Ecohydrology: Processes, Models and Case Studies

An approach to the sustainable management of water resources

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A catalogue record for this book is available from the British Library, London, UK.

Library of Congress Cataloging-in-Publication Data
Ecohydrology : processes, models and case studies : an approach to the sustainable management of water resources / editors, David Harper, Maciej Zalewski & Nic Pacini.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-84593-002-8 (alk. paper)
1. Ecohydrology. 2. Water-supply–Management. I. Harper, David M. II. Zalewski, Maciej. III. Pacini, Nic.

QH541.15.E19E263 2008
551.48–dc22

2008007715

ISBN-13: 978 1 84593 002 8

Typeset by AMA Dataset, Preston.
Printed and bound in the UK by Cromwell Press, Trowbridge.

The paper used for the text pages in this book is FSC certified.
The FSC (Forest Stewardship Council) is an international network to promote responsible management of the world's forests.

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Preface

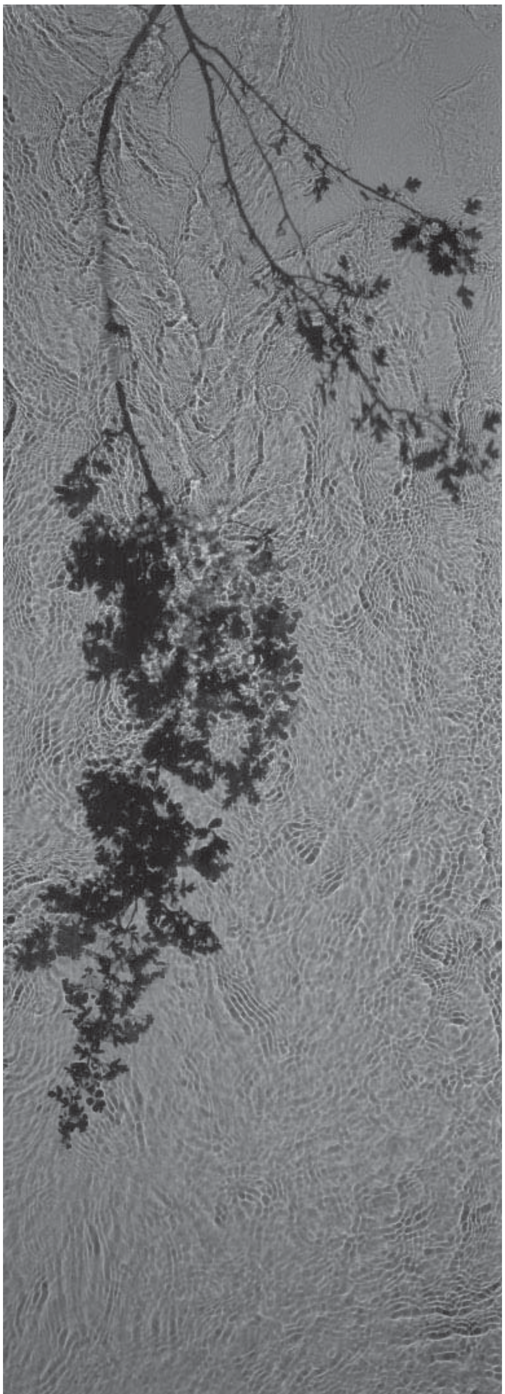
The River Taw flows from its source in the high ground of north Dartmoor to the north Devon coast near Barnstaple. Its journey is one of change, growth, maturation and dispersal. It is a long transparency embodying an infinite number of liquid states – I think of it as a living entity reflecting a human microcosm.

Susan Derges, 1997

Scientific discourse is absolutely loaded with metaphors, and it must be so in order for it to have meaning. It's not a bad thing, it's a good thing, but of course, you have got to have the right metaphors. The dominant metaphors in biology at the moment are metaphors of survival, competition, selfish genes etc., which has its origins in Darwinism and 19th-century economics, but it seems to me that a better metaphor, one that is truer to nature, is that of creation and transformation, and therefore inevitably participation. Participation involves subjectivity, which is a very tricky area for most scientists, because subjectivity has no obvious rules. . .but I believe that subjectivity, and intuition, are in fact the source of understanding wholes and the reality of nature. You can understand the parts with your analytical mind, but to understand the whole you have to use your intuition, and that involves participation.

Susan Derges in dialogue with Brian Goodwin, 1997

Overleaf: Susan Derges photogram *The River Taw (Hawthorn), 25 May 1998*



1 Linking Biological and Physical Processes at the River Basin Scale: the Origins, Scientific Background and Scope of Ecohydrology

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What is Ecohydrology?

Ecohydrology, as used in this book, is a new term (used since the late 1990s) to describe a new scientific way of managing the water cycle in order to achieve the sustainable use of water by societies. It is an understanding of how hydrological processes integrate with ecological ones (e.g. the discharge regimes of rivers, lakes, wetlands and reservoirs influence the populations and interactions between them, superimposed on dynamics of their physical performance in ecosystems) and conversely, how ecological ones may subsequently regulate hydrological ones (e.g. how distribution of vegetation in a catchment affects the hydrological cycle by modification of evapotranspiration and runoff at basin scale, riparian vegetation and debris dams in headwaters and floodplain wetlands in lower reaches of rivers regulate discharge timing). It then integrates the knowledge of those two processes and uses it to find innovative solutions to the problems of river basin degradation caused by our society.

Ecohydrology is thus a sub-discipline of hydrology, dealing with the ecological aspects of the water cycle. It is based on the assumption that hydrological processes are the major abiotic drivers of natural ecosystems – the main templet (Southwood, 1977) of lotic systems for example (Zalewski and Naiman, 1985; Poff and Ward, 1989). Thus the authors in this book use the term 'Ecohydrology' as opposed to 'Hydroecology', because they see the need to understand how hydrology regulates ecology (and how biota affect local hydrology), in order to utilize that knowledge to achieve the optimal management of ecosystem capacity.

Eighty-three per cent of the land surface of this planet has been modified by the engineering activities of human beings (Meybeck, 2003), in most cases without any understanding of how the impacts of those modifications have changed processes in natural ecosystems, such as biogeochemical cycles and energy flows. Virtually all those modifications have had direct and indirect impacts upon disturbances of the water cycles, sometimes both locally and globally. The technical benefits that many of these modifications brought (e.g. power and drinking water from dams, food from irrigation, treatment of sewage) have not been shared equitably around the world and, as a result, access to safe water is a major one of the UN Millennium Development Goals (United Nations, 2005).

