Applied hydro-ecological science for the twenty-first century

M. J. DUNBAR & M. C. ACREMAN
Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, UK
e-mail: mdub@ceh.ac.uk

Abstract In this paper we provide an overview of the need for sound science on which to base decisions in regulated river management. A tool-box of techniques for informing such decisions is introduced, in the context of various, mostly recent, institutional developments. These have given management agencies more powers to manage river flows in an integrated way. We review the underpinning science of applied hydro-ecology, noting that not only is our knowledge incomplete but also there are barriers (not least financial) in its day-to-day application. We then go on to highlight common themes arising from the accompanying group of papers, and to link them to a broader context of applied hydro-ecology. These papers arose from the workshop on “Riverine Ecological Response to Changes in Hydrological Regime, Sediment Transport and Nutrient Loading”, held at the IUGG congress in 1999.

Key words hydro-ecology; ecohydrology; interdisciplinary science; freshwater ecology; river regulation; environmental impact assessment; data collection; modelling; prediction

INTRODUCTION

What is “hydro-ecology”?

Ecological studies that have linked the distribution of freshwater biota to physical factors (such as water velocity and temperature) are not new. Debate as to how such linkages can be used in a river management context has continued for the past 30 years or more (e.g. Baxter, 1961). However, a unifying working definition of “hydro-ecology” remains somewhat elusive due in part to the potential range of the subject area and the existence of overlapping terms such as “eco-hydrology”.

Of particular interest in the context of IAHS are Instream/Environmental flows*: the use of freshwater science and hydrology to manage the ecological impact of river regulation. Implicitly linked to this is a desire to ask “what-if?” questions. This desire is one of the key drivers of research in hydro-ecology due to the funding opportunities available: ultimately driven by public concern for the present and future environment and the value of water as a commodity. Thus the primary focus of this volume is a realm of applied hydro-ecology, the study of the regulation of river systems in order to understand and make predictions about human influences.

This gives rise to the definition of applied hydro-ecology used in this volume as the linkage of knowledge from hydrological, hydraulic, geomorphological and biological/ecological sciences to predict the response of freshwater biota and

* The term “instream flow” originated in North America (Tennant, 1976, was one of the first uses in the literature), while “environmental flow” is the term commonly used in South Africa and Australia.
ecosystems to variation of abiotic factors over a range of spatial and temporal scales. In turn this enables us to open up a sometimes-blurred distinction between applied hydro-ecology, and fundamental aquatic ecology, which is focused on understanding and explaining observed phenomena (Poff et al., 1997).

Studies of water movement between atmosphere, terrestrial vegetation and soil, which have been covered recently in Baird & Wilby (1999) are not discussed here. Furthermore study of nutrient fluxes and freshwater ecosystem management, as considered by Zalewski et al. (1997), are only touched upon.

**IUGG Congress Birmingham 1999**

This collection of papers arose from an international workshop on “Riverine Ecological Response to Changes in Hydrological Regime, Sediment Transport and Nutrient Loading” at the XXII General Assembly of the International Union of Geodesy and Geophysics (IUGG) at Birmingham, UK, in July 1999. The workshop was the first of its kind at an IUGG/IAHS-organized conference and attracted presentations across a broad range of topics. Although hydro-ecology has been a component of some previous IAHS publications (Petts, 1995; Kovar et al., 1998) this volume is the first to be exclusively on hydro-ecology, and the workshop was the first on hydro-ecology to be held at an IUGG General Assembly. Given this pedigree it is perhaps not surprising that many of the papers were presented by scientists from a hydrological background, however ecologists and interdisciplinary scientists were also represented, and all of the presentations involved interdisciplinary studies.

A high proportion of the presentations have become papers in this volume. It has thus set a positive tone for bringing hydro-ecological science to a large number of hydrologists at future conferences. This introductory paper aims to synthesize the papers into a broader context of applied hydro-ecology. To this end, a special effort is made to reference a wide range of supporting material.

