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Guest editorial

Ecohydrology — the scientific background to use ecosystem properties as management tools toward sustainability of water resources

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1. Introduction

In the face of water resources declining on a global scale, the international scientific community has emphasised the need for new solutions. Why are present methods not providing satisfactory results? First, human activity has severely degraded the most dynamic and most vulnerable regulatory component of that water cycle — the biota — especially during the last two centuries. Second, water management has been dominated by a mechanistic–hydrotechnical approach, when in reality the water cycle at a river-basin scale is the result of biogeochemical evolution. Ecohydrology, the study of the functional interrelations between hydrology and biota at the catchment scale, is a new approach to achieving sustainable management of water. It is based on three principles:

1. Integrating water and biota at the catchment scale, in Platonian superorganisms;
2. Understanding the evolutionarily established resistance and resilience of the superorganism to stress; and
3. Using ecosystem properties as management tools (of effectiveness measured by biodiversity, water quality and quantity).

One of the fundamental tenets of sustainable development is that the homeostasis of ecosystems must be maintained. This is important for human survival, because over-exploitation or degradation of the biotic structure leads to the point at which the ecosystem can no longer produce adequate resources. The present global ecosystem is the result of biogeochemical evolution. Therefore, understanding biological processes on many scales within the abiotic environment is the key to achieving sustainability in the face of exponential human population growth. This understanding is fundamental for controlling and restoring ecological processes that will enhance the ecosystem's resistance and resilience. In this context, the degradation of freshwater ecosystems, and thus of water resources, has two facets: pollution, and the disruption of water and nutrient cycles.

Pollution can be substantially eliminated by technology. The much more complex degradation of evolutionarily established water and nutrient cycles is usually linked with destruction of the biotic structure within the catchment and within the freshwater system. Improving understanding

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of these biogeochemical and biological processes, at scales from the catchment to molecular processes, creates the necessary basis for controlling and regulating nutrient and water dynamics, ultimately enhancing the resistance or robustness and resilience of aquatic ecosystems to human impact (Mitsch, 1993). Thus, improving knowledge has been fundamental to using ecosystem properties as management tools for improving water resources and maintaining biodiversity (Zalewski, 1999).

2. This special issue

This special issue of Ecological Engineering presents selected papers from the International Hydrological Programme (IHP-V2.3/2.4) Symposium on Ecohydrology, held at the University of Lodz, Poland, in May 1998. According to the World Science Report (UNESCO, 1998), the safeguarding of the sustainability of water resources in the face of increasing deterioration of the global environment has been defined implicitly as one of the priority goals for science. The gravity of the problem was already appreciated and so it was the urgent need for new solutions that was emphasised at the International Conferences on Water and the Environment held in Dublin (1992) and Paris (1998).

Why is a new approach to more efficient management of water resources necessary? In decision-making theory, every successful strategy is made up of two elements — reducing threats (danger) and increasing opportunities. The recent prevalent hydrotechnical approach has focused on eliminating dangers such as point source pollution and flood control. Removing these threats is crucial but not sufficient, and may lead to over-engineering, which reduces biodiversity, cultural and aesthetic values, and, most importantly, disturbs the ecosystem's homeostatic processes. This purely technical control, excluding any consideration of the biology of the system, is a trial and error approach to water management rather than a policy toward sustainable use of water. To guarantee the sustainability of freshwater resource use, it is necessary not only to reduce or eliminate pollution emission but also to extend the number of potential tools to manage excess nutrients, pollutants, minerals, and organic matter in the landscape.

The approach will be more efficient when the temporal and spatial patterns of water dynamics are understood at the catchment scale. Four components determine these patterns: climate, geomorphology, plant cover and biota dynamics, and human interference. The quantity and quality of the water are determined mostly by climate, but also by biotic factors. The sequential changes of global climate depend mostly on interplanetary torque and solar modulation. Temperate ecosystems evolved after glaciation as a series of successional stages. Every stage depended on climatic or hydrologic condition and on nutrient availability as a factor triggering primary productivity. Subsequent phases were characterised by the unique composition of plants and animals whose inherent properties determined the ability of the system to retain water and nutrients (Odum, 1969). So water resources can be sustained not only by reducing human impacts but also by regulating the aquatic and terrestrial biota within the drainage basin (Zalewski et al., 1997).

