Ecohydrology and Hydrologic Engineering: Regulation of Hydrology-Biota Interactions for Sustainability

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Abstract: In the context of global environmental and social change, with increasing pollution and decline of biodiversity of terrestrial and aquatic ecosystems having its deep roots in drastic modifications to hydrological mesocycles, there is an urgent need for a new approach for sustainability. The two often contradicting approaches to water resources management, i.e., (1) hydrotechnical, and (2) ecological, can be reconciled within the context of ecohydrology (EH). It seeks for the understanding of the underlying water-biota interactions as well as providing a new tool for management of water resources. While the majority of changes are nonreversible in the framework of ecohydrology it is possible to regulate (dual regulation) the processes, especially in novel ecosystems, as an alternative to conservation and restoration measures, in order to increase their carrying capacity in the four dimensions, as follows: (1) water resources, (2) biodiversity, (3) ecosystem services, and (4) resilience. The proposed approach aims to initiate a discussion and joint efforts of hydrological engineers, hydrologists, and ecologists towards formulation of the comprehensive strategy and scientific background for harmonization of society needs with the enhanced ecosystem potential. It stipulates for a change in paradigm not only in the environmental sciences but also in the global economy, engineering, and education systems. **DOI: 10.1061/(ASCE)HE.1943-5584.0000999.**

Author keywords: Paradigm shift; Holistic perception of nature; Regulation of processes; Ecological engineering; Water resources management; Water-society harmonization.

Introduction

In our times the so-called spaceship Earth is facing huge global environmental challenges. The planet becomes dry, freshwater polluted, and both terrestrial and aquatic ecosystems' biodiversity declines. This happens because of profound modifications to hydrological mesocycles. Acceleration of surface water outflow from the landscape has been increased by drainage, deforestation and expansion of impermeable surfaces. Modification of most of the Earth's surfaces (agricultural and urbanized areas) resulted in reduction of evapotranspiration by biota and increase of evaporation from abiotic surfaces, causing a decline in water recirculation (e.g., convective rains) and retentiveness at a catchment scale. Moreover, the freshwater ecosystems became overexploited, used as sewage recipients and the landscape-level ecological complexity has been reduced. With such a weakened self-purification potential of the landscape emissions from non-point sources of pollution become the dominating limitation of ecosystem services of flowing water systems, exacerbated by river channelization. Also dams, if constructed without bypasses, modify mineral and organic matter transport and reduce migration of organisms along the river continuum (RC). All of the above mentioned forms of human impacts on freshwater ecosystems and coastal zones are interlinked, and might be amplified to various extents on different continents due to demographic and climatic changes.

In the face of the global demographic, economic, and climatic changes, within the context of the United Nations' Millennium Development Goals, which defined sustainability as a strategic goal for humanity, a new strategy and measures for achieving this goal is an urgent need. Cases when entire civilizations disappeared because of unsustainable resource use were already noted in the past; however, in the Anthropocene era in which we live now humanity is approaching the carrying capacity of the global ecosystem, threatening destabilization at a global extent. To avoid the cascade of environmental consequences and related social conflicts from local to global scales and to achieve sustainability, an urgent shift in paradigm in the environmental sciences is necessary.

There are two extreme approaches to water and environmental management that still prevail: (1) on one side, hydrologists and hydroengineers are concentrated on providing sufficient water resources for the economy with the technical measures; and (2) on the other, ecologists put their utmost attention to the damage to biodiversity or a potential modification to ecology that the hydrotechnical intervention in focus might cause. Meanwhile, the modification of the landscape and as a consequence the land cover driven hydrological cycle went so far that it is impossible to eliminate the ever intensively occurring threats (water deficits and floods; cf., Ryszkowski and Kedziora 1999) with hydrotechnical measures alone. Luckily, there is a steady evolution of the approach in ecological sciences, leading to the transformation of the structure-oriented thinking by the processes-oriented approach (Zalewski 2013). As a consequence, it was possible to start a dialog with hydrological and hydrology-based sciences, and to formulate a transdisciplinary paradigm, ecohydrology (EH), to deal with water-related problems.

