Hydrological Sciences–Journal–des Sciences Hydrologiques, 47(5) October 2002

Ecohydrology—the use of ecological and hydrological processes for sustainable management of water resources

MACIEJ ZALEWSKI
International Centre for Ecology, Polish Academy of Sciences, Warsaw, Poland
and
Department of Applied Ecology, University of Łódź, Poland
mzal@biol.uni.lodz.pl

Abstract The increasing human population and degradation of biological integrity of ecosystems has been expressed, to a great extent, as a decline in water resources, the most critical factor to achieve sustainable development. This is because overexploitation and degradation of the biotic structure alters ecosystem processes to the point at which the ecosystem ability to provide desired resources is seriously diminished. The progress in ecology during recent years has created a background for integration of ecology and hydrology. UNESCO, under the International Hydrological Programme IHP-V, has initiated and provided a framework for such an interdisciplinary effort. During the programme, the conceptual background and principles of the surficial processes of ecohydrology were defined: first, by integration and quantification of biological and hydrological processes at the basin scale; second, by the enhancement of basin ecosystem absorbing capacity against human impact; and third, by using ecosystem properties as a management tool. Those principles are targeted, not only to eliminate threats, but also to amplify the opportunities for sustainable development as far as the control and regulation of nutrients and water cycling at the basin scale become possible. According to Popper's philosophy, the predictive planning of the future cannot be generated by extrapolating from recently used solutions. The integration of environmental sciences should create not only new scientific disciplines, but also a new solution which can face new challenges—sustainable management of the biogeosphere.

Key words ecohydrology; water resources; sustainable development; ecosystems; hydrobiology; ecological engineering

Ecohydrologie—la prise en compte de processus écologiques et hydrologiques pour la gestion durable des ressources en eau

Résumé L'accroissement démographique et la dégradation de l'intégrité des écosystèmes ont pour conséquence, dans une grande mesure, un déclin des ressources en eau, facteur le plus critique vis à vis du développement durable. La raison en est que la surexploitation et la dégradation de la structure biotique altèrent les processus de l'écosystème à un point tel que l'aptitude de l'écosystème à produire les ressources désirées est sérieusement diminuée. Les progrès en écologie des dernières années ont produit une base pour intégrer l'écologie et l'hydrologie. L'UNESCO, à travers le Programme Hydrologique International PHI-V, a initié et fourni un cadre pour un tel effort interdisciplinaire. Durant le programme, le bagage conceptuel et les principes des processus supérieurs de l'écohydrologie ont été définis: premièrement l'intégration et la quantification des processus biologiques et hydrologiques à l'échelle du bassin versant; deuxièmement le renforcement de la capacité des écosystèmes du bassin versant à absorber les impacts anthropiques; et troisièmement l'utilisation des propriétés des écosystèmes comme outil de gestion. Ces principes sont identifiés, non seulement pour éliminer les menaces, mais aussi pour amplifier les opportunités de développement durable dans la mesure où le contrôle et la régulation des cycles de l'eau et des nutriments deviennent possibles. Selon la philosophie de Popper, la planification prédictive du futur ne peut pas être l'extrapolation des solutions récemment mises en œuvre. L'intégration des sciences environnementales devrait créer, non seulement de nouvelles disciplines scientifiques, mais aussi une nouvelle solution pour faire face au nouveau défi de la gestion durable de la biogéosphère.

Open for discussion until 1 April 2003

Mots clefs ecohydrology; water resources; sustainable development; ecosystems; hydrobiology; ecological engineering

INTRODUCTION

The Ecohydrology (EH) Concept developed within the framework of the UNESCO International Hydrological Programme IHP-V (Zalewski *et al.*, 1997) has been largely inspired by conclusions from the International Conference on Water and Environment (ICWE) held in Dublin in 1992. This conference highlighted the inadequacy of existing solutions in water management practices to achieve sustainability of water resources, as well as the need for new concepts and new solutions.

In the face of declining global water availability (Meybeck, 1998; Shiklomanov, 1998), the starting point for formulating the EH Concept was two realizations. First, the weakness of traditional approaches to water management based on a mechanistic vision of freshwater ecosystem functioning became clear. Solutions from this approach were not sustainable, because water problems are the result of multiple cause/effect dependencies. Efforts to compensate for anthropogenic modifications of the water cycle, resulting from catchment cover modification, urbanization, agriculture, over-exploitation and pollution, for example, have not been successful (Kundzewicz, 1999). Second, solutions applied in developed countries up to now, based on civil engineering methods, are unsustainable because of financial and energy constraints (e.g. Somlyody *et al.*, 2001; Wagner *et al.*, 2002).