Ecohydrology addresses solutions to the global problems of the 21st century through enabling scientists to identify how they can use the ecological regulatory processes to increase the assimilative capacity of ecosystems (Zalewski, 2000), particularly their change in resilience and adaptation in the face of global changes (e.g. Chapin *et al.*, 2006).

Ecohydrology is a thus a new way of thinking and acting for scientists, most of whom are, even today, usually sectorially-educated. It offers insights into environmental processes, integrating water resources and ecosystem sciences, based not only on hydrology and ecology but also considering molecular biology, genetics, chemistry, as well as socio-economic and legal sciences. It proposes a new scientific paradigm, or way of thinking and seeking solutions to the many new problems that humankind's development has created. Most of the problems have been caused by the way in which society has sought to utilize and 'tame' nature over the past few centuries. The utilization has now frequently become over-utilization (e.g. over-fishing, soil erosion) and the 'taming' (e.g. rivers for flood control, dams for hydropower and water supply) has resulted in simplification for single goals, which has now led to major losses elsewhere (e.g. loss of floodplain assimilative capacity for water quality and quality after its disconnection from the river channel) (Fig 1.1).

Practicing science in an interdisciplinary fashion is necessary for achieving the acceptance of a regulatory science by society, which itself is the only way to achieve sustainable development goals. It has been seen as the necessity for maintenance of scientific research funding; is expressly stated within the Millenium Development Goals; is essential for ecosystem rehabilitation and restoration (Hulse and Gregory, 2004) and has been identified as a need in a critical review of ecohydrological and related concepts (Hannah *et al.*, 2004). It is a natural stage in the evolution of a new paradigm, as will be shown in this book. The International Council for Science (ICSU, 2005) has identified key elements of 21st century sciences to be integrative, problem-solving and interdisciplinary. Ecohydrology provides these three elements.

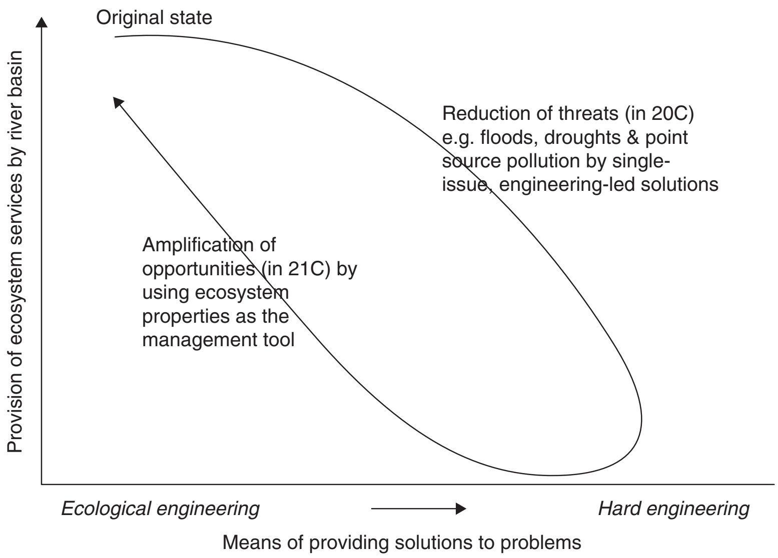

Fig. 1.1. Ecohydrology principles in the context of decision-making theory. Modified from Zalewski *et al.* (1997).

The Definition(s) of Ecohydrology

In its development, ecohydrology has been given several different definitions; none of them yet in hard-copy dictionaries. Its origins are clear - it comes from *eco*, *hydro* and *logy*, derived from the Greek, *oikos*, *hudôr* and *logos*, respectively meaning house, water and science. Therefore eco-hydro-logy is the science of water and ecology. It has not yet though achieved a single definition established by agreement or by common usage. Its range of definitions is most easily found through an internet search-engine, or a keyword search on a science database. Three subject areas appear. The first is focused upon plant–water dynamics on land – ranging from a single species, through vegetation type to a landscape and its (micro)climate (Baird & Wilby, 2001). The second is more connected with quantities in the water cycle and the impact of changes in quantity upon ecology in rivers (Acreman, 2001). The third meaning is inclusive of the subjects addressed by the first two and advocates an integrated vision of physical and biotic processes driving the dynamic evolution of river basins (Zalewski, 2006); it is this one that has driven the production of this book.

Two terms have been commonly involved in these three areas of development – ecohydrology and hydroecology. These and the three contexts in which they had been used, were given a thorough review by Kundzewicz (2002a). He made the point that any new concept passes through a phase of multiple uses of its descriptive terms. In describing ecohydrology, he wrote:

> It is indeed being *in statu nascendi*, offering scientific challenges galore, room for excitement and dynamic development. It will take some time before the notion ripens and a broad consensus is reached.

The value of the term was also debated in an issue of the *Hydrological Sciences* Journal in the same year (Kundzewicz, 2002b). Bonnell (2002) concluded his discussion with the comments, 'Thus the ecohydrology umbrella is providing a means of integrating landscape hydrology with freshwater biology, and this is the important paradigm shift.'

The term, as it is defined in this book, is the most widely used in the scientific world. It was first defined by Zalewski *et al*., (1997) in the technical manual introducing it as a sub-programme of the 5th UNESCO International Hydrological Programme (IHP) initiative. As a consequence of the Programme's development, a more appropriate definition now is:

> The quantification and modelling of the dual regulation of biota by hydrology and vice versa within a basin, understanding their modification and synergistic integration in order to buffer man-made impacts with the ultimate goal of preserving, enhancing or restoring the capacity of the basin's aquatic ecosystems for sustainable use.

The concept that this definition espouses, falls into four linked parts:

- It is first of all *a scientific approach,* which can generate testable hypotheses and hence offers transparent rigour about the *dual regulation*. It represents a key to the interpretation of empirical data and models.
- Second, the concept is used to *promote integrative science* – hydrology and ecology – *for problem-solving* between professional scientists, decision-makers and stakeholders, at a river basin scale.
- Third, the integration directs the management of natural processes in the water cycle within the basin to try to *enhance the resilience, resistance and adaptation of aquatic ecosystems*.
- The ultimate goal of this management is to provide *sustainable use of a river basin's natural resources* for the benefit of nature and its human population.

The Need for Ecohydrology

Every country in the world has problems of water allocation because there is too little, of the right quality, in the right place. The government of every country in the world recognizes this, though few are taking action, many recognize it but are taking limited action, and too many recognize it but are doing nothing because the timescale of the solution exceeds the timescale of government rule. UNESCO (the lead agency in science) and UNEP (the lead agency in environment), among the major inter-governmental organisations addressing environmental issues, had recognized the problems of water scarcity and allocation in their support for the ecohydrological approach. Implicit in this support is the recognition that past water management approaches are no longer appropriate or effective for the 21st century, and new approaches are needed.