The major message of this paper is to initiate a discussion and joint efforts of ecologists, hydrologists, and hydrological engineers

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Note. This manuscript was submitted on December 13, 2012; approved on March 11, 2014; published online on March 13, 2014. Discussion period open until April 5, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, © ASCE, ISSN 1084-0699/A4014012(14)/$25.00.

for further integration and transformation into practice the advancements of their respective disciplines for sustainability in water resources management. The paper presents several steps to be made, e.g., (1) change in a paradigm of thinking from structure-oriented to processes-oriented, (2) use of ecohydrological biotechnologies based on "dual regulation" and ecological engineering, and (3) introduction of a new model of education. It proves that hydrotechnical solutions do not need to be destructive for ecosystems and biodiversity. If researchers are able to understand how the basic environmental processes were formed by evolution, it will be possible to use hydroengineering solutions accompanied with biotechnologies to solve water quality and quantity issues, and to develop low-cost conceptually advanced methods and system solutions for integrated water resources management (IWRM).

Methodological Background of Science in Achieving Sustainable Development: Current and New Paradigms

Sustainable development is a well-established concept. However, there are still disputes on how and what would be the best way to achieve it. One of the conflicting issues is cooperation between environmentalists and engineers. It has deep roots in the system of education, which in turn is based on its foundations in the mechanistic and deterministic philosophies of the seventeenth and eighteenth centuries (Renes Descartes, Izaak Newton, and Julien Offray de La Mettrie), the foundations of the current scientific reasoning and analysis. In these paradigms the universe and all its components are determined by the nature of the laws of physics and thus can be predicted. Such thinking implies still deeper and deeper analysis of the components of the matter, which should at the end lead to an explanation of the nature of the entirety. As a result, researchers tend to concentrate on continuously smaller details of the whole, missing the entire nature of the phenomenon. Researchers create teams of specialists who try to deal with the problem with their specific methods. Engineers, who in fact become real decision makers in environmental management, concentrate on reducing the threat of flooding and droughts, and on obtaining the most energy production possible from a given amount of water. Environmentalists instead aim at conserving particular temporal and spatial landscape structures and ecosystems, or restoring them if degraded. Both fragmented views are doomed to failure because, for example, in case of Europe about 70% of land is drastically modified by man and the hydrological cycle is modified to such an extent that conservation or restoration measures can be effective only in a very limited scope. As a result, the technical solutions are already not sufficient to bear the consequences of the observed land cover degradation, which demonstrate themselves in a more stochastic character of hydrological fluxes and increased loads of minerals, nutrients, and pollutions into waters. Should the solution lie in intensifying those antagonistic measures? The key is integration of hydrological engineering knowledge and experience with the ecohydrological methodology in a more holistic framework. Therefore there needs to be a change of the paradigm from reductionist and sectored thinking to a holistic perception of nature. This would in turn let the society go forward to a transdisciplinary scientific approach to provide a methodological background for harmonization of the society needs with the enhanced ecosystems potential (Zalewski 2002a; Zalewski and Robarts 2003; Zalewski 2005; EcoSummit 2012). The holistic concept of nature is a prerequisite for the development of synergistic system solutions integrating engineering and ecohydrological solutions. However, for these solutions to be efficient it is necessary to define the hierarchy of components the holistic concept is based on. The condition *sine qua non* is acceptance of the following three assumptions:

1. Evolutionarily established environmental processes create a system of mutual and multidimensional interdependencies from molecular to landscape scales.
2. Water is fundamental for all forms of life and most human activities on Earth. Water cycling is a key element of all environmental processes. It is not only a medium to transfer biogenic substances across molecular to catchment scales, but also a key element to determine ecosystem biodiversity and bioproductivity (Zalewski 2002a).
3. Only a paradigm change, from structure-oriented to processes-oriented thinking where the key drivers of these processes are defined, will permit researchers to understand the dynamics of ecosystems and develop effective system solutions. The prerequisite for a change should be integration of different disciplines of science into a transdisciplinary science, and formulation of a concise and comprehensive vision and strategy for sustainability.