In many situations this mechanistic approach has led to overengineering of the environment (canalization, impoundment), which seriously reduces the role of ecological processes in moderating the water cycle. Additionally, it has driven these ecological processes toward further reduction of water quality or amplification of secondary pollution, e.g. eutrophication (Robarts, 1998). Water resources at the basin scale are the result not only of climatic conditions and geomorphologic structures, but also, to a great extent, of biological evolution and succession. This link has been widely neglected in water science and management up to now. Consequently, even in developed countries, decisions concerning freshwater resources management have often been taken without a scientific and empirical background, addressing only short-term and single goals (e.g. Naiman *et al.*, 1995). The appearance of the term "integrated lake and reservoir management" in the 1990s indicated the beginning of a new way of thinking. At this stage, however, identifying major hydrological and ecological problems and proposing new solutions based on decision-making theory, e.g. cost–benefit approach, investment, policy strategies (Ayres *et al.*, 1996), were not based on an holistic framework for integrating hydrology and ecology.

One of the negative consequences of the degradation of biological structures and dynamics has been an increase in the range of extreme hydrological events. This, in turn, amplifies physical processes which modify geochemistry and create negative feedback on the biological structures and dynamics of ecosystems. The Intermediate Disturbance Hypothesis (Connell, 1978), suggested that the greatest diversity of biotic communities appears at the intermediate level of abiotic (e.g. hydrological) disturbances. So, increase in the variability of physical factors, as a consequence of mechanistic, short-term solutions in water management, reduces the terrestrial storage capacity of river basins for nutrients and sediments. This, in turn, leads to the decline of biological diversity and productivity of terrestrial ecosystems and to over-fertilization and siltation of aquatic systems that reduces the storage capacity of reservoirs and degrades water quality. All these processes could significantly be amplified in the future by predicted global climate changes.

WHY DO BIOLOGICAL PROCESSES HAVE TO BE INTEGRATED WITH HYDROLOGY?

Water quality in freshwater ecosystems is dependent to a great extent on biological processes. This is because freshwater ecosystems are situated in landscape depressions and, thus, are permanently supplied by organic matter from terrestrial ecosystems (including human activities, e.g. sewage), which is decomposed by aquatic biota—invertebrate grazing and bacterial and fungal enzymatic processes. The importance of biological processes in nutrient cycles in aquatic ecosystems is determined by four major factors: temperature, light, nutrient availability and water mass dynamics. The pattern and intensity of hydrological variability significantly moderate biotic structure and activity (e.g. spring water levels in reservoirs determine the reproductive success of fish, which in turn determines zooplankton density and filtering activity and, consequently, the appearance and intensity of algal blooms; Zalewski *et al.*, 1990). On the other hand, biotic structures regulate abiotic ones: wetland and flood-plain plant cover significantly determine the extent of river self-purification capability (Mitsch & Gosselink, 1993). As a consequence, the issue of water quality at the basin scale cannot be resolved without a profound understanding of the effects of hydrology on biotic processes and of biota on hydrology.

Attempts to integrate ecological and hydrological processes first began in the 1970s (Hynes, 1970), but during the next 10–20 years were mostly focused on specific aspects such as invertebrate ecology and biomonitoring (Ward & Stanford, 1979; Statzner *at al.*, 1988), fisheries sciences (Welcomme, 1979), "cartographie polythematique" (Roux, 1982), sediments (Walling, 1980) and oxygen metabolism of watersheds (Naiman, 1983). The predictive ability of ecology was still limited and this fragmented efforts to provide an holistic framework. Three decades ago, the International Biological Programme of UNESCO created a background for quantifying ecological processes, such as energy flow through ecosystems in terms of physical units (calories, joules) (Grodzinski *et al.*, 1975). Development of this approach has continued (Kooijman, 2000), because the quantification of ecological processes and the understanding of regulatory mechanisms at the ecosystem level allowed a broader, holistic perspective and enabled important progress to be made in the predictive ability of ecological interactions. This created conditions for partnerships between ecology and hydrology. Such a partnership is apparent in the development of some fundamental theories in the last 20 years, e.g. the river zonation concept was replaced by that of the river continuum (Vannote *et al.*, 1980) and the biomanipulation practice developed from trophic cascade theory (Gulati *et al.*, 1990).

