this threshold by examining macroinvertebrate samples from waterbodies downstream of dams where pre-dam and post-dam data existed and to assess whether the degree of ecological alteration was related to the degree of hydrological alteration. For some sites there was a tendency for more variation in samples with altered flow regimes. However, in general, natural variations in macroinvertebrate samples (due to a range of factors at different sites) are greater than changes due to dam operations (Dunbar, Holmes & Young, 2008). Hence, it was not possible to verify fully the 40% threshold. The results have stimulated the establishment of new invertebrate monitoring downstream of dams to improve future assessment.

Stakeholder participation

The WFD recognises the importance of developing effective mechanisms to support public and stakeholder participation and encourages involvement in river basin decision-making processes, but their role is not explicit; certainly there is no defined role in environmental flow assessment. However, even accounting for different political and institutional contexts, reviews of participation in five European countries (Portugal, Greece, The Netherlands, the U.K. and Spain) have concluded that there is little real opportunity for the active involvement and collaboration of the interested parties (Videira *et al.*, 2006). Participation is largely an information-dissemination exercise for government departments or implementing agencies, with an opportunity to comment. For example, the Scottish National Stakeholder Forum 'provides access to Scottish Ministers on any aspect of WFD implementation in Scotland and presents information to key stakeholders on the introduction of the WFD' (Scottish Environment Protection Agency, 2008). Competent authorities have the responsibility to implement the WFD and so need to make final decisions. In some cases the interaction with stakeholders has been counterproductive as the stakeholders become frustrated that they were promised participation, but they are merely being informed or at best consulted with little prospect that their views will be acted upon. Some stakeholder participation occurs in the development of a vision process for developing River Basin Management Plans or for specific activities, such as the development of measures where waterbodies fail to achieve GES.

The WFD is based on objective-based decision-making (Acreman & Dunbar, 2003) where the target status of the waterbody is fixed in advance (at least good status), using the classification shown in Table 1. This constitutes a move away from scenario-based decision-making where options are presented and stakeholders can influence the selection of the most appropriate scenario. In South Africa, for example, the target class for the river is defined by consensus of local stakeholders (Department of Water Affairs and Forestry, 1999). To some extent the experience in Europe with catchment-based stakeholder participation has not been all positive. Local negotiations led to different water allocations in different river basins which were seen to be un-equitable at national scale. Negotiations were often dominated by a few vocal water users which led to bias, and only key stakeholders were invited to meetings. Thus, conspiracy theories arose and the outcomes were not trusted. A particular challenge of implementing the WFD has been resolving the potential conflict between having consistent science, and its application, and being able to consider the views of 'small stakeholders' who may be interested only in their local site, and the large-scale decisions that are made at government level on the socioeconomic factors. This has been addressed by creating a stakeholder forum in each river basin and explaining the scientific approach taken and allowing access to data files and results.

Implementation

European Union member states are required to identify a competent authority to implement the WFD. Many of these authorities have tended to work in the past on balancing the needs of water users and the environment. They work at the river basin level and hold separate discussions with different water users or small stakeholder forums. In this way, different decisions may result in different waterbodies as a consequence of negotiated compromises. The WFD removes much of the flexibility that the implementing authorities had previously, as it defines a single, homogenous, EU-wide target status. It means a centralised approach with less local autonomy. However, it will produce better consistency in river health and fairer allocation of water. The ownership of water is not addressed in the WFD; it just requires waterbodies to be in at least Good Status. Operating rules for most reservoirs have been agreed between the dam owners (e.g. water or hydropower companies) and government regulators, and these rules are revised to include environmental flows. In many cases, especially those involving major dams, the owners are required to provide river flow data to prove that they are operating the dam within the agreement. The competent agencies (mainly environment protection agencies) are then responsible for biological monitoring which provides a significant part of the actual test of whether the waterbody is at GES. Dam management is likely to require an adaptive management approach, since the precise environmental flows required to achieve GES are not known and thus releases and abstraction allowances may need to be altered following the results of monitoring. Monitoring for the WFD will also have to be integrated with other needs such as conservation of designated habitats and species and management of invasive species.