One of the most effective ways to control biota dynamics is by regulating hydrological processes: for example, by increasing water retention through reforestation (Petts, 1984); by restoring land/water ecotones (Naiman and Decamps, 1990; Schiemer et al., 1995); and by restoring river wetlands. Wetland restoration enhances in-stream retention of water, sediments and nutrients by amplifying biogeochemical cycles such as (Mitsch and Gosselink, 1993). Recent research has greatly increased our understanding of hydrological dynamics and in parallel, biotic and biogeochemical dynamics of freshwater ecosystems. The holistic integration of these components through ecohydrology (implicitly a Platonian superorganism) should significantly extend not only our scientific understanding, but also our predictive ability and the repertoire of management tools that can be applied to freshwater resources. Moreover, using biotic processes allows aquatic ecosystems to clean themselves, and reduces costs of water quality maintenance significantly. Cost reduction is especially important, as globalisation enhances the awareness of the opportunities that science offers for accelerating socio-economic development. However, the increasing costs of science may widen the gap between the industrialised and the developing world. Closing this gap has been one of the implicit goals of the IHP V UNESCO programme.

3. The links among ecological engineering, ecohydrology, and ecosystem biotechnologies

To win a war, leaders need the vision to create a sound strategy, flexible tactics, and an efficient operational level. In the war on global sustainability, Patten and Odum's (Patten and Odum, 1984) concept of the cybernetic nature of ecosystems can be thought of as the vision, supplemented with the Gaia hypothesis (Lovelock, 1995). In the case of river basins, the ecohydrological Platonian superorganism may play a similar role. Ecological engineering, the concept of control and regulation of ecosystem scale processes (Mitsch, 1993), might be considered a sound strategy for improving required resources. The importance and urgent need to develop such a creative approach to environmental management has prompted the emergence of convergent terms and definitions, e.g. ecotechnology (Straskraba, 1994), and ecosystem biotechnologies (Zalewski et al., 1995), the latter term relating to tactics, describing the human control of biological conversion at the ecosystem scale. In the present context the ecohydrological approach should be considered the strategy that integrates the interactions among the biota, climate, and hydrological processes in attempting to enhance the resistance and resilience of freshwater ecosystems against stresses imposed by humans. Thus, restoration of evolutionarily established cycles in a freshwater ecosystem may be achieved by regulating nutrients and energy conversion using hydrology and the biota in the landscape: this is the ecological engineering approach using ecosystem biotechnology.

4. The application of ecosystem biotechnology for upgrading water resources in a river basin

The term biotechnology traditionally has been defined as an application of biological processes at a laboratory or commercial scale to convert matter from one form to another, e.g. the use of yeast to produce beer from barley. By analogy, regulating the rate of conversion of matter in a river catchment by, for example, increasing denitrification intensity in a wetland by raising the water level can be considered an application of ecosystem biotechnology (Zalewski et al., 1995, 1997), upgrading the quality of freshwater resources. This is because the ammonium is converted to N_2 and transferred from the aquatic system to the atmosphere. The restoration of a eutrophic reservoir with toxic algal blooms by reducing the nutrient flow into the water, through different ecosystem biotechnologies (Fig. 1), is an example of an ecohydrological approach at the river basin scale. Starting from the top of the catchment, the first stage has to be enhancement of nutrient retention within the catchment by reforestation, creation of ecotone buffering zones, and optimisation of agricultural practices. The buffering zones (shelterbelts) at the land–water interface reduce the rate of groundwater flux due to evapotranspiration along the river valley gradient (Ryszkowski and Kedziora, 1993). This process may increase the nutrient uptake by cultivated land up to 30% (Statzner and Sperling, 1993). Nutrient transformation into plant biomass in ecotone zones may further reduce the supply into the river. The wetlands in the river valley form the buffering zone: they reduce the mineral sediments, organic matter and nutrient load transported by the river during flood periods through sedimentation (Carling and Petts, 1992; Mitsch et al., 1995). Also, in some artificial wetlands, nitrogen load can be reduced significantly by regulating the water level to stimulate denitrification through anaerobic processes (Tomaszek and Czerwieniec, 1995).