The Ecohydrology Concept

Environmental scientists, faced with dramatically increasing global degradation by the end of the 20th century, seemed to focus their research on single problems, single factors or single species. In reality, the environment is very complex. To solve problems, environmental scientists must not only be integrative but also provide a bridge between pure science and society. UNESCO has for a long time recognized this and its programmes have contained an inherent methodological approach that leads scientists of complementary disciplines into close cooperation, e.g. Role of Land/water Ecotones in Landscape Management and Restoration, Man and Biosphere Programme (MAB) of UNESCO and its continuation, and the development of the Ecohydrology Concept under IHP-V. Programmes such as these have stimulated progress toward a more profound understanding of various aspects of the interplay between hydrological, geomorphological and biological processes (Zalewski *et al.*, 1997; Baird & Wilby, 1999; Rodriguez-Iturbe, 2000; Ormerod & Watkinson, 2000; Dunbar & Acreman, 2001). In the face of increasing pressure on freshwater resources, there remains an urgent need for new practical tools to achieve their sustainable management.

Such management must improve the coexistence of man and nature. The Ecohydrology Concept suggests that this can be done by two types of actions: reduction of energy and material use *per capita*—expressed by the UNEP concept of ecoefficiency or "factor four" (von Weizsacker *et al.*, 1997) and enhancing the absorbing capacity of ecosystems. This latter action is derived from decision theory, which suggests that a successful strategy has to not only eliminate danger but also amplify opportunities (Fig. 1). Recent studies have shown that, by regulating hydrological processes, the biological dynamics of systems (and consequently the quality of water resources) can be controlled and *vice versa* (e.g. Zalewski *et al.*, 1990, 1998; Mitsch, 1993; Jorgensen, 1996; Staskraba & Tundisi, 1999). Ecohydrological solutions will work towards reducing the stochastic variation of water dynamics and their consequences, e.g. erosion and accelerated nutrient transfer across landscape gradients. This can be done by using biota–land cover, ecotones, in-stream processes, wetlands, and manipulation of nutrient allocations between trophic levels (biomanipulation).

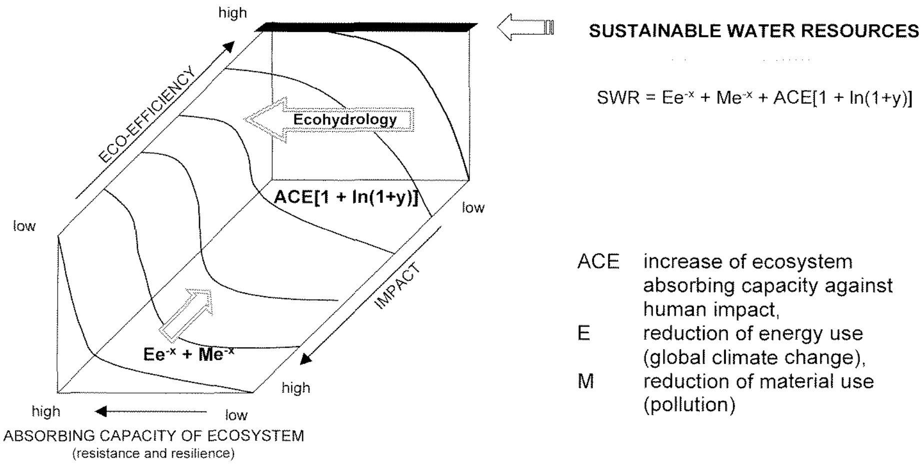

Fig. 1 The model integrating the concepts of ecohydrology and eco-efficiency for sustainable water resources. Ecosystem of high absorbing capacity (nutrients, pollutants), e.g. large, deep Lake Tanganyika; ecosystem of low absorbing capacity: shallow, temperate lake.