Former water management consisted of capital-intensive, high-technology, engineering-based schemes (collectively known as 'hydro-technology'). Construction of dams, water diversion, flood relief, agricultural development implying drainage and irrigation, and sewage treatment schemes all fit this description.

The schemes almost always tried to control, or at best to exploit, the natural elements of the water cycles rather than work with them. They almost always resulted in more widespread and unpredicted deterioration of the natural components of the water cycle. Individually-small perturbations can be seen almost everywhere on the globe; for example on a very small scale, the eutrophication of Esthwaite Water in the English Lake District was begun by the construction of the sewage treatment works in the village of Hawkshead, when a piped water supply was first laid into the village in 1923 and flush toilets replaced earth closets (Pennington, 1981). Individually-large and catastrophic examples are not so ubiquitous and not so obvious to the 'ordinary person', implying that such mistakes continue to be repeated; for example the damming of rivers in Africa or the salinization and drying up of the Aral Sea in Central Asia (shared by Uzbekistan and Kashakstan) through the diversion of Amu Darya and Syr Darya tributaries to help grow cotton. The Aral Sea has shrunk by more than half of its surface (68,329 km^2) and by 75 per cent of its volume after 90 per cent of the natural inflows were diverted to irrigate massive cotton monocultures, originally extending for more than 7 million ha in the USSR (Kindler and Matthews, 1997; SIWI, 2001).

Most 'hydro-technical' schemes fall closer to the Esthwaite Lake example than the Aral Sea one, so most people are not aware of their individual negative impacts. In most cases too, the proponents and the constructors were not, at the time, aware of the extent to which their activities would disrupt the homeostasis of the natural ecosystems. Collectively though, small impacts have added up and cause both environmental and health hazards. There is no longer a single lowland river in England unaffected by nutrient enrichment due to diffuse pollution and treated sewage effluents (Muscutt and Withers 1996; Demars and Harper, 2005a). Neither is there one un-impacted by discharge regulation through direct abstraction or by land drainage schemes (Brookes, 1995). The 'vicious circle', set by technologically-intensive environmental solutions, producing unpredicted environmental damage is drawing to an end however, with the growing realisation that the human population will exceed the total carrying capacity of the planet very soon (Cohen *et al.*, 1995). Every small decision, at every governmental level, affecting land, water and air, now needs to be taken with the true application of the principles of 'sustainability' in mind – using the natural properties of an ecosystem's capacity to absorb human impact and to mitigate damage. The effort directed at environmental change for maximising nature and human benefit must be turned on to a more 'precise' understanding of natural processes and a better perception of the risk engendered by resource exploitation.

The Genesis of Ecohydrology

Ecohydrology was born in the UNESCO stable as part of the 5th IHP (International Hydrological Programme, 1996-2001). This was in one sense a response to the formal statements arising from the Dublin Conference on Water and promotion of Integrated Water Management (Solanes and Gonzalez-Villarreal, 1999) but in another sense it represented the intellectual development of the

UNESCO Man and the Biosphere (MAB) Programme. MAB, launched in 1971, had quickly realized the importance of human impact on aquatic systems, as it was reflected, among others, in the *Land Use Impacts on Aquatic Systems* project of the MAB programme (Jolánkai and Roberts, 1984). This importance was translated into a determination to understand the potential role of sub-systems on buffering the worst effects of human impact, resulting in the 5-year MAB programme *Role of Land/Inland Water Ecotones in Landscape Management and Restoration* (Naiman *et al*., 1989; Naiman and Decamps 1990; Zalewski, *et al*., 2001). The final meeting of the Ecotone project in 1994 concluded that an important development would be the integration of ecology and other sciences, a natural development of earlier integrative initiatives within UNESCO. Consequently, the lessons from the Ecotone project, which had laid emphasis on ecological issues, became incorporated into the needs of the new IHP-V project, which saw the close cooperation between freshwater ecology, geomorphology, hydrology and water engineering as a central component to make ecohydrology the holistic 'tool for the sustainable management of aquatic resources' (Zalewski *et al*., 1997) that is the subject of this book. Throughout this period, key staff members of the UNESCO IHP programme had the vision and the intellect to drive the evolution of the concept forward, by providing support for conferences, meetings and subsequent publications.

Development of integrated thinking about water resources occurred concurrently with the recognition of the importance of the meaning of 'sustainability' before and after the 1992 United Nations Conference on Environment and Development (UNCED, known as the 'Rio Convention') (Membratu, 1998). Although recognition of our general environmental deterioration had started before Rio – it can be traced back to varied sources such as 'Silent Spring' by Rachel Carson in 1963 and the 1972 Stockholm Conference (Meadows *et al.*, 1992) – the specific impact of this deterioration on water resource availability was highlighted by the Dublin Conference on *Water & the Environment* early in 1992 that helped to prepare for UNCED in Rio. Dublin was followed by the Paris conference, 6 years later – *Water, a Looming Crisis*? (Zebidi, 1998).

The community of aquatic scientists had also been moving along several parallel routes towards an integrated approach to aquatic management, for a decade prior to the first use of the term ecohydrology in this context. Academic conference titles since the early 1990s show this: for example *Hydrological, Chemical and Biological Processes of Contaminant Transformation and Transport in River and Lake Systems* (Jolánkai, 1992), *Habitat Hydraulics* (LeClerc *et al*., 1996), *Hydro-ecology* (Acreman, 2001), *Environmental Flows for River Systems* (Petts, 2003), *Aquatic Habitats: Analysis and Restoration* (Garcia and Martinez, 2005). These meetings and proceedings encouraged aquatic scientists to work with their neighbouring disciplines. Proceedings showed the beginnings of integration of ecology with hydrology, through 'habitat hydraulics' or 'ecohydraulics' or 'environmental flows' – the terms given to the allocation of flows in rivers or releases from reservoirs for the maintenance of aquatic habitats and life.

Over the same time period, policy was moving in the same direction. The new democratic South Africa enshrined the concepts of 'water for people' and 'water for nature' in one of the first pieces of legislation in 1996. The European Union's Water Framework Directive (WFD), by inviting a strategy for dealing with cumulative basin impacts rather than focusing on pre-determined discharge-point limits, instituted a strong regulatory principle calling for integrated river basin management. The management of fluvial hydrology is at the heart of the WFD, as stated in Article 1, which addresses the hydrological needs of aquatic, terrestrial and wetland ecosystems (1a) as well as floods and droughts (1e). Several guidance documents, defined under the Common Implementation Strategy phase of the WFD, such as the 'Wetlands Horizontal Guidance' and 'Impacts and Pressures' have highlighted that. Even though the WFD does not cite ecohydrology explicitly, it clearly expresses a concrete scope for its implementation. The development of ecohydrology as a management tool for guiding sustainable water management in the UK has moved on from just being a tool for dealing with flow regulation issues ('Hydro-Ecology') into one fully addressing the need to achieve 'good ecosystem quality' under the WFD (Environment Agency, 2004).