Many river basins are over-abstracted due to past licence agreements or lack of licences. The major issue for the future is implementing the environmental flows needed to achieve GES in these over-abstracted rivers or maintain GES where it exists. Some of the approaches being tried in the U.K. are:

Negotiations with water users

Users are asked to give up some abstraction to increase their 'green' credentials or in exchange for priority attention in seeking alternative water sources.

Demand management

Farmers are increasingly investing in efficient technology or on-farm storage of water during high flows for use during dry periods. To encourage this, licensing authorities may agree to higher total abstractions if water is taken during high flows. In addition, publicity campaigns, free advice and water metering, with increasing tariffs for higher use, have all proved successful.

Time-limited licences

All abstraction licences granted by the Environment Agency are Time Limited, usually for a period of 12 years to a Common Date for a catchment, so resources can be re-evaluated and adjustments made to licences for sustainable levels of abstraction at a specific date for each catchment.

Licence trading

Some users own licences that they do not exploit. Often these are kept as a back-up in times of drought and there has been no incentive to give up the licence even though this restricts other users' requests for new licences. Under new U.K. laws, licences may be tradable, where they are loaned or sold to other water users. Market mechanisms for this have not yet been established.

Increased water bills for consumers

In most EU countries water tariffs are controlled by the state and are not necessarily set by market forces. In some cases, water suppliers can increase charges to customers to offset costs of new infrastructure required to reduce abstractions from over-abstracted waterbodies.

Legal mechanisms

The Environment Agency has legal powers to propose a change to an abstraction licence. This may require the payment of compensation for the loss of the resource.

Conclusions

The following lessons can be learnt from the European WFD:

1 Developing a legal framework for an entire continent, which will be turned into national legislation, is very ambitious, because of massive variations in existing legislation, customer law and civil rights and lack of consistent techniques and data sets. Without the consistency, different decisions will be made in different parts of Europe, which is seen as inequitable. Inconsistency can be overcome, but requires investment in major R&D programmes costing many millions of Euros. Establishing a consistent environmental flow policy for a large region is expensive and time consuming.

2 Establishing major prescriptive legislation means that many technical concepts need to be clearly defined. European countries are still struggling to agree on definitions of and methods for identifying reference conditions, HMWBs and other concepts. This has important implications for interpretations and procedures to implement these definitions that are very difficult to agree on.

3 Look-up tables provide a simple means of setting environmental flow requirements, but are inflexible and uncertain at any individual site. Functional analysis (such as BBM) is generally the recommended approach as it combines explicit knowledge of the hydrological and ecological system to provide a site-specific solution; however it is costly. The main recommendation is for a tool-kit that contains a range of procedures which can be selected according to the issue and river type. The tool-kit would contain look-up tables for scoping and broad-scale analysis, structured expert opinion, functional analysis and physical habitat models.

4 Stakeholder participation in key requirement if community involvement is to be achieved. This is particularly so in implementation, where water users may have to give up some rights. The WFD is weak on specifying full participation, and mere consultation under the guise of true participation can create ill-feeling and be counter-productive.

5 Recovering water in over-abstracted river basins remains the most difficult obstacle to implementing environmental flows. However, various methods are being tried, from demand management to tradable permits that may prove positive.

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References

Acreman M.C. (1998) Principles of water management for people and the environment. In: *Water and Population Dynamics* (Eds A. de Shirbinin & V. Dompka) pp. 25–48. American Association for the Advancement of Science, New York.

Acreman M.C. (2001) Ethical aspects of water and ecosystems. *Water Policy Journal*, **3**, 257–265.

Acreman M.C. (Ed) (2001) *Hydro-Ecology: Linking Hydrology and Aquatic Ecology*. IAHS Publication 266, Wallingford.

Acreman M.C. & Dunbar M.J. (2003) Defining environmental flow requirements: a review. *Hydrology and Earth System Sciences*, **8**, 861–876.

Acreman M.C., King J., Hirji R., Sarunday W. & Mutayoba W. (2006) *Capacity Building to Undertake Environmental Flow Assessments in Tanzania*. Proceedings of the International Conference on River Basin Management, Morogorro, Tanzania, March 2005. Sokoine University, Morogorro. Available at: http://www.iwmi.cgiar.org/Research_Impacts/Research_Themes/BasinWaterManagement/RIPARWIN/Outputs.aspx.