**THE CONTEXT OF APPLIED HYDRO-ECOLOGY**

**The human impact on the river environment**

Artificial regulation of river flows has been undertaken for at least 8000 years, but has increased dramatically over the last 100 years. Such regulation has been designed to meet increasing human needs for water and power, caused both by population increases and improved standards of living. Regulation is often designed to smooth out

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<th>Type of hydrological variation</th>
<th>Regulation</th>
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<tr>
<td>Water shortage: between and within years</td>
<td>Impoundments, surface water abstraction, groundwater abstraction, aquifer recharge</td>
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<td>Flooding</td>
<td>Impoundments, channel modification</td>
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<td>Spatial</td>
<td>Water transfer schemes</td>
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temporal and spatial hydrological variation, as illustrated in Table 1. Combinations of river impoundment and channel modification have also been used to reclaim land for agriculture and development and subsequently to protect the land from unwanted flooding. Water may also be used in irrigation of this land. The World Commission on Dams (2000) noted that at least one dam affects 46% of the world’s 106 primary catchments and that the US and EU regulate the flow of 60–65% of their rivers.

Exploitation of groundwater resources in both humid and arid regions has in some cases led to overexploitation and reductions in river flows at times of year considered critical to instream ecology (e.g. Elliott et al., 1999). Recent dam construction in Europe and America has decreased dramatically, however worldwide, it continues. For example world hydropower production is predicted to grow at 2–3% per year (Thanh & Biswas, 1990), there are an average of 160–300 new dams commissioned per year, and 1700 large dams under construction (40% in India) (World Commission on Dams, 2000).

### Hydro-ecological application: instream flows

Very often, such river regulation has gone hand in hand with engineering efficiency, with environmental values of low or no concern (Collier et al., 1996). Controversy provoked by disagreements surrounding predicted environmental impacts is common (International Rivers Network, 1997). This has been despite the fact that the link between the regulation implicit in such water projects and declines in ecological quality, notably fisheries, has been known for some time (e.g. Gustard et al., 1987).

In some cultures, recognition of rights of instream water uses goes back thousands of years; in the UK, human-orientated water rights became formalized during the industrial revolution. Following a rapid increase in water resource development in the twentieth century, although there were some early attempts at providing for downstream environmental requirements when developing water resource schemes (e.g. Baxter, 1961, Stalnaker & Arnette, 1976), it was not until later in the 1970s that significant progress was made in addressing flow-related environmental concerns in a formal fashion. This led to explicit acceptance that water remaining within a river (the “instream flow”) can simultaneously perform multiple useful functions; examples of which are outlined in Table 2.

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<th>Table 2</th>
<th>Values of instream water uses.</th>
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<tr>
<td>Fisheries (recreational and commercial)</td>
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<td>Whole-river ecology (King et al., 2000)</td>
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<tr>
<td>Biodiversity (IUCN, 2000)</td>
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<td>Protection of important, rare or endangered species</td>
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<td>Recreation (Whittaker et al., 1993; Flug &amp; Montgomery, 1988)</td>
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<tr>
<td>Prevent saline intrusion into estuaries</td>
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<td>Dilute effluent (Thanh &amp; Biswas, 1990)</td>
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<tr>
<td>Prevent algal blooms (Biggs, 1996)</td>
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<tr>
<td>Protect cultural features, visual amenity, aesthetics (Coles, 1995; Tunstall et al., 1997)</td>
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<tr>
<td>Maintain channel diversity</td>
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<td>Maintain sediment and flood carrying capacity (Blood, 1987; Hill &amp; Beschta, 1991)</td>
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<tr>
<td>Prevent proliferation of pest species (O’Keefe, 2000)</td>
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<tr>
<td>Maintain supply for downstream human uses</td>
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In the 1990s, internationally, there is a genuine belief that the environment is a legitimate user of water. Some countries have gone further, for example Australia: “water belongs to the environment”. Principle 9 of the new water law of South Africa states that: “the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems”. The European Commission has stated that “water is not a commercial product but, rather, a heritage, which must be protected, defended and treated as such”, although this is certainly disputed in many cases. Demands for water supply will continue to increase, both in the developed and developing world (Gleick, 1996). The need to balance direct human uses with environmental protection has led to the following developments:

**Scientific:**
- quantitative environmental assessment methods such as habitat modelling (Stalnaker, 1995);
- procedures for interactive design of desired environmental flow regimes even where data may be sparse (King et al., 2000);
- increased appreciation of the value of past data in making difficult water management decisions.