Thus integrated ecological and hydrological thinking, regardless of its name, was moving in the same direction – the need to understand human impacts and find ways of mitigating or reversing them. Integration is a precondition necessary for an ecohydrological approach now enshrined in modern water management terms – the *Catchment Management Planning* (CMP) concept and particularly the *Integrated Water (*or *River) Basin Management* (IWBM) concept, which is being promoted by the major international environmental NGOs such as IUCN (as *Water and Nature initiative*) and WWF (as *Living Waters Programme*). Ecohydrology is the major means of achieving Integrated Water Basin Management, within what is now called *The Ecosystem Approach* (IUCN, 2008).

The Scientific Evolution of Ecohydrology

The principles of ecohydrology have evolved since the late 1990s in such publications, promoted by UNESCO support, as: Zalewski (2000); Zalewski and Harper, (2002); Zalewski *et al*., (2004). They have focused upon the links between the disciplines and the use of low-cost ecological technologies for the management of wetland, instream and riparian plant communities. These were first given the term *Ecological Engineering* (Mitsch and Jørgensen, 1989) and have now become an integral part of ecohydrology, termed 'phytotechnologies'. The linkage gained support from the United Nations Environment Programme (UNEP), in recognition of phytotechnologies' widespread global value as a low-cost sustainable solution to mitigating pollution on land and water (Zalewski, 2002; Zalewski *et al*., 2003; Zalewski, 2004). The range of techniques that can be enhanced through ecological engineering to increase the ecosystem services that river basins can provide is illustrated in Fig. 1.2 and 1.3.

The scientific development of ecohydrology can be traced to two major theories at different scales – that of the 'ecosystem' and that of 'Gaia'. Both of them describe the emergent properties of groups of interacting living organisms. Both have sought the analogy of a 'super-organism' to aid understanding.

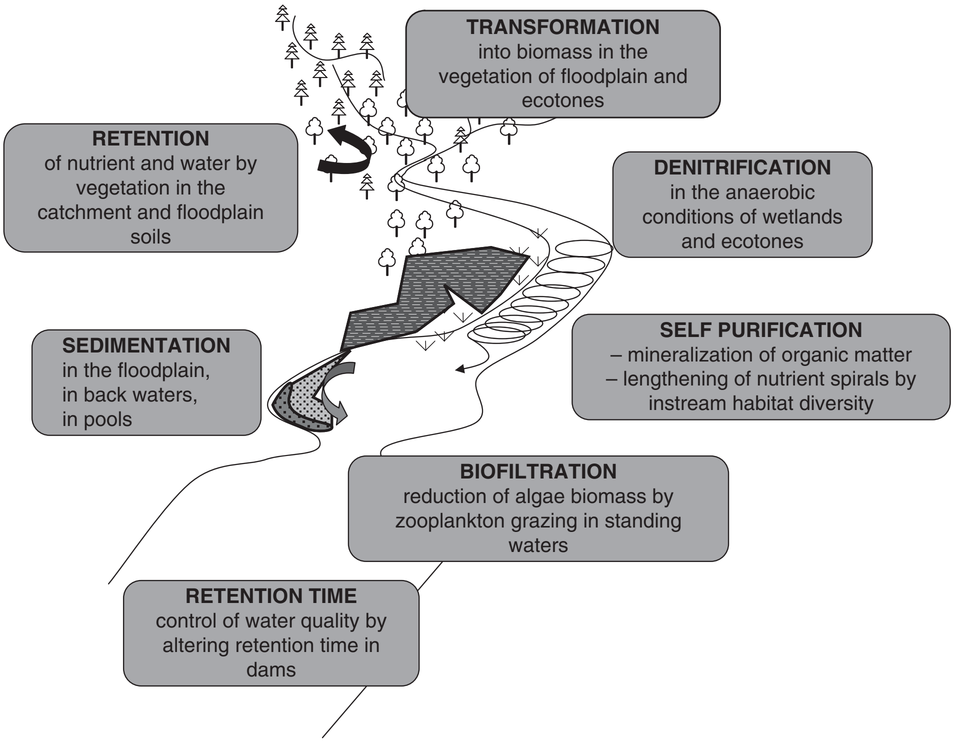

Fig. 1.2. Diagramatic representation of ecohydrological processes, which, in different parts of the catchment, can be used to control hydrological and hydrochemical ones.

The ecosystem

The smaller scale and earlier concept, that of the ecosystem, comes from a term coined by Arthur Tansley (1935) but reflecting 40 or so years of earlier thinking about the linkage between biological systems and their environment. The ecosystem was proposed as an alternative to the super-organism concepts of vegetation that had been proposed by Clements (1916). The simile of a super-organism has been used repeatedly during the 20th century to describe a group of organisms having the physiological properties of a single organism (Lincoln *et al.*, 1982). It has difficulties if it is used literally, because an individual organism is the template for natural selection to operate upon; but it does have value if used metaphorically to assist the understanding of a concept with emergent properties, such as Ecosystem or River Basin.

An important theory in support of the earliest thinking about ecosystems, was the apparent homeostasis in lakes created by its feedback loops in, for example, nutrient cycling. This can be traced back to the last few decades of the 19th century, when Forbes (1887) envisaged a lake as a ‘microcosm’, where ‘a balance between building up and breaking down [occurs], in which the struggle for existence and natural selection have produced an equilibrium’. The