Complex Relations between Humans and the Environment: Exploitative Resource Use and the Way Out

An intensive change in the mutual relations between humans and the environment begun with the advent of the industrial era. It was fueled by the conviction of an unlimited potential of nature that can be used for any recognized needs of the humanity (UNESCO 2012; Fig. 1). After the phase of a wild exploitation of the natural resources there came a reflection of the need to protect the nature and later on of its restoration.

However, there are two important aspects of the current relations between humans and the environment. The first is a limited understanding among researchers of the integrity of ecological processes, i.e., circulation of water, nutrients, and energy in ecosystems that are governed by evolution and are also under constant modification by man, and of their change over time. Consequently, human actions based on incomplete information and inadequate understanding of the consequences of the planned actions, with no control form the outside lead to degradation of the environment (Zalewski and Penczak 1981) and loss of their fundamental services. The second aspect is an awareness of the complexity of a catchment that is a template for water resource management, including elaboration of river basin management plans. Primarily, every catchment possesses a specific hierarchy of water cycle drivers related to the unique geomorphology, climate, plant cover, and so on. To various extents these drivers were modified due to social development and population growth combined with a variety of economy driven activities such as deforestation, urbanization, industrialization, and transportation. All of the previously mentioned forms of human interventions into water cycle have changed the catchment's heat budget, wind speed, and rate of water outflows from the catchments accelerating it. This in turn has increased by orders of magnitude the transfer of mineral and organic matter, nutrients, and pollutants from land to rivers, reservoirs, lakes, and costal zones (Meybeck 2003; Wolanski 2007; Chicharo and Zalewski 2012; Kiedrzyńska et al. 2014). As a consequence researchers encounter that the landscapes across all continents become not only drier but also less fertile due to the loss of nutrients and organic matter from soils.

Therefore, while fundamental ecological cycles such as water and nutrient cycling and energy flow become so deeply modified,