**Institutional:**
- an environmental assessment framework of new and existing water schemes, including a “tool box” of techniques to be applied as appropriate;
- acceptance of the link between biodiversity and sustainable development (Agenda 21—UN Conference on Environment and Development, 1992) and their incorporation in the remit of resource management agencies (Gallagher, 1996; Gow, 1996);
- increased appreciation of the benefits of multiple water uses and users;
- application of integrated catchment management, including iterative development of management objectives via catchment stakeholder participation;
- procedural/allocation improvement (e.g. water licensing, consistency and transparency of decision-making process).

**Abiotic–biotic interactions in freshwater ecology**
Concurrently with the development of the instream flow concept, freshwater ecologists began to synthesize their huge but diverse knowledge base (e.g. Hynes, 1970). Giller & Malmquist (1998) give a later treatment of the basic concepts in freshwater ecology, while Calow & Petts (1992) and Harper & Ferguson (1995) provide more detailed overview of key topics at the interface between science and management. Conferences in the early 1980s (Lillehammer & Saltveit, 1984; Craig & Kemper, 1987) and then a synthesis by Petts (1984) set the stage for an understanding of the effects of impoundment regulation. Smith (1992) and Vogel (1994) provide further insight into fundamental ecological topics relating specifically to water movement.
Coming from an ecological perspective, there have been several key publications which have set the stage for the concepts and methods in applied hydro-ecology. These include (partly based on Petts, 2000) papers relating to hydrology-ecology links (Junk et al., 1989; Bayley, 1991; Poff & Ward, 1989; Poff et al., 1997; Puckridge et al., 1998), the importance of habitat, particularly hydraulic habitat in controlling freshwater biota (Statzner & Higler, 1986; Statzner et al., 1988; Hildrew & Giller, 1994; Hildrew, 1998; Poff & Ward, 1990), water temperature (Stanford & Ward, 1979; Jacobsen et al., 1997; Ward & Stanford, 1995) and energy flow and connectivity (Vannote et al., 1980; Petts & Amoros, 1996).

In addition to the explicit recognition of a range of spatial scales in hydro-ecology, there is a further requirement, that the dynamic nature of rivers, driven by variation in a range of physical factors (such as hydrological, solar, temperature cycles) is of fundamental importance. Jewitt et al. (2001) states “Environmental sciences require consideration of nested systems across spatial and temporal scales and the linkages and intricacies among and between the various components”.

Thus we conclude that explicit consideration of both space and time is essential in hydro-ecological studies. Some topics in freshwater ecology and hydrology (such as empirical explanations of species distributions, hydrological modelling which concentrates on reproducing a regime at a catchment outlet) are often of limited use in applied hydro-ecology.

**Hydro-ecology: the link to impact assessment and prediction**

There are considerable compromises that must be made when transforming our existing breadth of knowledge of hydro-ecology into practical tools for river flow management. Despite the fact that rivers are complex, changing hydrological and ecological systems, targets for flow management, or indices of flow regime change will necessarily need to be made simple in order for them to be implemented. Unfortunately, the simplest objective is a single “minimum flow”. Seasonal criteria and position within catchment are critically important elements, natural hydrological variation must be considered. Furthermore there is a danger, if a minimum flow is defined, for it to become an expectation.

One must recognize that for the foreseeable future, our knowledge of the environmental requirements of rivers will remain incomplete. In this case, there will always be a danger that the objective will be set too low, resulting in damage to a river, or too high, resulting in potential waste of resources, or exploitation of other more sensitive water resources. Thus we emphasize the importance of a precautionary approach, combined with sound science in Instream/Environmental flow investigation and assessment.

The papers in this volume give an idea of some of this science. In this overview, the following characterization has been adopted:

- data and modelling,
- applications to applied problems,
- frameworks for decision making.

With this background, it can be seen that the papers presented in this volume serve two functions: they both inform the body of scientific knowledge and they give great hope
that practical approaches to instream/environmental flows are possible. Some key points, outlined further in the next few pages are that:

- river physical habitat is dynamic (Rountree et al., 2001), conceptual models can be useful;
- long-term data before and after studies are vital (Wood et al., 2001; Sutcliffe & Parks, 2001);
- understanding of process is essential if predictions outside of calibration range are to be made (Hardy & Addley, 2001);
- simple models can be useful both for understanding process and for building stakeholder participation (Jewitt et al., 2001);
- true interdisciplinary team studies are not new (Sutcliffe & Parks, 2001).