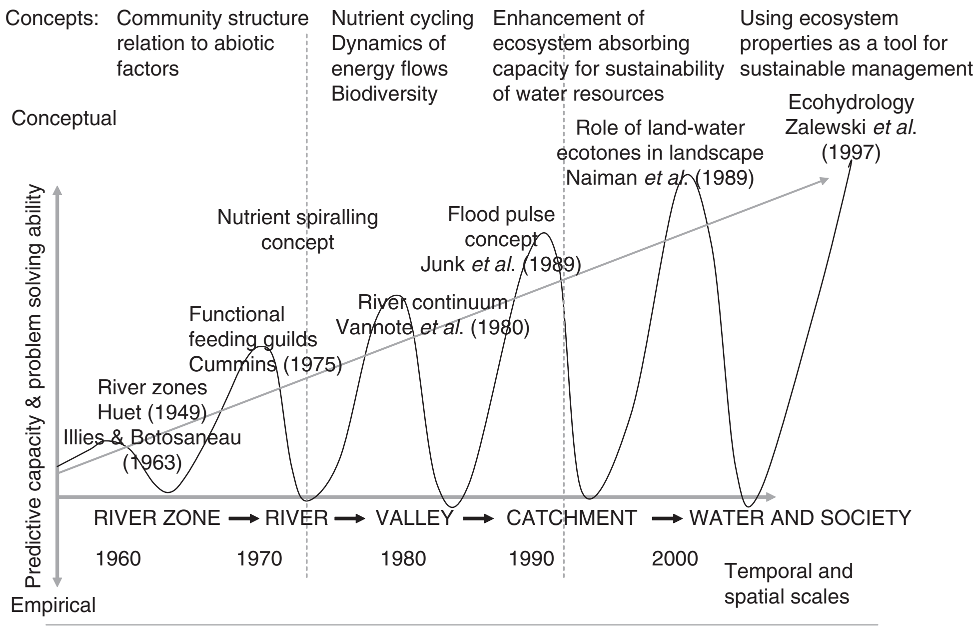

Fig. 1.3. Diagrammatic representation of the evolution of ecohydrology as an integrating concept in water science and management from earlier aquatic science concepts, which enabled the increase in scales and predictive capacity.

understanding of nutrient cycling brought ideas from geochemistry into ecological thinking, such as those of Lotka (1925), who envisaged the earth as a single system whose parts, linked by chemical changes, were all driven by solar input. Important progress was made by Lindeman (1942), who clearly showed the abiotic-biotic linkages in a bog-lake ecosystem, through interpretation of the food web in terms of energy flow through the different trophic levels. He interpreted ecological succession in terms of energy transfer efficiencies. Odum (1953) subsequently placed the ecosystem concept and the link with biogeochemical cycles firmly in the forefront of ecological thinking in his textbook, *Fundamentals of Ecology*, which had a major influence on the discipline of ecology over the following 30 years. Thomas Odum (1971, 1983) developed Lotka's physical approach much further, making the link with physical laws clear by showing how ecosystems operate under thermodynamic laws. This thinking has attracted continuous interest (e.g. Jorgensen and Kay, 2000; Jorgensen and Svirezhev, 2004)

Odum (1969) established ecosystem characteristics (covering community energetics and structure, life history, nutrient cycling, selection pressure and overall homeostasis). He made predictions of the internal trends to be expected in the succession of an ecosystem through its development stages, mature stages. He later included predictions for stressed ecosystems (Odum 1985).

Both Eugene and Thomas Odum had always integrated man into their concept of the ecosystem (Odum, 1971, 1983,). Eugene Odum's predictions of anthropogenic impacts (Odum, 1985) were tested by Schindler (1987, 1990) in whole lake experiments, which found that either the lake's recovery from stress (nutrient enrichment or acidification) was much slower than its initial degradation or that the ecosystem's dynamic equilibrium state had changed.

The importance of the energy that does not enter the biotic component, in structuring a lake ecosystem through its effect upon stratification and mixing, had already been recognized by Juday (1940). The importance of biotic influence upon energy flow was given impetus by the treatise of Gates (1962), a physicist. Other physical scientists were able to understand larger scale processes of river basin development as well as just individual lakes, through the application of thermodynamic principles (Leopold and Langbein, 1962). Several ecologists had argued for the integrity of the basin for much of the 20th century as part of the intellectual debate about the ecosystem (Golley, 1993).

Ecological theory was taking longer timescales into its frame of thinking as well as incorporating the physical driving laws, linking the processes of ecosystem succession with complexity and stability (Margalef, 1960, 1963). Spatial scales were seen to be important influences both upwards as well as downwards; Connell (1978) showed that instability on the point scale may result in a high stability in the total system. Natural selection, operating at the level of the individual, had earlier appeared to contradict these theories of ecosystem properties, but Southwood (1977) developed a new concept of how natural selection operates on an organism through its habitat. This Habitat Templet concept (Southwood 1988) hypothesized that the spatial and temporal gradients provide the frame, upon which evolution forges characteristic assemblages of species traits. The habitat of the species can be characterized by two gradients: the spatial heterogeneity (adversity gradient) and the temporal variability (disturbance gradient) of the environment (Townsend and Hildrew, 1994). Both gradients can be characterized by three components defining the realized niche (Hutchinson, 1970) of the species: biotic (competitors, consumers), chemical (alkalinity, nutrients, pollutants) and physical (geomorphological).

O'Neill (2001) recently questioned the ecosystem concept and suggested that, although the metaphor of the super-organism has been replaced by the machine analogy to facilitate communication of ecology to the public, the scientific paradigm needed to be rejuvenated. He saw the most serious scientific gap to bridge was an explanation of the stability of the ecosystem (self-regulation) without using the old concept of 'Balance in Nature' and with the integration of more evolutionary biology. His last two paragraphs about ecosystem theory are important for ecohydrological thinking:

> Perhaps the most important implication involves our view of human society. *Homo sapiens* is not an external disturbance, it is a keystone species within the system. In the long term, it may not be the magnitude of extracted goods and services that will determine sustainability. It may well be our disruption of ecological recovery and stability mechanisms that determines system collapse.
>
> Certainly, we don't want to dismiss the current theory prematurely. But we must understand that the machine analogy is critically limited. In so far as the local system maximizes environmental potential, it necessarily sacrifices stability when that potential changes. The challenge to the ecological system is optimization to a

> moving target. Optimize too rapidly and the system is trapped in a local attractor and, like an overspecialized species, cannot adapt when conditions change. So it would not be wise to send the old dobbin to the glue factory before we determine how well the new one takes the bit. But it certainly seems to be time to start shopping for a new colt.
>
> (Robert V. O'Neill, 2001)

Ecosystem and super-organism concepts have now been incorporated into ecological risk assessment guidelines, which developed in the United States during the early 1990s (USEPA, 1998). Even if several basic differences do exist, in many ways ecological risk assessment is perceived as an extension of risk analysis methodologies developed to protect human health. A super-organism analogy can be perceived in the definition of essential ecosystem functions, 'ecosystem physiology', and in the environmental destiny of multiple stressors being transferred between different matrices (air, water, soil, sediment) in a similar way to substances transferred between the organs of a single organism. Risk-based thinking has become a central tenet of modern environmental management (as in, for example the EU Water Framework Directive) to which ecohydrology is contributing its vision of river basin unity and its attention to habitat integrity.