Acreman M.C., Dunbar M.J., Hannaford J. *et al.* (2008) Developing environmental standards for abstractions from UK rivers to implement the Water Framework Directive. *Hydrological Science Journal*, **53**, 1105–1120.

Acreman M.C., Dunbar M.J., Hannaford J. *et al.* (in press) Environmental flows from dams; the Water Framework Directive. *Engineering Sustainability*.

Armitage P.D. & Ladle M. (1991) Habitat preferences of target species for application in PHABSIM testing. In: *Instream Flow Requirements of Aquatic Ecology in Two British Rivers*, Report 115 (Eds A. Bullock, A. Gustard & E.S. Granger), pp. 87–122. Institute of Hydrology, Wallingford.

Armstrong J.D., Kemp P.S., Kennedy G.J.A., Ladle M. & Milner N.J. (2003) Habitat requirements of Atlantic Salmon and brown trout in rivers and streams. *Fisheries Research*, **62**, 143–170.

Arthington A.H. & Lloyd R. (1998) *Logan River Trial of the Building Block Methodology for Assessing Environmental Flow Requirement: Workshop Report*. Centre for Catchment and Instream Research and Department of Natural Resources, Brisbane, Qld.

Arthington A.H., Bunn S.E., Poff N.L. & Naiman R.J. (2006) The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, **16**, 1311–1318.

Booker D.J., Dunbar M.J., Acreman M.C., Akande K. & Declerck C. (2004) Habitat assessment at the catchment scale; application to the River Itchen, UK. In: *Hydrology: Science and Practice for the 21st Century*, **Vol. II** (Eds B. Webb, M.C. Acreman, C. Maksimovic, H. Smithers & C. Kirby) pp. 10–18. Proceedings of the British Hydrological Society International Conference July 2004. British Hydrological Society, London.

Boon P.J. (1988) The impact of river regulation on invertebrate communities in the U.K. *Regulated Rivers: Research and Management*, **2**, 389–409.

Cortes R.M.V., Ferreira M.T., Oliveira S.V. & Oliveira D. (2002) Macroinvertebrate community structure in a regulated river segment with different flow conditions. *River Research and Applications*, **18**, 367–382.

Cowx I.G. (2001) *Factors Influencing Coarse Fish Populations in Rivers*. R&D Publication 18, Environment Agency, Bristol.

Cowx I.G., Noble R.A., Nunn A.D. & Harvey J.P. (2004) *Flow and Level Criteria for Coarse Fish and Conservation Species*. Environment Agency R&D Report, W6-096, Bristol.

Cranston E. & Darby E. (2004) *Ranunculus in Chalk Rivers*. R&D Technical Report W1-042/TR. Environment Agency, Bristol.

Crisp D.T. (1996) Environmental requirements of common riverine European salmonid fish species in fresh water with particular reference to physical; and chemical aspects. *Hydrobiologia*, **323**, 201–221.

Department of Water Affairs and Forestry (1999) *Resource Directed Measures for Protection of Water Resources*. Department of Water Affairs and Forestry, Pretoria.

Dunbar M.J., Gowing I.M. & Linstead C. (2000) *PHABSIM Investigations on the River Wylye: PHABSIM Model Calibration and Time Series Analysis*. Report to Environment Agency Contract SWCON61, Institute of Hydrology, Wallingford.

Dunbar M.J., Holmes M.G.R. & Young A.R. (2008) *Guidance on Environmental Flow Releases from Impoundments to Implement the Water Framework Directive. Project Extension 2: Validation of Managed Flow Standards*. Scotland and Northern Ireland Forum for Environmental Research, Edinburgh. Available at: http://www.sniffer.org.

Dyson M., Bergkamp G. & Scanlon J. (Eds) (2003) *Flow: The Essentials of Environmental Flows*. IUCN, Gland.

Elliott C.R.N., Johnson I.W., Sekulin A.E., Dunbar M.J. & Acreman M.C. (1996) *Guide to the Use of the Physical Habitat Simulation System*. Report to National Rivers Authority. Institute of Hydrology, Wallingford.

Environment Agency (2001a) *Resource Assessment and Management Framework. Report and User Manual (Version 2)*. W6-066M. Environment Agency, Bristol.