COLLECTION AND ANALYSIS OF HYDRO-ECOLOGICAL DATA, AND MODELLING

Abiotic and biotic data

The scientific study of both hydrology and ecology requires data. However a glance of the subjects' published literature or textbooks would show that approaches to the gathering and processing of these data have often been linked closely to the academic discipline of the practitioner. For example "... full interdisciplinary collaboration between biologists and geomorphologists has been slow to evolve and the full benefits of such collaboration are yet to be realized" (Petts, 2000). This may be due to a worldwide lack of postgraduate training in truly interdisciplinary freshwater science. In some circumstances discipline-based teaching can lead to each discipline (hydrology, ecology) viewing the other in an over-simplified fashion.

In addition to the challenge of undertaking true interdisciplinary data collection, the science of environmental flows in itself presents further technical challenges. There are issues associated with:

- finding adequate treatment/control sites,
- difficulty in demonstrating relationships due to multiple operating factors (cause and effect), and
- measurement/sampling problems—related to spatial and temporal scaling: to investigate multiple factors requires long time series.

Rigorous experimental approaches, despite the difficulties in achieving them, are highly desirable. An elegant example of experimental work is given in Downes et al. (1998), while potential problems are documented in Anderson & Gribble (1998), Michener (1997), Underwood (1991, 1992). In this volume, Oyebande (2001) documents experimental flood releases of varying magnitudes in order to determine the link between discharge regime, inundated flood plain and fish productivity.

Hydrological, hydraulic and ecological modelling

There are some differences between the "traditional" approaches taken by hydrologists/hydraulicians and ecologists. Hydrologists work on the basis that
hydrological processes are governed by physical laws, which can be deduced directly from theory and indirectly through the development and testing of process-based models. General introductions to hydrology can be found in Shaw (1994), Wilby (1997) and Gordon et al. (1992). Hydrological models range from fully process-based (such as MIKE-SHE—Abbott et al., 1986) to mostly conceptual, e.g. IHACRES (Jakeman et al., 1991). Even the more conceptual models still incorporate some intuitive degree of process representation.

Ecological science, on the other hand, due to the variability and complexity of natural systems, has tended to be more directly data-driven. Models are often constructed to answer specific questions, and while they may be dynamic or steady-state, compared to hydrology there are few process-based generic approaches (e.g. D’Angelo et al., 1997). In recent years, the development of energetics-driven models of fish habitat use (Hayes et al., 2000; Guensch et al., 2001) offers one example of a breed of process-based ecological model that could in the future offer vastly improved impact assessment prediction if coupled with appropriate hydrological/hydraulic models.

Often freshwater ecologists view hydrology as a means to an end in terms of explaining observed abiotic–biotic linkages. Furthermore, few hydrologists are interested in spatial distribution of flow along a river*, instead concentrating on reproducing a flow regime at a gauging station (leading to understanding of process and making of predictions under some future scenario). Thus a major opportunity, that of hind-casting synthesized spatial hydrological data at ungauged sites, and its use to explain observed patterns of biota is so far being neglected.

Themes from papers in this volume

In this volume, a broad range of approaches is apparent. Wood et al. (2001) describe a hydro-ecological study on a single river, making use of a set of sites, and crucially, six years of detailed biological data. These data were collected using a standardized methodology and at the same time of year, and covered a range of preceding climatic conditions. The breadth of these data in time and space (along a river system) allows powerful inference to be made about community change driven by hydrological variables. More work is required to the derived relationships on these rivers. Other papers to note in this area are: Clausen & Biggs (1997, 2000). Sutcliffe & Parks (2001) similarly emphasize the importance of long-term data, while Oyebande (2001) highlights problems with separating the effects of drought and artificial regulation through observation alone.