Gaia

The higher theory within which ecohydrology fits, is the Gaia theory of planetary self-regulation. This, first proposed by Lovelock (1972, 1979, 1988), explained that the homeostasis of the Earth's atmosphere was maintained by the negative feedback activities of the biosphere, because it was far from thermodynamic equilibrium. The theory was at first heavily criticised for three reasons, because:

- Lovelock and Margulis (1974) had ignored much earlier scientific works putting forward the idea of the influence of the biota on its environment (e.g. as early as Spencer 1844, Huxley 1877),
- they did not fully foresee the homeostatic, teleonomic and optimising implications of their theory (Kirchner 1989), and
- the metaphor of the Earth (Gaia) seen as a living entity, which did not reproduce, was not compatible with neo-Darwinism, even if the metaphor was illustrating the second law of thermodynamics (Lotkla 1925; Schrödinger 1944).

Patten and Odum (1981) tackled the teleonomic epistemological gap to defend the view that ecosystems are cybernetic systems (c.f. Margalef 1968, Odum and Odum 1971) and rejected the idea of the super-organism, in response to Engelberg and Boyarsky (1979). Lovelock was himself heavily criticized at the American Geophysical Union's Annual Chapman Conference, in March 1988, dedicated to Gaia (Kirchner 1989; Schneider & Boston 1991). His theory then had to integrate the neo-Darwinist criticisms to survive and try to demonstrate that emergent properties may arise from biota at the global level and regulate the atmosphere. This it did (Watson and Lovelock 1983; Lenton 1998; Lenton and Lovelock, 2000).

Many books have been written about Gaia. This has strengthened its credibility (e.g. Williams 1996, Volk 1998) and applicability (Bunyard 1996). Recently Dagg (2002) suggested a common ground for *The Extended Phenotype* (Dawkins 1982) and *Gaia* (Lenton 1998) as a result of emergentism.

The Role of Aquatic Sciences

Lake ecology had made major contributions to the development of ecological theory in the early–mid-20th century, and running water ecology soon caught up. Thirty years ago, the beginnings of understanding of the consequences of flow for riverine ecosystem structure (Cummins, 1974), led to a major step forward in integrating physical and ecological processes in running water (Vannote *et al*., 1980), the River Continuum Concept (RCC). This also made sense of an earlier, more descriptive phase of aquatic ecology, river zonation, which had been based on fish communities (Huet, 1954) and the typology of river stretches (Illies, 1961; Illies and Botoseanu, 1963) summarized by Hynes (1970) and Hawkes (1975). The RCC did this by integrating the physical driving forces from source to mouth with these biological zones in a river:

> 'in natural river systems biological communities form a temporal continuum of synchronized species replacements following the flow from the spring to the river mouth'
>
> (Vannote *et al.*, 1980)

Some aspects of the continuum, particularly the spiralling behaviour of nutrients in rivers, had already been suggested (Webster and Pattern, 1979) and were elaborated shortly after the RCC (Newbold *et al.*, 1983). Subsequently the RCC was reshaped and extended to encompass broader spatial and temporal scales (Cummins *et al*., 1984; Minshall *et al*., 1985). The role of woody debris in holding back river discharge (Triska, 1984) and influencing floodplain structure on temporal scales for up to hundreds of years, was the most important ecological regulatory process highlighted. This triggered further research and many investigations have been devoted to this subject since then (Harmon *et al*., 1986; Gurnell *et al*., 1999; Robertson and Augspurger, 1999). The RCC had not explicitly initially addressed human impact, but the Serial Discontinuity Concept (SDC) by Ward and Stanford (1983) was a way of understanding the magnitude of disruption, initially by dams. In larger rivers the influence of the river floodplain on the main channel in the lower reaches was not fully included in the RCC and as a result the Flood Pulse Concept (FPC), was formulated – initially for the largest flood plain system of the world, the Amazon and its basin (Junk, 1982; Junk *et al*., 1989). More recently, its ideas were extended to include temperate floodplains (Tockner *et al.*, 2000). Although flooding has major consequences for floodplain functioning and productivity at all latitudes (Bayley, 1995; Zalewski, 2006), the flood pulse effect is particularly relevant in the tropics due to temperature coupling, i.e. the seasonal convergence of high discharge and high temperatures, which maximise biotic processes such as fish development and biomass accumulation (Junk *et al.*, 1989; Junk, 2000; Junk and Wantzen, 2003). The Riverine Productivity Model (RPM)

(Thorp and Delong, 1994) identified the different sources of organic carbon in: (i) local autochthonous production; (ii) direct inputs from the riparian zone, and; (iii) instream primary productivity, so placing the floodplain's influence in material cycling in the context of its whole catchment.

Attention was increasingly directed to the ecological problems in rivers that were heavily modified by regulation and human use of water resources, which highlighted the loss of connectivity between the main river channel and the aquatic habitats in the flood plain. The way connectivity was impaired by regulation measures was highlighted by Ward and Stanford (1995) and the impact of engineering works shown by Bravard *et al*. (1986). The role of deposition resulting from geomorphic processes and ecological succession in disconnected side channels was described by Petts and Amoros (1996). Bornette *et al*. (1998) had described in detail how the diversity of aquatic plant life is linked to the level of connectivity in flood plain water bodies. Most recently Demars and Harper (2005b) found that hydrological connectivity along heavily-modified lowland rivers, and isolation between rivers, better explains aquatic plant distribution than did local (artificial) environmental conditions such as impoundments created by water mills.

Many hydrologists and environmental engineers had initially moved towards ecology through recognition of the wider importance of nutrient and sediment loading (Vollenweider, 1970; Wischmeier and Smith, 1978; Vollenveider and Kerekes, 1981; OECD, 1982). Even in the 19th century however, Hungarian water engineers had termed the obligatory release flow from dams into rivers as the 'living water', indicating, at least in terminology, that they wished to preserve life in the rivers. Modelling of freshwater systems was triggered by Odum´s (1957) study on the energy budget of a large spring system and quickly followed the development of computing power (Imboden and Gachter, 1975; Lorensen, 1975; Jörgensen, 1983), leading to an holistic approach to the processes of the entire basin (Jolánkai, 1983; Thornton *et al*., 1999).