The framework for developing the principles of ecohydrology is logically the water basin scale, where the importance of integration of ecological processes is most clear. At this scale, four phases of the water cycle can be distinguished:

- Global climate dynamics and changes (e.g. Kaczmarek *et al.*, 1996) and palaeoclimate and palaeohydrology (e.g. Starkel, 1988) that determine climate patterns and the amount and timing of precipitation. It is worth noting that the human perception of temperature changes is one order of magnitude less than in ecological systems, e.g. the shift in plant species distribution and its phenology appear when average annual temperature changes by 0.6°C (Fitter & Fitter, 2002).
- Climate and the biosphere interact via energy and material fluxes and play key roles in the water cycle (Rodriguez-Iturbe, 2000; Kabat, 2002). Terrestrial plant cover patterns control the amount and quality of water provided to surficial systems (see excellent synthesis by Baird & Wilby, 1999).
- Land/water (riparian) ecotones play a dual role. One is the filtering of nutrients and pollutant transfer along catchment gradients with conversion into organic matter and the second is flood plain trapping of organic matter, nutrients and pollutants transported along a river continuum with in-stream/river channel processes such as acceleration of self purification (Naiman & Decamps, 1990; Zalewski *et al.*, 1998; Zalewski & Harper, 2001; Zalewski & Wagner, 1998).
- Reservoir/lake ecosystems are important foci where the sedimentation of minerals and the retention and conversion of transported nutrients and organic mineral matter can largely be controlled by the regulation of biota by hydrological processes (Zalewski *et al.*, 1990; Staskraba & Tundisi, 1999). The last two phases are presented in Fig. 2.

ECOHYDROLOGICAL PRINCIPLES

In the initial stage of the development of the concept, the need for the integration of existing fragmented knowledge on hydrological and biological processes at the basin scale into a holistic framework was underlined (Zalewski *et al.*, 1997). Following this, further progress in the development of the ecohydrology concept has been the formulation of three principles (Zalewski, 2000):

The first principle (framework) is developed on the basis of classical papers by Hynes (1970), Walling (1980) and Naiman (1983). It conceptualizes the catchment as a "superorganism" in a similar fashion as the Gaia concept of the planet as a "superorganism" (Lovelock, 1995). A hierarchy of factors influences this "superorganism": (a) scale—the mesocycle of water circulation in the basin (terrestrial/aquatic ecosystem coupling) has been the template for quantification of ecosystem processes; (b) dynamics—water and temperature have been driving forces for terrestrial and freshwater ecosystems; and (c) hierarchy of factors in the river basin—the abiotic processes are dominant (hydrology), but, when they are stable and predictable, biotic interactions start to manifest themselves (Zalewski & Naiman, 1985).

The second principle (target) is that the conceptual "superorganism" can be viewed in a natural state as possessing resistance and resilience to stress. These are properties apparent at the basin scale as a result of the biological interaction of the component

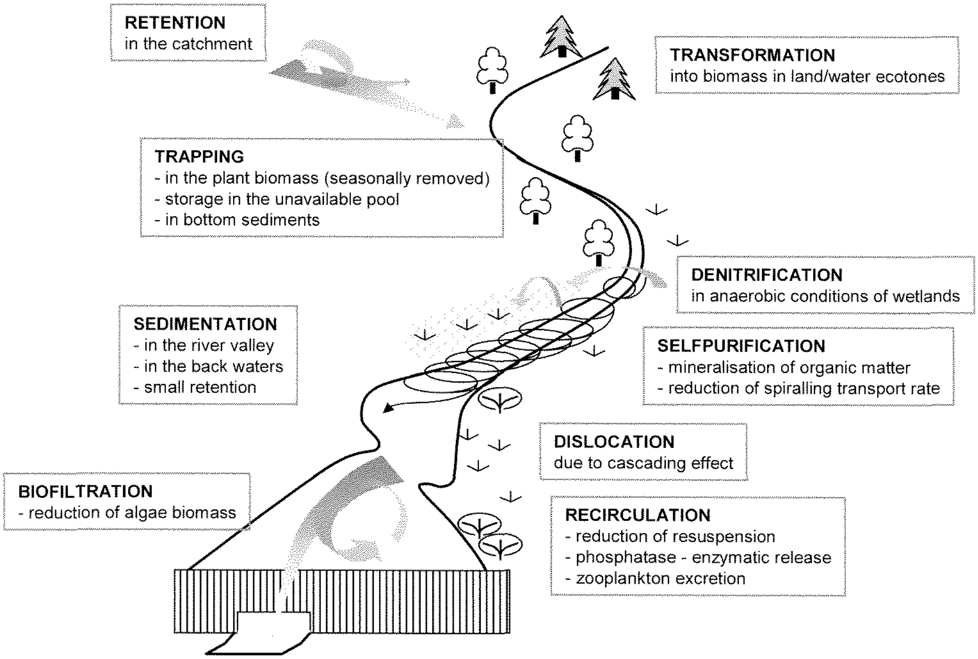

Fig. 2 The ecohydrological concept of the restoration of an eutrophic shallow reservoir, by applying various ecosystem biotechnologies as an example of catchment-scale ecological engineering (adapted from Zalewski, 2000).

parts. This provides the basis for the enhancement of the absorbing capacity of basin ecosystems against human impact in holistic management.