In highly populated catchments it is possible to amplify the self-purification process. Zalewski et al. (1995), Zalewski (1998) showed that by increasing the intermediate complexity of the riparian ecotone, by increasing light access to 300–700 $mE\ cm^{-2}\ s^{-1}$, self-purification measured as nutrient uptake by instream biota can be increased over 100% compared with shaded stream sections. If, despite considerable nutrient reduction by technical methods and such ecosystem biotechnology, the nutrient concentrations in a reservoir are still too high, these nutrients may be converted at high temperatures into primary producer biomass or even into cyanobacterial toxic algal blooms. In such cases nutrients may be blocked in plant biomass (reeds, willows), and dislocated (dispersed?) successfully between the trophic levels by biomanipulation — enhancing zooplanktonic biofiltration by reducing zooplanktivorous fish pressure (Gulati et al., 1990). As for controlling the dynamic pool of nutrients in reservoirs and lakes to avoid eutrophication, further work is needed to control recirculation by reducing nutrient resuspension and phosphatase activity, and to regenerate zooplankton. Since properties of a large-scale system cannot be predicted from properties of its component elements, such a complex strategy for restoring nutrient cycling in a catchment landscape and freshwater ecosystem should be assessed continuously at every stage of implementation and adjusted to improve the efficiency of further steps. This is the adaptive environmental assessment and management approach (Holling et al., 1994).

This ecohydrological approach to the restoration of river basin systems using ecological engineering and ecosystem biotechnology methods should be considered rather as a challenge than as a final solution.

5. Papers in this special issue

In the first paper Janauer (2000) highlights the link between hydrology and biology by reviewing some ecological concepts relevant to ecohydrology, as a key for integration, and considers the scale of the processes. He suggests that it is important for the future development of ecohydrology to add quantitative hydrological data to the concepts and models of the limnologists. Filling the gaps between the methods and scales of both approaches will require the closest possible team level co-operation.

The papers of this special issue have been ordered along a gradient from small- to large-scale processes. Understanding and quantifying small-scale ecohydrological processes in differing freshwater habitats provides the basis for constructing large-scale predictive models. Recent failures in

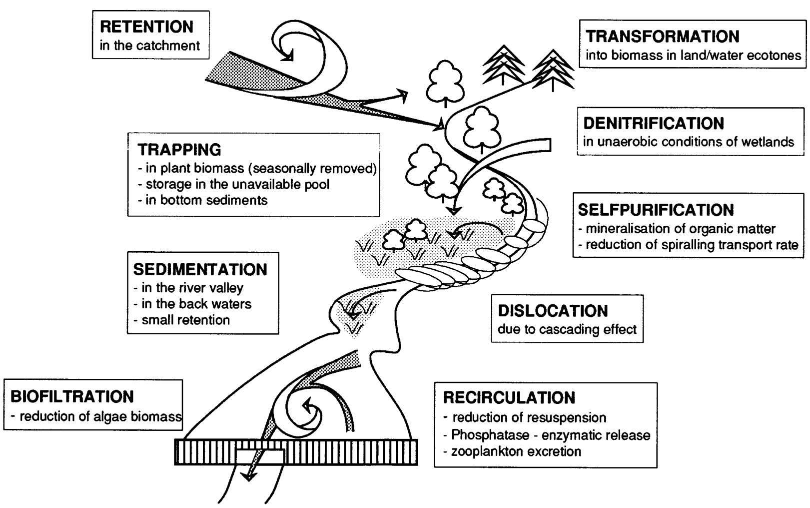

Fig. 1. The ecohydrological concept of the restoration of a eutrophic shallow reservoir, by applying various ecosystem biotechnologies as an example of catchment-scale ecological engineering.

water management have often been due to treating problems at only an operational or tactical level without elaborating a strategic plan. This was because the small-scale processes were incompletely understood and could not be incorporated properly into holistic large-scale models. Sound water management has to be based on large-scale planning models of processes, themselves based on understanding of such small-scale phenomena, if predictive ability for sustainable management at the catchment scale is to be improved.