At the other extreme, the paper by Hardy & Addley (2001) describes intensive sampling to quantify fish habitat use. They use a hierarchy of high-technology techniques to enable intensive data collection. Starting with remotely sensing imagery used to map river habitats over long distances (and thus select and classify field sites), a combination of photogrammetry and acoustic (echo-sounder)/GPS (global positioning by satellite) technology to obtain out-of-water and in-water topography,

* Situations where spatially distributed flows/routing are needed are (a) flood hydraulic modelling, and (b) water quality modelling (in the latter, the hydrology required is often highly simplified).
and further acoustic and GPS technology to map accurately water velocity fields in multiple dimensions. The data are used to test/validate, and upscale process-based models of fish response to hydraulic habitat, which are, it is hoped, able to be transferred with confidence to river systems where impact assessment is required.

Somewhere in between these two approaches lies the work described by Linstead (2001) and Buffagni (2001). Both describe hydro-ecological investigations that contain novel elements. In the case of Linstead (2001), the use of hydraulic modelling to examine the effects of Large Woody Debris (LWD) on fish habitat, in the case of Buffagni (2001), the linkage of river flow and production of invertebrate biomass.

Linstead (2001) describes an approach to the study of Large Woody Debris (LWD) in small rivers. LWD is considered to be ecologically important (Lemly & Hilderbrand, 2000; Thevenet & Statzner, 1999), and must act, in part, through its effects on channel hydraulics. As part of a wider study, Linstead (2001) applied the PHABSIM suite of hydraulic models in order to predict water depths and velocities for conditions both with and without LWD, across a wide range of flow conditions.

This contrasts well with the approach taken by Buffagni (2001), who set about answering the very general question of what should be the minimum residual flow in a regulated reach of river. This was undertaken by looking at linkages between river flow and invertebrate production through a habitat-based approach. Instead of a direct numerical description of habitat, as is used in a model such as PHABSIM, Buffagni (2001) uses a more geomorphological approach, defining habitats through visually recognizable characteristics, then linking the habitats both to invertebrate communities, and thus production, and to flow, through the field mapping of how habitat composition changes with flow. This work is complementary to studies by Kemp et al. (2000), Parasiewicz (2001), while Fisher & Kummer (2000) similarly demonstrated the effects of habitat fragmentation on the distribution and movement of bullhead (Cottus gobio). The importance of setting instream flow recommendations in a geomorphological context is highlighted in the paper by Rountree et al. (2001), who highlight the dynamic nature of channel forms in a semiarid river.

Whereas most papers in the volume have concentrated on physical aspects of hydro-ecology, water quality is clearly a vital component in understanding impacts of the aquatic ecosystems. García et al. (2001) have recorded arsenic concentrations in river sediments ranging from 96 to 6575 mg kg\(^{-1}\) in the Tolimán River near Mexico City coming from lead, silver and zinc mining. The fluvial processes disperse and, in some cases, concentrate pollutants that are later incorporated into the food chain through absorption and retention by the plants.

APPLICATIONS OF HYDRO-ECOLOGICAL SCIENCE

Reference condition and ecological integrity

In the past, it has been common to describe river ecosystem deterioration in terms of the health of populations of key species (chosen for a variety of reasons—economic, or “indicator”), often in terms of departure from a reference condition. More recent thinking is that for a river to be able to perform functions useful to society (such as
those in Table 2), its own internal biological composition should itself be functioning. But how should that be measured? One way of looking at this is to try to define overarching concepts such as “ecological integrity” (Karr, 1991; Karr & Chu, 1999; Jungwirth et al., 2000) and ecological status (European Parliament and Council, 2000). However, these concepts are relatively new, and quantitative hydro-ecological science is only just beginning to operationalize such concepts previously thought of as abstract (Maddock, 1999). Cairns (1995) sums this up by stating that we are simply lacking ability to measure this at the correct scale (large) so we resort to reductionist approaches. A similar argument is put forward by Jewitt et al. (2001) who states that “any judgement of integrity depends on scale”.

What is clear is that hydro-ecological science must simultaneously become more sophisticated in quantifying ecosystem processes (the absence of ill-effects in individuals does not mean no ill-effect overall) and yet also more simplistic, in that it must be capable of summarizing current and future “status” at the catchment scale and higher.

The search to predict

Moving beyond approaches for assessment of status, which is covered in some detail elsewhere (e.g. Jungwirth et al. 2000; Rogers & Bestbier, 1997), there exists several fundamental questions:
- what is the desired future (improved) status of individual rivers?
- what actions should be taken to move towards that status?
- how much will it cost?