The third principle (methodology) is the use of these ecosystem properties in water management. Overengineering of aquatic systems has been evidence of a lack of understanding of ecological processes by environmental managers. In their opinion, freshwater biota can only serve as a secondary indicatory system (after chemical indicators), but an urgent need exists to raise awareness. This principle has an obvious link with ecological engineering (Mitsch, 1993; Jorgensen, 1996).

DISCUSSION

It is these critical properties which can be turned to practical value in the holistic management of river basins. For the first time in human history there exists the potential danger of human population density (recently over 6 billion) catastrophically impacting global carrying capacity (estimated at 9–13 billion). Since human populations follow similar general rules to other organism populations on Earth, such a collision would generate dramatic sociological, economic and political consequences. Therefore, there is a moral incentive for science to provide an answer to the question: How do we increase the absorbing capacity of ecosystems, and especially vulnerable water resources, to provide the conditions and time to achieve dynamic equilibrium between population density and carrying capacity?

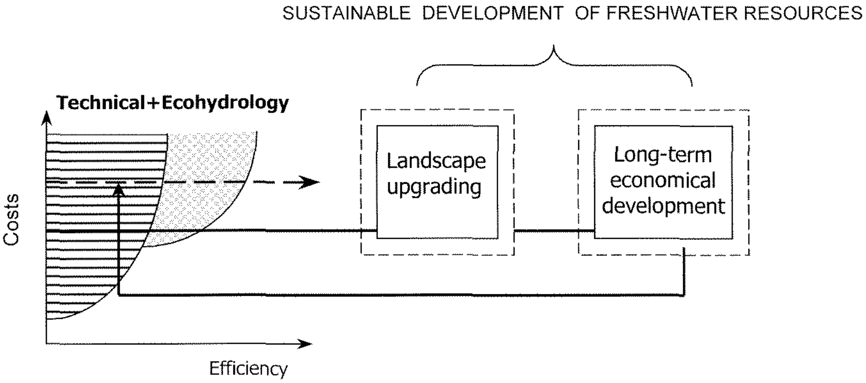

Fig. 3 The positive feedback: toward sustainable use of aquatic resources in a river valley. The key point is the integration of technical methods with ecohydrology toward efficiency improvement and cost reduction. As an effect of the cost-efficient upgrading of the aquatic ecosystem, the attractiveness of the region will increase, generating economic growth which, in turn, provides further funds for conservation and management of the freshwater ecosystem (after Zalewski *et al.*, 1997).

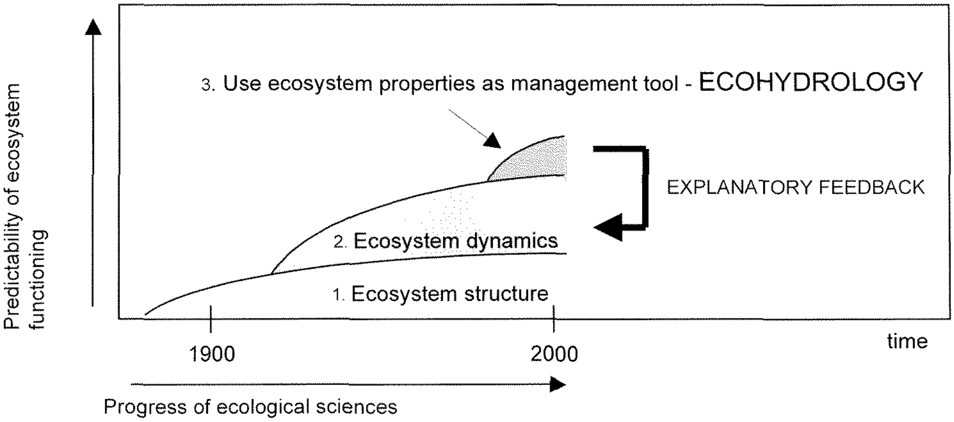

Fig. 4 Explanatory feedback generated by the Ecohydrology Concept as the contribution to the methodology of environmental sciences.