Environment Agency (2001b) *Managing Water Abstraction: The Catchment Abstraction Management Strategy Process*. Environment Agency, Bristol.

European Commission (2000) *Directive 2000/60/*EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. Official Journal 22 December 2000 L 327/1. European Commission, Brussels.

Extence C., Balbi D.M. & Chadd R.P. (1999) River flow indexing using British benthic macro-invertebrates: a framework for setting hydro-ecological objectives. *Regulated Rivers: Research and Management*, **15**, 543–574.

Falkenmark M. & Widstrand C. (1992) Population and water resources: a delicate balance. *Population Bulletin*, **47**, 1–36.

Gilpin A. (1995) *Environmental Impact Assessment: Cutting Edge for the Twenty-First Century*. Cambridge University Press, Cambridge.

Ginot V. (1995) EVHA, un logiciel d'evaluation de l'habitat du poisson sous Windows. *Bulletin Francais de la Peche et de la Pisciculture*, **337**/338/339, 303–308.

Harby A., Baptist M., Dunbar M.J. & Schmutz S. (Eds) (2004) *State of the Art in Data Sampling, Modelling Analysis and Applications of River Habitat Modelling*. Final Report of COST 626. Available at: http://www.eamn.org.

Holmes N.T.H., Boon P.J. & Rowell T.A. (1998) A revised classification system for British rivers based on their aquatic plant communities. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**, 555–578.

Institute of Hydrology (2000) *Flood Estimation Handbook*. Institute of Hydrology, Wallingford.

IPCC (2007) The physical science basis. *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller). Cambridge University Press, Cambridge.

Jiménez J.A., Calvo J., Pizarro F. & González E. (2005) *Conceptualización de Caudal Ambiental en Costa Rica: Determinación Inicial Para el Río Tempisque*. IUCN, San José, Costa Rica.

Jorde K. (1996) Ecological evaluation of instream flow regulations based on temporal and spatial variability of bottom shear stress and hydraulic habitat quality. In: *Ecohydraulics 2000, Proceedings of the Second International Symposium on Habitat Hydraulics* (Eds M. Leclerc, H. Capra, S. Valentin, A. Boudreault & Y. Cote). Quebec, pp. 6163–6174, INRS-Ea4.

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

Killingtveit Å. & Lundteigen Fossdal M. (1994) The River System Simulator – an integrated Model system for water resources planning and operation. In: *Hydraulic Engineering Software V Water Resources and Distribution* (Eds W. R. Blain & K. L. Katsifarakis), pp. 35–41. Ecology and Environment. vol **7**, Wessex Institute, Sorthampto, UK.

King J.M., Tharme R.E. & 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.

Lytle D.A. & Poff N.L. (2004) Adaption to natural flow regimes. *Trends in Ecology and Evolution*, **19**, 94–100.

Mann R.H.K. (1996) Environmental requirements of European non-salmonid fish in rivers. *Hydrobiologia*, **323**, 223–235.

Millenium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being*. Island Press, Washington, DC. Available at: http://www.millenniumassessment.org/.

Moore M. (2004) *Perceptions and Interpretations of Environmental Flows and Implications for Future Water Resources Management; A Survey Study*. MSc Thesis, Department of Water and Environmental Studies, Linköping University, Linköping.

Moriarty P., Butterworth J. & Batchelor C. (2004) *Integrated Water Resources Management*. IRC, Delft. Available at: http://www.irc.nl.

Newbold C. & Mountford J.O. (1997) *Water Level Requirements of Wetland Plants and Animals*. English Nature Freshwater Series 5. English Nature, Peterborough.

Nilsson C., Reidy C., Dynesius M. & Revenga C. (2005) Fragmentation and flow regulation of the world's large river systems. *Science*, **308**, 405–408.

Petts G.E. (1984) *Impounded Rivers: Perspective for Ecological Management*. Wiley, Chichester.

Pirot J.-Y., Meynell P.-J. & Elder D. (2000) *Ecosystem Management: Lessons From Around the World. A Guide for Development and Conservation Practitioners*. IUCN, Gland.

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.

Poff N.L., Allan J.D., Palmer M.A., Hart D.D., Richter B.D., Arthington A.H., Rogers K.H., Meyer J.L. & Stanford J.A. (2003) River flows and water wars: emerging science for environmental decision making. *Frontiers in Ecology and the Environment*, **1**, 298–306.