In many cases, a river system will be subject to a “cocktail” of impacts, to its physical structure, hydrological regime and chemical composition, so that given the direct financial costs of making changes, accurate predictive models are vital. Integrated models are required for such complex problems, the level of detail can be tailored to the urgency with which an answer is required and the perceived importance of the impact (Dunbar et al., 1998).

A modelling approach may still be appropriate to predict the extent of change in ecological status in cases of single-issue impact, however, model extent and complexity should be appropriate to the scope of the problem. A “model” may primarily involve transfer of knowledge from other systems to the impacted system under study. It may be that such spatial substitution modelling can, with some fine-tuning (for example overcoming scale effects), obviate the requirement for extensive additional data collection. Observation of cause and effect is unfortunately often confounded by the extensive natural variability that river systems exhibit.

In other cases, a trade-off between approaches is evident:
(a) the approach sometimes favoured by ecologists (the proposition that all aspects of a natural flow regime are in some sense ecologically important (Richter et al., 1996; Poff et al., 1997), combined with historical knowledge of how other, similar-yet-different river systems are known to have responded), and
(b) the use of simplified predictive models, calibrated to specific river reaches (commonly favoured by engineers). The required upscaling (e.g. to subcatchment/river segment level) is commonly achieved by selection of reaches
to represent the mapped river segment (Jewitt et al., 2001; Vadas & Orth, 1998; Jowett, 1993; Maddock & Bird, 1996), and is not without its problems (Poole et al., 1997).

Time and economic constraints often feature. Considerable effort is currently being expended in trying to move these two ways of thinking (which can be considered as bottom up and top down) closer together. King et al. (2000) summarize progress in this area.

Themes from papers in this volume

The utility of monitoring-based approaches, such as in Wood et al. (2001) has been demonstrated by Extence et al. (1999). Firstly, they demonstrated a relationship between historical river flows and an aggregate index of invertebrate community structure (termed “LIFE”). They then propose to capitalize on the extremely large amount of invertebrate biomonitoring data collected for biological water quality assessment and classification. Issues of scaling and the generality of relationships across catchments still need to be addressed, as do the utility of the discharge indices used. Extence et al. (1999) identifies summer flow variables as most important, while Wood et al. (2001) suggest flow 4–7 months before.

In the paper by Buffagni (2001), development of an assessment technique is also very much in the forefront, it contains elements of a habitat-based approach, with particular emphasis on relating the timing of flow events to the life cycles of particular invertebrates. Fuchs (2001) illustrate a specific model, designed to model shifts in flood-plain vegetation associated with different water level management strategies, and thus determine “acceptable” variations in stage in regulated waterways. Whatever constitutes acceptable must still be defined, either using a traditional management planning approach or a more holistic typology-based approach such as that advocated by the European Water Framework Directive (as considered further in the next section).

The Sutcliffe & Parks (2001) paper provides a clear indication of the impacts of altered hydrology on the ecology of a large area, and its use of spatial variation and habitat elements to help work out mechanisms is noteworthy. Despite the fact that much of the data was collected decades ago, they demonstrate a clear method of deduction that the hydro-ecologists of today would do well to follow. In particular, they emphasize that mechanistic approaches are important if predictions are to be made, and give examples of mitigation proposals. They elucidate key parameter such as critical water levels from available data and use hydrological models to hindcast abiotic conditions again to link with biological data. Finally, they predict the effects of feasible alternative regimes, rather than adopting the current fashion for determining “acceptable” flows or achieving a certain status.

The paper by Abam (2001) illustrates several general issues associated with determination of impact from regulation, as well as more specific problems associated with dams. As with many cases, not just in developing countries, abiotic data are sparse, particularly pre-project data, ecological data even more so. This makes inferences about causes and effects, and key abiotic drivers difficult. However the author is able to make general inferences because of the knowledge he transfers from
more detailed studies undertaken elsewhere. The effects of dams both on flood regime and downstream sediment supply are well known, however he makes the point that following dam construction, there is further progressive change in these key abiotic drivers; as the impoundment slowly fills with sediment, the flood attenuating power of the dam reduces.