The largest challenge that integration of ecology and hydrology faces is that of scale. Numerical dimensions of sampling sites, expressed by terms like point, catchment, meso-, macro-, or mega-scale are not at all defined within each field, and even more numerical deviation will be found if projects in ecology and hydrology are compared. Hydrological elements used by Sloane *et al*. (1997) were about 100 km^2 in size. It is rare for limnological investigations to deal with minimum element areas of this size. Even by trying to come closer to biological dimensions, Sloane *et al*. (1997) remained short of a real biological view of the environment. The same applies to the meso-habitat scale of Bovee (1996) who tried to reduce the need for 'high precision sampling techniques', since useful ecological information, like species composition, is very often only available by direct observation on the spot and cannot be worked out by more remote techniques. Structural ecological elements like ecotones are usually below the size of typical hydrological point scale investigations. Highly aggregated biological structures in a fluvial system like corridors, ecotone complexes or a mosaic of habitat patches may just reach the meso-scale of hydrology.

The linking of hydrological variables with biological properties at the appropriate scale is the key to the uptake and the success of ecohydrological thinking.

Evaluating the ecological health of a river basin, in terms of its deviation from a supposed 'natural state', has been an important goal for water science and management since the late 1970s. Methods have been developed which, on their own, evaluated a part of river health, but in combination and through ecohydrological thinking, can now provide a greater value than the sum of the parts. Within a hierarchy of scales, the added value of ecohydrology is in its emphasis upon the range of scales within which the biota can cause feedback regulation of the hydrological processes. This integration constitutes a fundamental forward step from understanding the more obvious regulation of ecological processes by hydrology. It is illustrated diagrammatically in Fig. 1.4 by the range of ecological and technological measures being implemented and planned on the Pilica river in Poland to mitigate high nutrient loads, which have rendered a downstream reservoir unfit for human domestic consumption.

The most appropriate scale for management activities is a middle scale since, at this spatial scale, it is possible to know the appropriate morphological or flow schemes that will control the local hydraulic heterogeneity, and thus the river's ecological processes. In fluvial systems, this approach allows a shift of observational targets from instream biological characteristics (i.e. diversity, trophic guild ratios) or processes (i.e. production/respiration) to physical characteristics that can be easily measured and with high precision. The establishment of such relationships provides the optimum opportunity for the ecohydrological

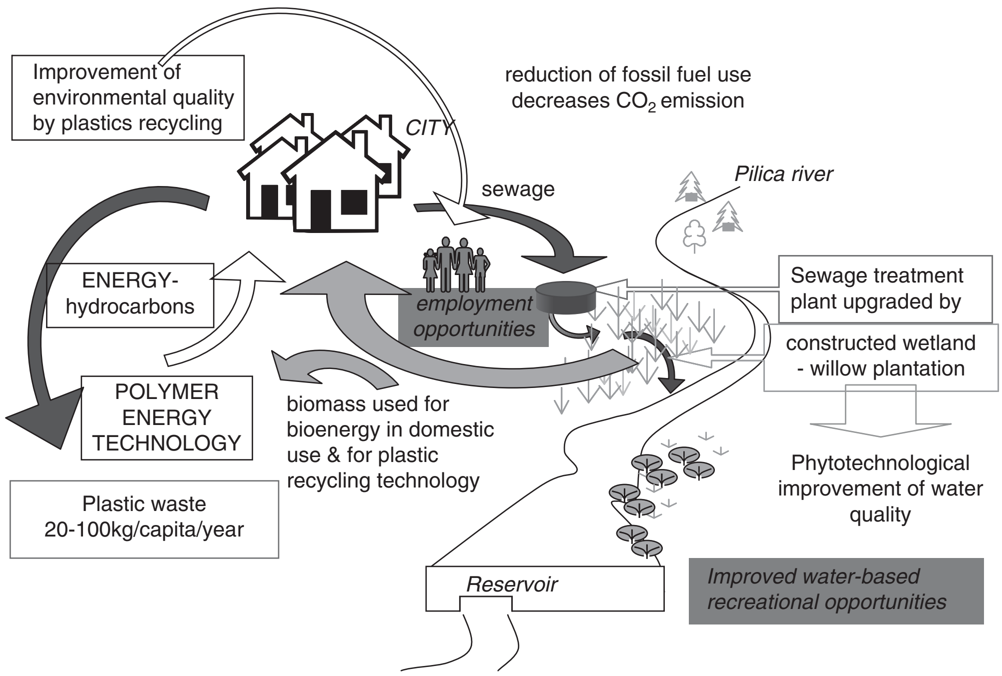

Fig. 1.4. Diagramatic representation of the development of ecohydrological methods in the Pilica River basin, central Poland, to reduce nutrient load to the downstream reservoir, reduce carbon emissions and increase employment opportunities.

management of water courses; mesohabitats (or their key hydraulic variables), can serve as monitoring tools within ecological assessment procedures. Biological assets can be improved by restoring the physical heterogeneity through direct substrate re-naturalisation or through the design of adequate flow management schemes.

At catchment scale, the integration of hydrological regimes within an ecosystem context is at the heart of the Continum Concept of Vannote *et al*. (1980). In certain river basin types, advances have been made in understanding and quantifying this integration. The best examples of processes in near-natural condition river basins, probably come from studies of undisturbed basins in Boreal latitudes (Naiman *et al*., 1986, Helfield and Naiman, 2001; Naiman *et al*., 2002; Helfield and Naiman, 2006), while the heavily modified rivers of Eurasia provide an example of the opposite extreme. There are no explicit procedures relating hydrological regime descriptors to anthropogenic changes in an ecosystem (Richter *et al*., 1996), but different practical methods for evaluating aspects of ecological health fit within a hierarchy of physical scales.

Ecohydrological principles can be implemented at a range of different scales through the development of integrative scientific methods, enabling new directions of research and management as well as a reinterpretation of former concepts. The value of ecohydrology is surfacing in regional and national legislation across the world. In Europe it is occurring through the development of methods designed to achieve ‘good ecological status’ as required by the EU Water Framework Directive (2000/60/EC); in the USA through methods designed to achieve ‘biotic integrity’ in implementing the Clean Water Act and the Water Quality Act; in South Africa through methods designed to achieve ‘the ecological reserve’ in implementing the National Water Act (Mackay, 1999) and in Australia through methods designed to achieve ‘ecological flows’ in implementing the Water Act and Landcare programmes.

The Purpose of This Book

It is the goal of this volume to promote the integration of ecology with hydrology to readers of either disciplines and to provide enough theoretical basis to demonstrate to the reader that ecohydrology not only works scientifically, but is also the concept most likely to deliver a ‘concrete advancement’, out of the many buzz-words in the first 5 years of the 21st century (Kundzewicz, 2002a). This volume provides support for the more practical Manual of Ecohydrology, published by UNESCO and UNEP (Zalewski and Wagner-Lotkowska, 2004) and its Guidelines (Zalewski, 2002).