This new paradigm of ecohydrology can be seen as the third phase in the development of ecology from a descriptive natural history (e.g. Linne), through an understanding of processes, to control and manipulation of ecological processes for enhancement of resource quality (Fig. 3). The term "eco-hydrology" has been used to describe the water dynamics driven by climate–vegetation–soil relationships by Rodriguez-Iturbe (2000), and Baird & Wilby (2001). Another related term "hydro-ecology" has been used recently to describe the hydrologists' perspective of in-stream hydrology/biota interactions (Dunbar & Acreman, 2001). The concept of eco-hydrology, as first proposed by Zalewski *et al.* (1997), embraces hydrology–ecology interactions in the surficial environment. The basin scale of the paradigm proposing, as a tool, the use of ecosystem properties, and, as a target, the enhancement of absorbing capacity, offers a scenario for the possible generation of positive explanatory feedbacks to reveal new functional "emerging properties" of ecosystems (Fig. 4).

An example of how such a feedback mechanism can stimulate the development of concepts is the hypothetical model explaining the biodiversity distribution patterns at a global scale by the synergistic effects of energy flow and water availability (Fig. 5). In temperate, subtropical and tropical areas, energy flow by the productive and diversified structure of plant communities, under noncatastrophic conditions and within a stabilized temperature regime, has been intensive. The surplus energy accumulated in plant tissues enhances the potential for development of alternative paths of energy flow within the ecosystem. This creates good conditions for speciation and, in consequence, high biological diversity. The cumulative effect of all forms of human impacts has been the reduction of biodiversity. One of the most dangerous consequences of species loss can be the decline in biotic adaptability to changes. The reduction of alternative pathways of energy and nutrient flow through ecosystems leads, among many negative consequences, to a lower potential for using biota for the restoration and regulation of ecological and hydrological processes.

To summarize, ecohydrology can be defined as an integrative science focused on the effects of hydrological processes on biotic processes and *vice versa* in freshwater and costal-zone ecosystems.

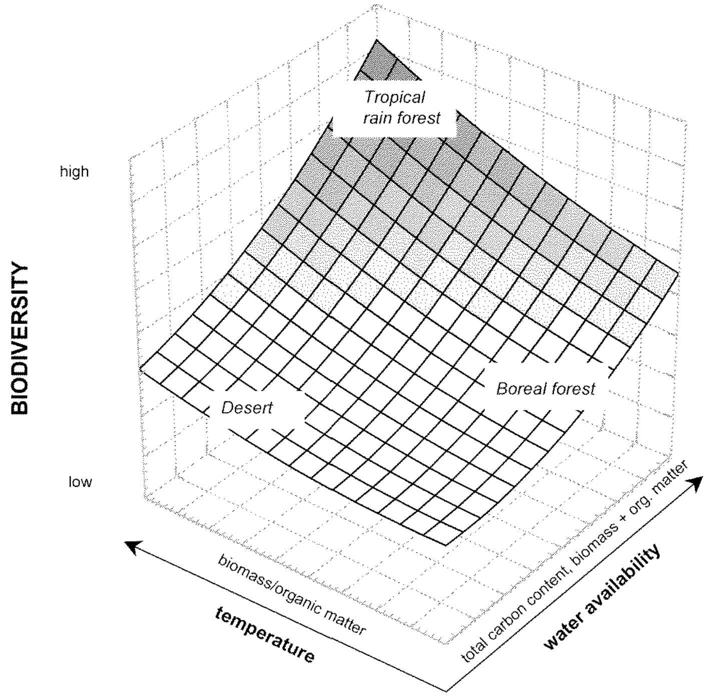

Fig. 5 The general distribution of global biodiversity as an effect of sun energy access and water availability. The water determines primary productivity and the rate of energy flow through the ecosystem; the temperature determines the ratio of decomposition, thus nutrient cycle dynamics; and the ratio biomass/organic matter indicates the dynamics of energy flow through the ecosystem. Total carbon content increases with water availability.

Considering water quality and enhancement of absorbing capacity as an implicit EH target, achievable by using ecosystem properties as a management tool, the sequence of key issues is as follows:

- integrative quantification of hydrological and biological processes at the basin scale;
- analysis of the timing of nutrient, organic matter and organism fluxes between terrestrial and aquatic components of catchments; and
- regulation of the abundance, distribution and intraspecific interactions of freshwater organisms.

Such an approach provides a new instrument for integrated water resources management (IWRM).