In using the PHABSIM model suite, Linstead (2001) applied a commonly used set of techniques in a novel setting. PHABSIM, as one of the components of the Instream Flow Incremental Methodology is commonly used to model impacts of water resource schemes on the physical habitat potential in river systems. Parasiewicz & Dunbar (2001) review the current state-of-the-art in habitat modelling, while Hardy (1998) provides a look towards the future. The semi-empirical, semi-process approach has been much criticized in the past, Hardy & Addley (2001) give an indication of the data requirements involved in developing and testing a new generation of abiotic models underpinned by a better understanding of process.

HYDRO-ECOLOGICAL FRAMEWORKS

Acceptable impact or desirable state?

The previous section outlined some of the processes involved in linking abiotic changes to biotic impacts. However, there remains the further step of using the knowledge of such linkages to manage positive changes (such as the abstraction of less water or the creation of new river habitats). So before defining how much water a river requires, or what is a desirable channel form, it is first necessary to determine broader objectives, which indicate the type of river desired.

When asked what “state” our rivers should be in, many people respond immediately that they should be natural. But traditionally, many rivers that are far from natural have been considered perfectly acceptable from the point of view of aesthetics, recreation, fisheries, and often conservation of rare species (Acreman et al., 2000). In some cases, people may find natural rivers unacceptable as they may not be visible due to bankside trees (Sear et al., 2000). In protected areas, degradation can be measured against a defined ecological status related to the reason for designation. In such cases, where specific objectives have been set, a biological baseline exists against which to consider potential impacts and improvements. For other rivers, the development of River Basin Management Plans by relevant authorities commonly involves the direct input of local stakeholders in establishing a vision and action plan. This marks a move towards increased community participation in deciding on the objectives for rivers. Scenario-based analysis may be used in conjunction with objective setting, or may be useful in its own right. Paradoxically, scenario-based approaches should be most useful either for rivers where nature management is the highest over-riding priority (Richter et al., 1996), or when considering heavily modified water bodies where the objectives will always be set by what is possible given directly-measurable economic constraints.

Apart from purely ecological reasons, such as the conservation of rare or endangered species that are important for biodiversity, environmental objectives may be driven by the high economic value of a river as a fishery or important social
reasons, including amenity and recreation facilities. However, the approach of the European Water Framework Directive marks a shift in thinking for river management in Europe. It requires that a reference status is defined for all rivers based on preservation of communities and functions when compared to type specific communities. This will have far-reaching consequences for river management.

Themes from papers in this volume

In the paper by Freistühler et al. (2001) the authors suggest that “For the ecological assessment of water projects, a detailed prediction of the hydro-ecological effects is needed in order to estimate future environmental damages”. Their system does rank alternatives, but it also appears to have absolute values. A key issue for application of such a framework, as mentioned previously is the balance between transferred and river-specific data. The paper takes a very generic habitat-based approach, relying on firstly habitat predictions of pre and post conditions, and secondly, categorical descriptions of habitat preferences, linked to generic semi-quantitative models (such as one predicting changes in benthic shear stress from flow alteration).

The paper by Xia et al. (2001) is an attempt at developing an even more generic approach for regional (or at least spatially distributed) generic assessment. It goes beyond traditional integrative approaches such as multicriteria analysis in a number of ways. It is multivariate, and centres around deriving an optimal solution given the available input data (from monitoring programmes). It uses normalization, so that whatever the natural scales of the data, they can be integrated. Pattern recognition is used to determine a series of relational functions which link data for individual determinands to pre-defined environmental quality standards. Final assessment of quality over all determinands is undertaken using weightings which take into account the different dimensions of the data, so that should there be a set of variables that are highly correlated, their overall individual weights will be less.

In contrast to some of the other frameworks in this volume, the paper by Jewitt et al. (2001) documents a working decision support system (DSS), that can, and has been used by managers as well as research scientists. A primary aim of their DSS is to be a tool to facilitate collaborative work. And although they take a modelling approach to link biotic response to abiotic drivers, they emphasize that the purpose of the model is to “illustrate general patterns of system behaviour rather than to make specific predictions”. This is in contrast to other examples of DSSs which develop into oversimplified tools to be handed over from scientists to managers. Their experiences mirroring those of Petts (2000), they emphasize that the members of successful interdisciplinary teams most often have to set aside their most “precious” detailed disciplinary analytical methods.