Poff N.L., Richter B.D., Arthington A.H. *et al.* (2010) The ecological limits of hydrologic alteration (ELOHA):

a new framework for developing regional environmental flow standards. *Freshwater Biology*, **55**, 147–170.

Ramsar Convention (2006) *The Ramsar Convention Manual. A Guide to the Convention on Wetlands (Ramsar, Iran, 1971)*, 4th edn. Available at: http://www.ramsar.org/lib/lib_manual2006e.htm.

Richter B.D., Baumgartner J.V., Powell J. & Braun D.P. (1996) A method for assessing hydrological alteration within ecosystems. *Conservation Biology*, **10**, 1163–1174.

Rowlston W.S. & Palmer C.G. (2002) *Processes in the Development of Resource Protection Provisions on South African Water Law*. Proceedings of the International Conference on Environmental Flows for River Systems, Cape Town March 2002. University of Cape Town, Cape Town.

Sambrook H.T. & Cowx I.G. (2000) Wimbleball pumped storage scheme: integration of water resource management, engineering design and operational control to compliment the needs of the salmonid fisheries of the River Exe, UK. In: *Management and Ecology of River Fisheries* (Ed. I.G. Cowx) 212–223. Blackwell Science, Oxford.

Sandin L. & Verdonschot P.F.M. (2006) Stream and river typologies: major results and conclusions from the STAR project. *Hydrobiologia*, **566**, 33–37.

Schmutz S. (2004) *Development Evaluation and Implementation of a Standardised Fish-Based Assessment Method for the Ecological Status of European Rivers (FAME): A Contribution to the Water Framework Directive*. Report to European Commission. Available at: http://www.fame.boku.ac.at.

Scottish Environment Protection Agency (2008) *Water Framework Directive: Stakeholder Groups*. Available at: http://www.sepa.org.uk/wfd/stake/index.htm.

Smith R.D. & Maltby E. (2003) *Using the Ecosystem Approach to Implement the Convention on Biological Diversity Key Issues and Case Studies*. IUCN, Gland.

SNIFFER (2006) *Development of Environmental Standards (Water Resources). Stage 3: Environmental Standards for the Water Framework Directive*. Report to the Scotland and Northern Ireland Forum for Environment Research. Centre for Ecology and Hydrology, Wallingford and University of Dundee, Dundee. Available at: http://www.sniffer.org.

SNIFFER (2007) *Guidance on Environmental Flow Releases Form Impoundments to Implement the Water Framework Directive*. Scotland and Northern Ireland Forum for Environmental Research, Edinburgh. Available at: http://www.sniffer.org.

Souchon Y. & Keith P. (2001) Freshwater fish habitat: science, management and conservation in France. *Aquatic Ecosystem Health and Management*, **4**, 401–412.

Tharme R.E. (2003) A global perspective on environmental flow assessment : emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications*, **19**, 397–441.

Tharme R.E. & 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.

Videira N., Antunes P., Santos R. & Lobo G. (2006) Public and stakeholder participation in European water policy: a critical review of project evaluation processes. *European Environment*, **16**, 19–31.

Wood P.J. & Armitage P.D. (1997) Biological effects of fine sediment in the lotic environment. *Environmental Management*, **21**, 203–217.

Wood P.J., Hannah D.M., Agnew M.D. & Petts G.E. (2001) Scales of hydroecological variability within a groundwater-dominated chalk stream. *Regulated Rivers: Research and Management*, **17**, 347–367.

Wright J.F. (2000) An introduction to RIVPACS. In: *Assessing the Biological Quality of Fresh Waters: RIVPACS and Other Techniques* (Eds J.F. Wright, D.W. Sutcliffe & M.T. Furse), pp. 1–24. Freshwater Biological Association, Ambleside.

Wright J.F., Armitage P.D., Furse M.T. & Moss D. (1988) Predicting invertebrate communities using stream measurements. *Regulated Rivers: Research and Management*, **4**, 147–155.

Young A.R., Grew R. & Holmes M.G.R. (2003) Low flows 2000: a national water resources assessment and decision support tool. *Water Science and Technology*, **48**, 119–126.

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