The water and climate–soil–vegetation interactions, *sensu* Rodriguez-Iturbe (2000), should be considered as a fundamental context for the above concept and its implementation. In an ecological perspective, the questions focus on the role of hydrology in regulating the life cycles and life strategies of freshwater organisms. Their consequences for water quality have, up to now, been largely neglected.

Acknowledgement The author expresses thanks and appreciation to David Harper and Richard Robarts for constructive comments on the manuscript of this paper. The research presented in this paper was supported by State Committee for Scientific Research grant no. KBN 6PO4 G 11220.

REFERENCES

Ayres, W. S., Busia, A., Dinar, A., Hirji, R., Lintner, S. F., McCalla, A. F. & Robelus, R. (1996) Integrated lake and reservoir management, World Bank approach and experience. World Bank Tech. Paper no. 358, Washington DC, USA.

Baird, A. J. & Wilby, R. L. (eds) (1999). *Eco-hydrology. Plants and Water in Terrestrial and Aquatic Environments.* Routledge, London, UK.

Connell, J. H. (1978) Diversity in tropical rainforests and coral reefs. *Science* **199,** 1302–1310.

Dunbar, M. J. & Acreman, M. (2001) Applied hydro-ecological sciences for the twenty-first century (overview paper). In: *Hydro-ecology: Linking Hydrology and Aquatic Ecology* (Proc. Birmingham Workshop, July 1999) (ed. by M. C. Acreman), 1–17. IAHS Publ. no. 266.

Fitter, A. H. & Fitter, R. S. J. (2000) Rapid changes in flowering time in British plants. *Science* **296**, 1689–1691.

Grodzinski, W., Klekowski, R. Z. & Duncan, A. (1975) *Methods for Ecological Bionergetics.* IBP Handbook no. 24. Blackwell, Oxford, UK.

Gulati, R. D., Lammens, E. H. R. R., Meijer, M.-L. & Van Donk, E. (eds) (1990) *Biomanipulation Tool for Water Management.* Kluwer, Dordrecht, The Netherlands.

Hynes, H. B. N. (1970) *The Ecology of Running Waters.* Univ. Toronto Press, Toronto, Ontario, Canada.

Jorgensen, S. E. (1996) The application of ecosystem theory in limnology. *Verh. Int. Verein Limnol.* **26**, 181–192.

Kabat, P. (2002) Biospheric Aspects of the Hydrological Cycle (BAHC). Editorial, *BAHC News* **9**, 2.

Kaczmarek, Z., Strzepek, K. M., Somlyody, L. & Priazhinskaya, V. (eds) (1996) *Water Resources Management in the Face of Climatic/Hydrologic Uncertainties.* Kluwer, Dordrecht, The Netherlands.

Kooijman, S. A. L. M. (2000) *Dynamic Energy and Mass Budgets in Biological Systems.* Cambridge Univ. Press, Cambridge, UK.

Kundzewicz, Z. W. (1999) Flood protection—sustainability issues. *Hydrol. Sci. J.* **44**(4), 559–571.

Lovelock, J. (1995) *Gaia. A New Look at Life on Earth.* Oxford University Press, Oxford, UK.

Meybeck, M. (1998) Surface water quality: global assessment and perspectives. In: UNESCO IHP-V (ed. by H. Zebidi), 173–186. Tech. Documents in Hydrology no. 18. UNESCO, Paris, France.

Mitsch, W. J. (1993) Ecological Engineering—a co-operative role with planetary life-support system. *Environ. Sci. Technol.* **27**, 438–445.

Mitsch, W. J. & Gosselink, J. G. (1993) *Wetlands* (second edn). John Wiley Inc., New York, USA.

Naiman, R. J. (1983) The annual pattern and spatial distribution of aquatic oxygen metabolism in Boreal forest watersheds. *Ecol. Monogr.* **53**, 73–94.

Naiman, R. J. & Decamps, H. (1990) The ecology and management of aquatic–terrestrial ecotones. UNESCO MAB series. The Parthenon Publishing Group/UNESCO, Paris, France.

Naiman, R. J., Magnuson, J. J., McKnight D. M. & Stanford, J. A. (1995) *The Freshwater Imperative. A Research Agenda.* Island Press, Washington, USA.

Ormerod, S. J. & Watkinson, A. R. (2000) Large-scale ecology and hydrology: an introductory perspective from the Editors of the Journal Applied Ecology. *J. Appl. Ecol.* **37**, 1–5.