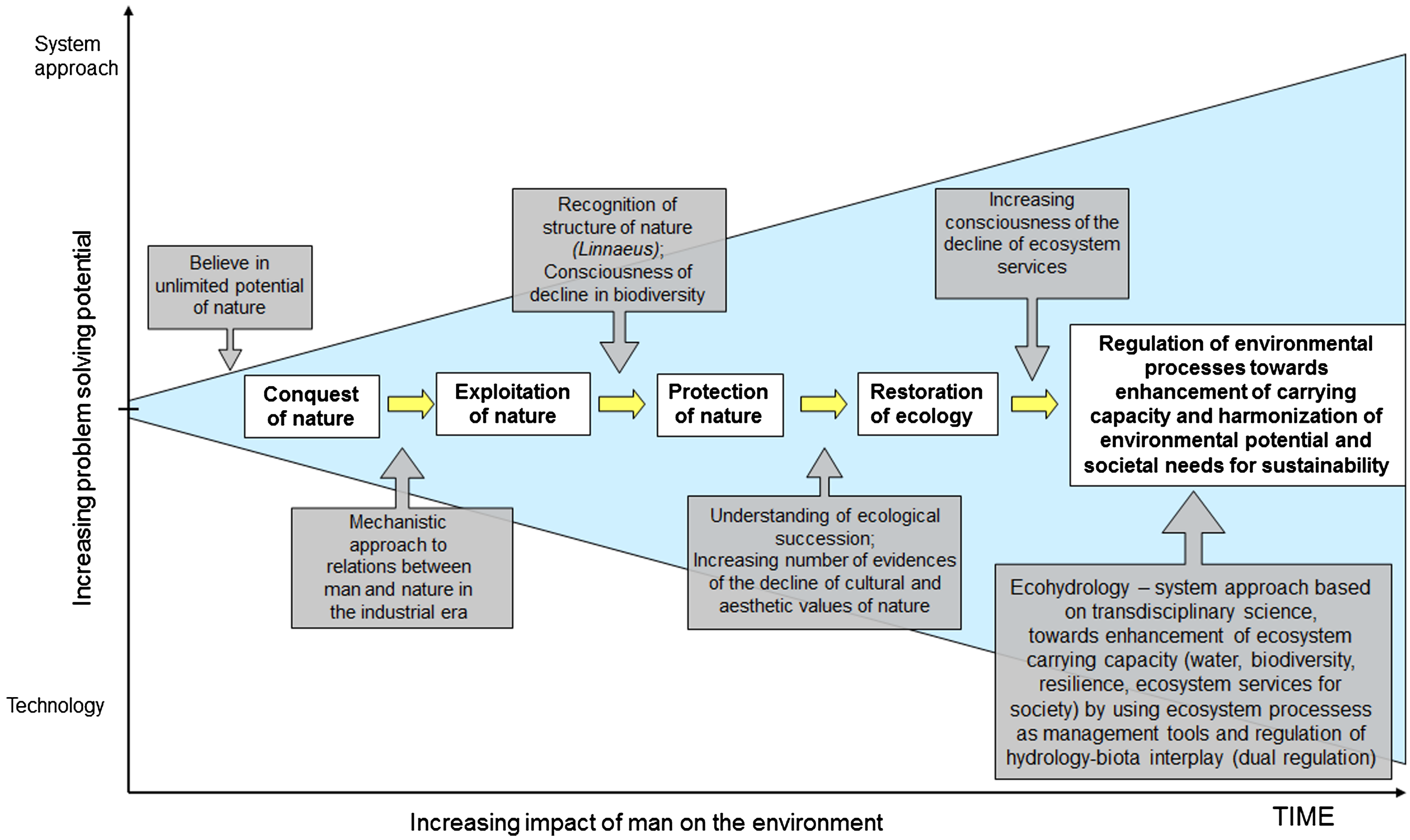

Fig. 1. Evolution of the human approach towards the use of natural resources, starting from the belief of unlimited potential of nature to the recent awareness of the necessity for regulating ecological processes for the enhancement of the ecosystem carrying capacity (Zalewski, courtesy of UNESCO 2012)

there is an urgent need to expand the range of available compensatory measures by those aiming at regulation of the processes controlling the water-biota interplay (Fig. 1).

Water As a Driver of Ecosystem Structure and Dynamics: Background to Ecohydrology Theory

The other two key interconnected issues that need to be addressed are (1) water cycle, and (2) its linkages with biocenoses. Firstly, the hydrological cycle has to be considered as a primary regulator of ecological potential [bioproductivity and biodiversity, e.g., Wojtal-Frankiewicz and Frankiewicz (2010)]. Secondly, understanding of the role of biocenoses in shaping the water and nutrient cycling is fundamental to reversing the declining potential of the biogeosphere (Tilman 1999; Vorosmarty and Sahagian 2000; Rodrigues-Iturbe 2000). In subsequent paragraphs it will be discussed in more detail.

Water is the primary factor limiting and regulating the ability of ecosystems to accumulate carbon, nitrogen, and phosphorus. When water is available ad libitum, then temperature determines the metabolic rates of microbial communities, plants, and poikilothermic animals. Thus, the assimilation of available nutrients is governed by stoichiometric relationships with limitation effect expressed by Liebig's law of the minimum. Moreover, biodiversity, a fundamental cumulative indicator of the human well-being and the prospects for sustainable future (Millenium 2005), is driven by water availability that determines plant yield (Visser 1971; Rodriguez-Iturbe 2000; Emaus et al. 2006) and solar radiation, related to biomass increase (Kowalik and Eckersten 1984; Kedziora 1996). Hence, in given geomorphological conditions water and temperature are the major determinants of biodiversity and bioproductivity (Fig. 2). This is because the amount of water in a given temperature range determines the amount of carbon accumulated in an ecosystem (in the form of living and decaying organic matter), while the temperature determines the allocation of carbon between the plant's biomass and soil organic matter. For example, when moving from boreal zone southward to the tropics with an increasing temperature there is a significant shift in allocation of organic matter, and therefore carbon, from soil into biomass. This is explained by the Van Hoff's law that relates the acceleration of organic matter decomposition processes to temperature increases. Thus, decomposition of organic matter in the soil can be up to 40 times faster in the tropics than in the boreal zones. High nutrients circulation rate and energy supply create good conditions for diversification of microbial, plant, and animal communities, and persistence of favorable mutations through natural selection and adaptation processes. Thus, researchers can assume that opportunities for diversification of genomes can be more than an order of magnitude more favorable in the tropics (biotic) then in the boreal zone (abiotic ecosystem regulation). What is more, under the harsh conditions of boreal zones, the short growing period for plants provides a very limited flow of energy and nutrients, and in consequence, catastrophic events may randomly eliminate emerging new genomes. Thus boreal and high mountainous ecosystems pose lower potential for regeneration and compensation of human impact. A similar phenomenon is observed in deserts where scarce biodiversity and