Also in contrast to current trends towards more holistic ecosystem response models, they echo Schraeder-Frechette & McCoy(1994) in proposing that improved models for individual species is a more pressing and achievable goal than complex ecosystem modelling. But whilst noting that representative-reach-type approaches are one of the only ways of incorporating catchment-specific data at a sensible scale, they also successfully upscale their work (Habersack, 2000) by sacrificing detail to “reveal larger spatial and temporal ecological patterns representing whole-system properties”.

RESEARCH NEEDS

Discussion of the papers contained in this volume leads naturally on to a summary of the needs for the future in interdisciplinary hydro-ecological research.

In 2001, the two key needs are still:

1. Functional connections between disciplines. This has not yet been achieved except in rare cases (Jewitt et al., 2001). More specialists must be trained in the skills required to work at the interface between disciplines such as hydrology and ecology.

2. Greater feed-through of developments in basic science (both hydrological and ecological) to produce general rules capable of supporting planning decisions taken at the catchment scale, and able to direct location and information requirements of more detailed study within a catchment.

A fine line needs to be trodden in that there is clearly a demand for more sophisticated models capable of describing and predicting abiotic driven biotic changes. Yet working at the interface between disciplines will necessarily require a fundamentally more simplistic approach than is commonly adopted by most research hydrologists and ecologists. More can be learnt from the methods that geomorphologists have adopted in this regard.

There is also a place for interdisciplinary assistance within detailed disciplinary science. Many freshwater ecologists studying species autecology or food web dynamics have an interest in abiotic driving factors. In recent years, more of them are collaborating with hydrologists and hydraulic engineers from the outset, rather than simply reading the excellent introduction given by Gordon et al. (1992) and proceeding on their own.

Many of the following further needs are highlighted by examples from this volume, key further references are included:

- pooling of expertise from different disciplines;
- experimental catchment studies to underpin future legal frameworks (such as the HELP initiative, Wallace, 2001);
- more detailed studies to elucidate process (such as to move away from empirical habitat models) (Hardy & Addley, 2001);
- recognition that detailed hydro-ecological studies can ultimately be used to underpin assessment methods, but not necessarily applied in assessment themselves;
- move away from univariate approaches (Xia et al., 2001; Freistühler et al., 2001);
- novel applications of existing approaches (Linstead, 2001), in the future this could be applied in developing countries, such as to disease vectors;
- better frameworks (Jewitt et al., 2001; Freistühler et al., 2001);
- long-term data (Abam, 2001; Sutcliffe & Parks, 2001);
- experimental/manipulative/before and after studies (Linstead, 2001; Michener, 1997; Anderson & Gribble, 1998).

In the twenty-first century, striking a balance between the environment and human demands will require ever closer collaboration across the physical and biological sciences. Some examples of the drivers and mechanisms, which will cause this to come about, are listed in Table 3.
Table 3 Some examples of the drivers and mechanisms striking a balance between the environment and human demands.

<table>
<thead>
<tr>
<th>World</th>
<th>Policy drivers</th>
<th>Research networks</th>
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<tbody>
<tr>
<td></td>
<td>Agenda 21 (UN Conference on Environment and Development, 1992)</td>
<td>HELP initiative (Hydrology for Environment, Life and Policy)</td>
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<td></td>
<td>Convention on Biodiversity</td>
<td>UNESCO programme on eco-hydrology</td>
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<td></td>
<td>World Commission on Dams (2000)</td>
<td>Future workshops at conferences (IAHS, Eco-hydraulics, regulated streams)</td>
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<td>National examples</td>
<td>Catchment abstraction management strategies (UK)</td>
<td>COST Action 626 “European Aquatic Modelling Network”</td>
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<td>LOCAR programme (UK)</td>
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As quantitative knowledge and prediction have been key arguments throughout this paper, we conclude by emphasizing the following quote "... we are essentially asserting a belief in quantitative knowledge—a belief that most of the key questions in our world sooner or later demand answers to 'by how much' rather than merely to 'in which direction'" (Tukey, 1977).

REFERENCES