Kemp et al. (2000) examine the influence of channel geomorphology and geology on the diversity of functional habitats, identified by distinct invertebrate assemblages. The deviation of a site from its predicted natural summer wetted width was used as an index of physical degradation.

Groundwater quality and dynamics was considered as a factor influencing water quality in Lake Stechlin. Holzbecher and Nützmann's (Holzbecher and Nützmann, 2000) paper describes processes during groundwater passage and presents a model for the distribution of its chemistry. The concept of a carbonate equation in the groundwater system is derived.

Biswas and Boruah (2000) explain the dramatic decline of highly diversified Himalayan Mountain Brahmaputra River fish fauna (166 fish species) by accelerated deforestation and land degradation due to 'careless' agricultural practices of the river basin. As a result, the river hydrological regime has been changed and siltation has increased. As a consequence, the river bed was modified and floodplain fish reproductive areas and rearing habitats were degraded.

Toxic algal blooms causes serious problems in eutrophic recreational or water supply reservoirs. Codd (2000) reviews the geographical and environmental occurrence of established toxins and advances in understanding of the hazards they present to human health. Management requirements to increase the ability to prevent or reduce the effect of cyanobacterial toxins are discussed. The author emphasises the need for awareness of the significance of cyanobacterial production and relevant health guidelines in decision-making for eutrophication control.

Nitrification and denitrification are important processes that may be controlled by ecological engineering to reduce nitrogen in freshwaters. Tomaszek and Czerwieniec (2000) present various methods for the quantitative evaluation of denitrification processes in shallow reservoirs. The key to achieving an adequate nitrogen balance for a given ecosystem is the precise estimation of the types of habitats and conditions enhancing or reducing the intensity of the denitrification process, so that the nitrogen load may be reduced by enhancing the most efficient habitats.

Tátrai et al. (2000) describe an artificial wetland as a trap for nutrients supplying Lake Balaton, one of the biggest lakes, and socio-economically the most important lake, in Europe. This wetland area of 18.5 km^2, with a mean depth of 1 m, and mean retention time of 4 weeks, is the first part of the Kis–Balaton water protection system. During the first stage of its functioning (1986–1997), 300 t of total phosphorus (TP), 80 000 t of suspended solids, 250 t of phosphates and 850 t of total nitrogen were retained. Recently, 52% of suspended solids, 38% of TP, $>81\%$ of phosphates, and 11% of total nitrogen have been retained in this area. The authors discuss the prospects of further development and the reaction of the lake communities.

Wagner and Zalewski (2000) discuss the potential for reducing the toxic algal blooms (symptoms of eutrophication) in a 2000 ha lowland drinking water reservoir supplying 1 000 000 people, by regulating hydrological processes in two main tributaries that differ in flow catchment characteristics and nutrient load. For the smaller tributary (flow, 3 $m^3\ s^{-1}$) with total phosphorus concentrations of 0.5 mg l^{-1} P, they concluded that the priority solution for reducing nutrients to the level eliminating toxic algal blooms should be neighboring and sub-catchment artificial wetlands (Tilley and Brown, 1998). For the larger tributary (mean flow, 24 $m^3\ s^{-1}$) with a much lower and more stable total phosphorus concentration of 0.1–0.2 mg l^{-1} P, the priority should be an ecotone buffering zone along the streams in agricultural parts of catchment and an artificial catchment wetland.