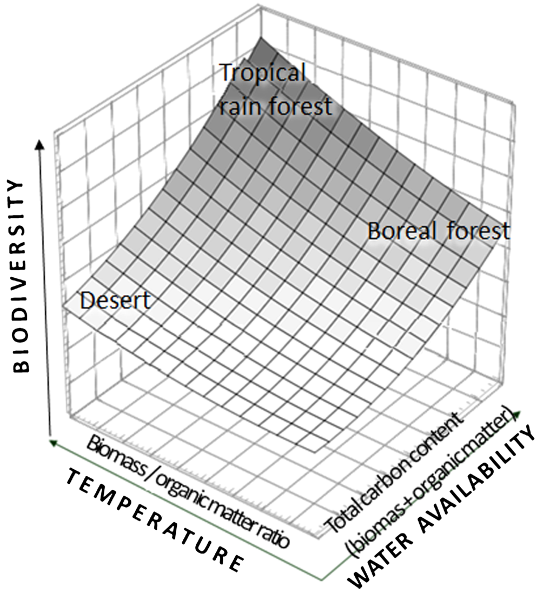

Fig. 2. Deductive background of ecohydrology theory, terrestrial phase, drivers of biodiversity; the amount of water determines the amount of carbon accumulated in an ecosystem while temperature determines the carbon allocation between biomass and soil organic matter; the maximum biodiversity and bioproductivity is achieved at highest water availability and highest temperatures (Zalewski 2002a, with permission from Taylor and Francis Ltd., http://www.tandfonline.com)

bioproductivity is driven by low water availability and high temperature leading as a consequence to low carbon accumulation in the soils [abiotic ecosystem regulation, i.e., per Zalewski (2002a, 2010); Fig. 3].

An example of the complexity of the interrelations between hydrology and biota, thus justifying the necessity of its profound understanding, is the abiotic-biotic regulatory concept (ABRC; Zalewski and Naiman 1985; Zalewski et al. 1986; Fig. 3). It was inspired by the river continuum (RC) concept (Vannote et al. 1980), which initiated the process-oriented thinking in river ecology, referring to the observed shift in production/respiration ratio in streams from upstream to downstream (Newbold et al. 1982). The ABRC as a background for ecohydrology was inspired also by a scientific debate of ecologists concerning density-dependent (biotic drivers) and density-independent (abiotic drivers) determination of ecosystems structure and functioning. The ABRC novelty was to underline the hierarchy of abiotic and biotic drivers in shaping the riverine ecosystems; only when abiotic (water) factors become stable and predictable the biotic factors start to manifest themselves. Extrapolating this notion into all types of freshwater ecosystems, researchers can expect analogical adaptation for different abiotic stress factors not only in the rivers, but also in lakes and reservoirs. In the boreal zone, riverine organisms adapt to harsh conditions by fat accumulation to compensate for temperature-limited food assimilation during long winters followed by a period of high energy expenditure due to hydrological stress during the snowmelt period. On the other hand, in hot and dry freshwater ecosystems [e.g., Naiman and Soltz (1981)], high metabolic rates of organisms and consequential high oxygen demands clash with the low water oxygen solubility due to high temperature and low oxygen availability during nights resulting from high respiration rates, thereby compromising the efficiency of Krebs cycle metabolic pathways.