Robarts, R. (1998) Factors controlling primary production in hypertrophic lakes (Hartbeespoort Dam, South Africa). *J. Plankton Res.* **6**, 91–105.

Rodriguez-Iturbe, I. (2000) Ecohydrology: a hydrological perspective of climate–soil–vegetation dynamics. *Wat. Resour. Res.* **36**, 3–9.

Roux, A. L. (ed.) (1982) Cartographie politématique appliquée a la gestion écologique des eaux. PIREN. CNRS, Paris, France.

Shiklomanov, I. A. (1998) *World Water Resources. A New Appraisal and Assessment for the 21st Century.* UNESCO, Paris, France.

Somlyody, L., Yates, D. & Varis, O. (2001) Challenges to freshwater management. In: *Catchment Processes Land/Water Ecotones and Fish Communities* (Guest eds: M. Zalewski, F. Schiemer & J. Thorpe). *Int. J. Ecohydrol. Hydrobiol.* **1**(1–2), 65–96.

Starkel, L. (1988) Global paleohydrology. *Bull. Pol. Acad. Sci: Earth Sciences* **36**, 71–89.

Staskraba, M. & Tundisi, J. G. (1999) Reservoir ecosystem functioning: theory and application. In: *Theoretical Reservoir Ecology and its Applications* (ed. by M. Staskraba & J. G. Tundisi), 565–597. Backhuys, Leiden, The Netherlands.

Statzner, B., Gore, J. & Resh, V. H. (1988) Hydraulic stream ecology—observed patterns and potential applications. *J. N. Am. Benthol. Soc.* **7**(4), 307–360.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E. (1980) The river continuum concept. *Can. J. Fish. Aquat. Sci.* **37**, 130–137.

Von Weizsacker, E., Lovins, A. B. & Lovins, L. H. (1997) *Factor Four. Doubling Wealth—Halving Resource Use. The New Report to The Club of Rome.* Earthscan, London, UK.

Walling, D. E. (1980) Water catchment ecosystems. In: *Water Quality in Catchment Ecosystems*, 2–47. John Wiley & Sons, Chichester, West Sussex, UK.

Ward, J. V. & Stanford, J. A. (1995) The serial discontinuity concept—extending the model to floodplain rivers. *Regulated Rivers* **10**(2–4), 159–168.

Wagner, W., Gawel, J., Furumai, H., Pereira de Souza, M., Texeira, D., Rios, L., Ohgaki, S., Zehnder, A. & Hemond, H. F. (2002) Sustainable watershed management: an international multi-watershed case study. *Ambio* **31**, 2–13.

Welcomme, R. (1979) *Fisheries Ecology of Floodplain Rivers.* Longman, London, UK.

Zalewski, M. (2000) Ecohydrology. The scientific background to use ecosystem properties as management tools toward sustainability of water resources. Guest Editorial. *Ecol. Engng* **16**, 1–8.

Zalewski, M. & Harper, D. (2001) Rationale. Ecohydrology—the use of ecosystem properties as management tool for enhancement of absorbing capacity of ecosystem against human impact (UNESCO IHP-V). *Ecohydrol. Hydrobiol.* **1**(1–2).

Zalewski, M. & Naiman, R. J. (1985) The regulation of riverine fish communities by a continuum of abiotic–biotic factors. In: *Habitat Modification and Freshwater Fisheries* (ed. by J. S. Alabaster), 3–9. FAO/UN/Butterworths Scientific, London, UK.

Zalewski, M. & Wagner, I. (1998) Temperature and nutrient dynamics in eutrophic Freshwater ecosystems. *Geographia Polonica* **71**, 79–92.

Zalewski, M., Brewinska-Zaras, B., Frankiewicz, P. & Kalinowski, S. (1990) The potential for biomanipulation using fry communities in a lowland reservoir: concordance between water quality and optimal recruitment. *Hydrobiologia* **200/201**, 549–556.

Zalewski, M., Janauer, G. A. & Jolankai, G. (1997) Ecohydrology. a new paradigm for the sustainable use of aquatic resources. UNESCO IHP Tech. Document in Hydrology no. 7, IHP-V Projects 2.3/2.4, UNESCO, Paris, France.

Zalewski, M., Bis, B., Lapinska, M., Frankiewicz, P. & Puchalski, W. (1998) The importance of the riparian ecotone and river hydraulics for sustainable basin scale restoration scenarios. *Aquatic Conserv: Mar. Freshwat. Ecosyst.* **8**, 287–307.