Landscape processes in the catchment, changed in different ways by humans, may modify surface water quality to differing degrees. Hillbricht-Ilkowska et al. (2000) discuss the varying levels of correlation between precipitation and discharge, and nutrient transport and transformation in a patchy environment. This study provides unique information to be used for control and regulation of landscape processes for improvement of water quality.

Schuller et al. (2000) discuss the problems of restoring the quality of water resources in a 1000 ha ecosystem highly degraded by intensive agriculture and overloaded with nitrogen. The authors show that the surface water quality and biota biodiversity may be improved relatively quickly by applying ecological engineering methods such as reconstructing wetlands, changing surface water profiles, reducing agricultural use, and reconstructing linear connectivity.

However, recovery of groundwater needs at least decades and there is no certainty that the original state will be recovered. Fashchevsky (2000) demonstrates that the relationship between the biomass productivity in a river floodplain and the intensity of the flood regime is parabolic. Such data may help in planning integrated floodplain use, flood control, and agricultural production.

The water quality in the mouth of the Dnieper River depends on water released from the Kakhovka hydropower station. Timchenko et al. (2000) show that a flow of 530 $m^3 s^{-1}$ is needed to maintain good water quality in the estuary in the face of 43 t day^{-1} load of autochthonous and allochthonous (anthropogenic) organic matter. This could be considered an example of a how to maximise of the resilience of a river ecosystem to anthropogenic stress.

The effect of large-scale hydrological processes, such as water level changes and chemical characteristics, on plant community structure was modelled mathematically (DEMNAT) by van Ek et al. (2000). A method to deduce nation-wide maps of ecosystem types from the national database for the Netherlands (FLORABASE) is presented by Witte and van der Meijden (2000). The ecosystem types on the maps are defined by abiotic factors, which determine the plant species composition of the vegetation. Both models create the basis for precise monitoring and decision making processes, especially for analyses of the consequences of restoration and evaluation of different water management practices on groundwater dependent ecosystems.

Spence and Hickley (2000) propose an interesting decision support system (PHABSIM) for restoring and sustaining biota, especially fish in rivers. It may be used for quantitative prediction of suitable physical habitat in a river reach, based on different flow scenarios, field measurements, hydraulic calibrations, and species physical habitat preferences.

Brinkmann et al. (2000) show the extent and specificity of historical processes by analysis of sediments in a large river floodplain. The recent floodplain structure determined the flooding pattern and ground water recharge area, and the geological history of the floodplain had an influence on recent hydrologic processes.

Dakova et al. (2000) identify minimum water discharge to maintain the water quality and biota diversity, by comparing biotic indices, water discharge, flow regime and water quality at a selected river stretch while Hovhanissian and Gabrielyan (2000) introduce the dramatic effects of excessive water extraction from the 1416 km^2 Lake Sevan in Armenia. The water level declined by 19 m, resulting in a 42% loss of water volume, deterioration of the littoral zone, eutrophication, decrease of fishery yield and elimination of endemic fish species. This dramatic degradation of the ecosystem stimulated a large-scale programme of restoration based on the ecological engineering approach. This focused on raising the water to its characteristic level, reducing water extraction for irrigation and energy needs, constructing alternative reservoirs, and transferring water from the River Arpa.

The hydrodynamic processes in reservoirs are important factor regulating the physical conditions (oxygen concentrations) and process of algal succession. The paper by Dubnyak and Timchenko (2000) quantifies the relationship between hydrodynamic processes and the reaction of biota. The author presents the possibility of indirect control of biotic processes and, as a result, water quality in reservoirs by regulation of the hydrodynamics and hydrology of the reservoir.

These papers represent a sample of the activities of 39 projects in 26 countries within the framework of the UNESCO IHP V Ecohydrology programme. We believe that discussions, information flow, and activities developed in this programme create a notable step toward the sustainable use of freshwater resources in the face of global changes. To meet the emerging global scale challenges, traditional discipline-oriented teams need to be replaced by problem-orientated interdisciplinary teams.

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