An understanding of the relationships expressed by the model (Figs. 2 and 3) is fundamental to reverse the worldwide observed loss of organic matter in soils (UNEP 2008), as well as siltation and eutrophication in rivers, lakes, reservoirs (Hillbrich-Ilkowska 1993), and coastal zones. Understanding of the previously mentioned processes requires an interdisciplinary knowledge of rudimentary physics, chemistry, plant physiology, biochemistry, geography, ecology, and evolution, and should be applied during hydroengineering realizations. What is more, a broad understanding of the previously mentioned processes to a great extent provides scientific background for the development of ecohydrological biotechnologies adaptable for different geographic regions (discussed in subsequent paragraphs).

Ecohydrology: New Paradigm for Sustainability

As mentioned at the beginning, the reductionist conception of nature followed by the sectorial organization of science led to

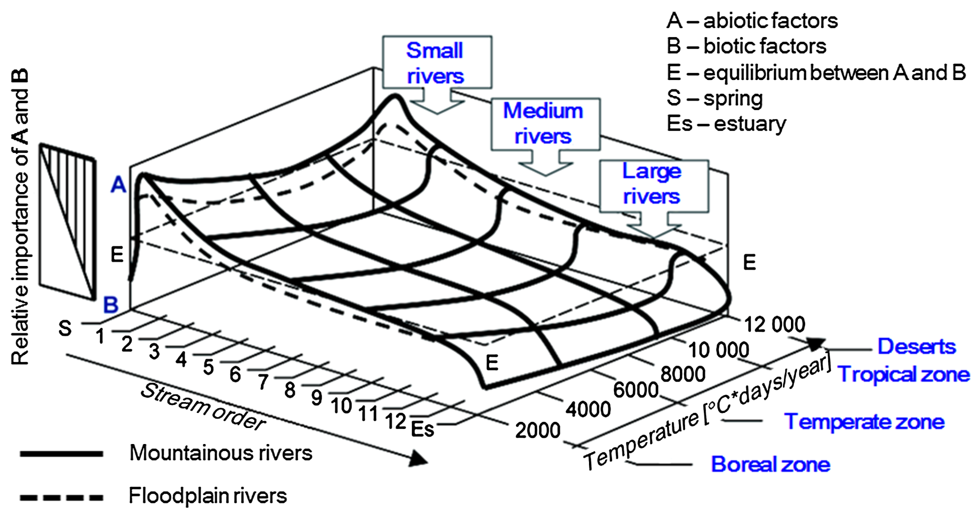

Fig. 3. Deductive background of ecohydrology theory, aquatic phase, the abiotic-biotic regulation concept; structure and dynamics of riverine fish communities are determined by a hierarchy of abiotic and biotic factors in specific ratios depending on the hydrology parameters determined by slope and stream order and on the energy budget of a given climatic zone determined by temperature; only when abiotic factors (hydrology) become stable and predictable the biotic drivers start to manifest themselves (adapted from Zalewski and Naiman 1985)

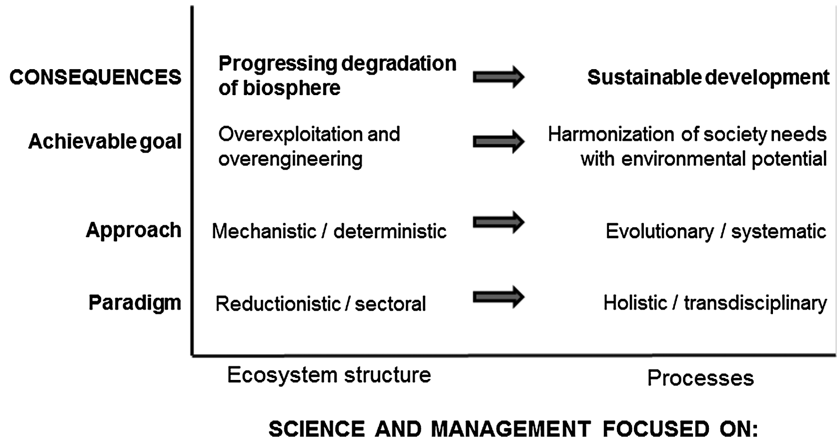

Fig. 4. Expected direction of a shift in environmental science paradigm from the currently prevailing structure-oriented paradigm (conservation and restoration actions, focused on the assessment of the effect of various human activities on biota) to process-oriented approach (regulation of ecosystem processes, i.e., circulation of water and nutrients, and energy flow) to create a background for harmonization of societal needs with ecosystem potential, and ultimately the sustainable development; the arrows represent the expected shift in the paradigm at three levels, as follows: (1) scientific, (2) operational/practical, (3) political, and the expected results