What does all this imply? First of all, that ecologists understand the hydrological and chemical drivers at the basis of the structure and function of aquatic systems (Chapters 2–7). Equally, it means that hydrologists understand the ecological consequences of natural and modified flows, both under their quantity and quality aspects (Chapters 8–10).

Scientists of all disciplines nowadays rely on modelling for understanding the present and predicting the future, but both scale and accuracy must be appropriate to their needs. This is particularly so at the 'sharp-end' of ecohydrology, which is the practical use of ecosystem processes to regulate habitat properties through hydrology. The ecohydrological concept only works when the spatial scale of a catchment is firmly kept in mind, even where the practical application may be larger or smaller, in order to achieve the regulatory feedback desired (Chapters 11–14). The temporal scale is arguably the most important for our society: increasing numbers of scientists and planners, using increasingly sophisticated models, are trying to predict future global changes. Understanding ecohydrological processes from the past is an important pointer to interpreting the future (Chapters 14–15).

Concluding Remarks

The ecohydrology concept is held together by a number of scientific threads, such as the ecosystem definition, the emergent properties across spatial and temporal scales and the metaphor of a super-organism. This super-organism metaphor, which had been used repetitively in the past – for example by the Greek philosopher Plato (c.429-c.347 BC), the polymath Leonardo da Vinci (1452–1519), and the geologist James Hutton (Hutton 1788) – was revisited during the latter half of the 20th century with the ecosystem and the Gaia concepts (Odum and Odum, 1959; Odum, 1969; Lovelock and Lodge, 1972; Lovelock, 1972). It might now be the key to unlock society's understanding of the urgent need for ecohydrological solutions in the crowded, warmer, world of the 21st century. So too might the recently-discredited term 'The Balance of Nature'. This concept came from the 19th century (Humboldt, 1845, 1847), lost favour but re-appeared in scientific literature in the second half of the 20th, when nature became likened to a living entity.

Metaphors are still used successfully today in science for example, *The Red Queen* (van Valen, 1973) and *The Selfish Gene* (Dawkins, 1976), but science is not only about metaphors. Ecohydrology seeks to bridge the sciences, arts and society to achieve its ultimate goal: the sustainable management of river basins. In doing this it has to follow the pace of the Red Queen (Carroll, 1871, van Valen, 1973), so that its principles are continually revised as sciences, arts and society move on.

It is clear that the next phase of the development of ecohydrology must be to better engage with people ('stakeholders') and policy and politics ('decision-makers'). It has been suggested that, in order to do so, ecohydrology must develop into a unified science from sociology, hydrology and ecology (Hiwasaki and Arico, 2007). That is not the view taken by the authors of this book. We all seek to engage with people in nations, river basins and local communities, in order to achieve meaningful and sustainable management of their water resources. But to do so, it is not necessary to reconstruct disciplines that already integrate well due to their common physical science base. However, it is very necessary to use a common language and to seek new ways of communicating about problems (such as films, see the UN University virtual field course web site), which coherently link disciplines, and in doing so provide solutions. This is illustrated in Fig 1.5.

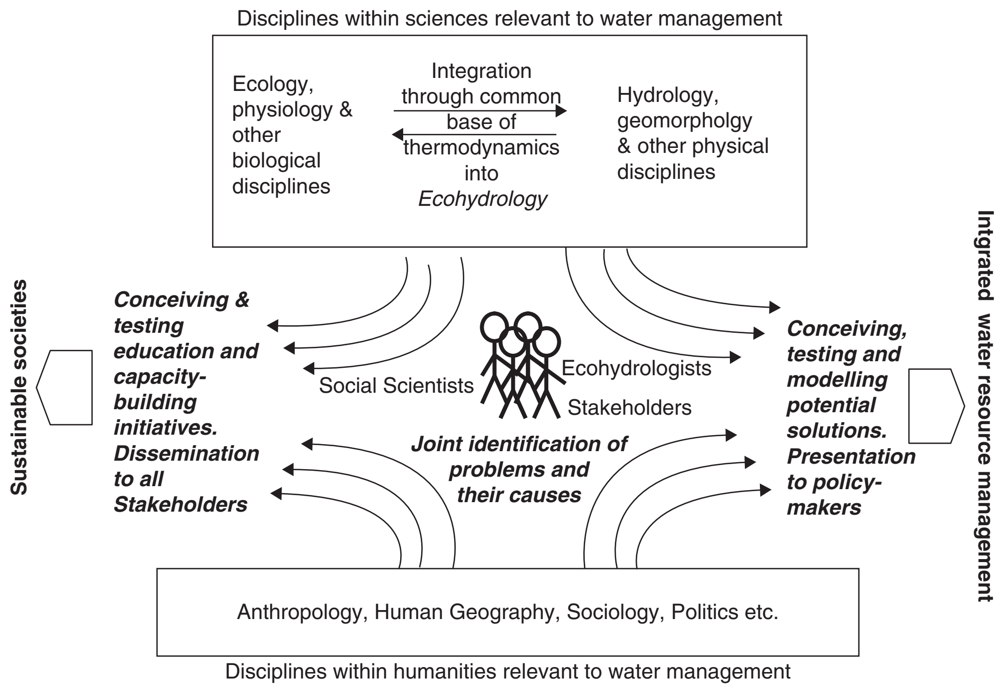

Fig. 1.5. A conceptual diagram showing the way in which ecohydrology must develop over the next decade in order to become a globally effective tool for sustainable water management, by engaging social science disciplines and educationists in a trans-disciplinary fashion to produce unified, integrated solutions to water resource problems and coherent educational tools.

The Preface of the book presents a Cibachrome photogram, which was made without a camera by directly immersing, at night, large-scale sheets of positive photographic paper beneath the flowing water surface and with exposition to a flashlight. The River Taw (Devon, England) was used as a negative and the landscape as the dark room. Ambient light in the sky added colour. This photogram is only one moment extracted out of a whole time series of photograms capturing daily and seasonal changes from source to sea, capturing the interplay of the river and its environment (Derges, 1997, 1999). Susan Derges' work on the River Taw is only part of a whole continually evolving body of experiments with nature on wave and particles, the observer and the observed, growth and forms (Derges, 1985, 1999). This work is firmly rooted in ancient philosophy (e.g. Zen philosophy, Watchmann and Kruse, 2004) and natural history (e.g. Reclus, 1869), yet remains intuitive, creative and communicative. It represents one artist's vision of an aquatic ecosystem in a way that can be shared with many. Ecohydrology seeks to do similar things – it creates a vision of a sustainable aquatic ecosystem, which if shared with enough people, can be achieved in reality. We hope that you will enjoy this book and share our vision.