mechanistic and deterministic perception of the environment, and had their consequences in the rally for maximizing resource use with minimal outlays (Fig. 4). However, it is postulated that to achieve sustainability the society needs to optimize their resource use instead of maximizing it.

The holistic conception of nature and its reflection in the transdisciplinary science needs to employ evolutionary and systematic approach to solving environmental problems. Until the early 1970s the ecology concentrated on structure of nature. Eugene P. Odum (Odum 1971) set fundamentals to break this paradigm by focusing on the functionality of ecosystems and their relation to economy. The further progress in understanding ecological processes in rivers (Heynes 1970; Vannote et al. 1980; Junk et al. 1989), reservoirs (Ward and Stanford 1983, 1995; Petts 1984, 1995) and lakes (Gulati et al. 1990; Hillbricht-Ilkowska et al. 2000) created a background for process-oriented approach in ecology (Wilkinson 2006) and a development of a problem-solving science, ecohydrology (Zalewski et al. 1997; Zalewski 2000, 2013). Hence, a paradigm shift to processes-oriented thinking in entire human activity, especially in the interface between ecologists and hydroengineers is necessary for effective implementation of system solutions in the holistically perceived catchment environment.

Process-oriented thinking in the integrative environmental science has to be driven by physics (e.g., thermodynamics is applied in bioenergetics of plants and some organisms expressed by the Van Hoff law, and heat budget of the landscape is quantified by geophysics). Furthermore, it needs quantification of the processes. For example, if due to deforestation of a landscape temperature increases growth rate of plants and poikilothermic organisms may be positively affected and generate increased yields, only if sufficient, increased amount of water is supplied.

Every strategy for success needs to be based on two elements as follows: (1) elimination of threats, and (2) amplification of opportunities to guarantee reaching its goals. For example, aiming at curbing the ever growing social and economic aspirations, exacerbated by the global demographic growth and overexploitation of resources, a factor four concept of von Weizsäcker et al. (1997) could be a viable alternative. It says that humans are able to double the wealth of humanity while halving the resource use through setting a new direction for technological progress. This can be achieved only when the strategy of economic growth is shifted from competition for resources to competition in their efficient use. On the other hand, the enhancement of ecological potential of the highly modified ecosystems, proposed by ecohydrology, is the only alternative for bringing back the degrading global biodiversity and bioproductivity that affects ecosystem services for society and overall resilience of the landscape to environmental and human-induced stress (environmental stability). Therefore, as a transdisciplinary approach, ecohydrology postulates for harmonizing societal needs with the enhanced ecosystem potential.

Principles of Ecohydrology As a Framework for Problem Solving and Implementation of the Ecohydrological Methodology

The fundamental assumption of EH is that water is the major driver of biogeochemical evolution and thus of biodiversity and bioproductivity. Terrestrial and aquatic organisms, through evolution, have adopted certain life strategies to match with the prevailing water quantity and quality dynamics in the catchment (Zalewski 2000, 2002a; Janauer 2000, 2006; Harper et al. 2008). Therefore, biocenotic processes are shaped by hydrology and vice versa, biocenotic structure and interactions to large extent modify hydrological processes, two-way water-biota interplay called "dual regulation."

The novelty of EH is that it does not only aim to understand the complexity of water-biota interplay, but also develops a methodology how to use the ecosystem properties and the processes as a management tool, often complementary to other water resources management measures (Zalewski 2002a; Zalewski et al. 2003, 2004). Ecohydrology expands the available management measures (conservation and restoration of ecosystems, aimed basically at maintaining their structure) with those of regulation of ecological processes (Zalewski 2013). The regulation measures should be applied primarily in the anthropogenically highly modified parts of river basins, the so-called novel ecosystems (Hobbs et al. 2006), and involve the processes from molecular to landscape scales. As far as the regulation of processes focuses on both the sides of the water-biota interplay the term dual regulation also applies for these intentional actions (Zalewski 2000, 2006b).

Understanding of the processes needs to be primarily focused on the understanding of the hydrology-biota interplay, and the hierarchy of importance of the abiotic and biotic factors that drive the ecosystems structure and functions from molecular to landscape scales. In accordance with that shift, the catchment and hydrological mesocycles should become the template for quantification of the processes and for the strategic spatial planning and environmental resources management. The use of the catchment template for management of existing resources, e.g., in the framework of IWRM, as well as the water cycle template for precise quantification not only of water budgets, but also nutrients, pollutants, ecosystem performance, and socioeconomic processes, provides background for development of systemic transdisciplinary solutions.

In order to stimulate the use of ecohydrology paradigm and its application to solving the sustainability water related issues the three principles of EH were formulated [see below, per Zalewski (2000, 2006a)]. They are the three steps and the three dimensions of analysis leading to understanding of the underlying ecohydrological processes in a given catchment and application of informed solutions. They also provide a systemic framework for integration into integrated water resources management (IWRM).

Whereas IWRM was defined by Global Water Partnership as "a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership Technical Advisory Committee 2000) ecohydrology aims at harmonizing society needs with enhanced ecosystem potential through increasing carrying capacity of ecosystems. Therefore, instead of balancing social and economic needs it opts for harmonizing them with ecosystem potential, and instead of/and apart from protecting pristine ecosystems it calls for regulating processes in the novel ecosystems in order to increase their ecological potential in terms of water resources, biodiversity, ecosystem services, and resilience to global change and anthropogenic stress (termed WBSR, from *w* for water, *b* for biodiversity, *s* for services, and *r* for resilience). As such ecohydrology is compliant with IWRM concept but gives novel potent tools to achieve sustainability.

The first principle of EH, the *hydrological principle* implies quantification of hydrological processes at the basin scale and the entire hydrological cycle as a template for quantification of ecological processes. The quantification covers the patterns of hydrological pulses along the river continuum and identification of various forms of human impacts, e.g., point and nonpoint sources of pollution. This principle is based in the assumption of superiority of abiotic factors over biotic interactions (Zalewski and Naiman 1985).

The second, *ecological principle* implies the need for understanding of the evolutionary-established water-biota interplay, and thus quantification of nutrient flows and energy fluxes dynamics at the water cycle and catchment templates defined in the first step. It also calls for analysis of the spatial distribution of different types of ecosystems, i.e., pristine, degraded, and modified, in order to identify the novel ecosystems that are subject for dual regulation. It is based on the assumption that under intensive global changes it is not enough to protect ecosystems, but the processes should be regulated.

Finally, the *ecological engineering* principle defines ecosystem properties identified in the framework of the first and the second principles as management tools. These tools are complementary to the already used hydrotechnical solutions and should be used towards enhancement of ecosystem carrying capacity for WBSR. The use of the ecosystem properties is compliant with the rules defined for ecological engineering (Mitsch 1993, 2012; Mitsch and Jorgensen 2003), with the following three assumptions in mind:

1. Biota is regulated by hydrology and vice versa, hydrology is regulated by the shaping role of biota or their controlling interactions; the deliberate action using ecosystem properties is called dual regulation;
2. Various types of biological and hydrological regulations should be integrated at a basin scale with other conservation and restoration measures to achieve synergy among them; and
3. Harmonization of ecohydrological measures with necessary hydrotechnical infrastructure (dams, irrigation systems, sewage treatment plants, and so on) should provide a system-based solution in a catchment (Fig. 5).

Ecohydrological biotechnologies are fundamental to the development of the low-cost and low-energy solutions recognized in the European Commission's strategic documents under the term green infrastructures.

Due to the complexity of the applied knowledge, the application of geographic information system (GIS) and development of mathematical models for high complexity hypotheses testing and

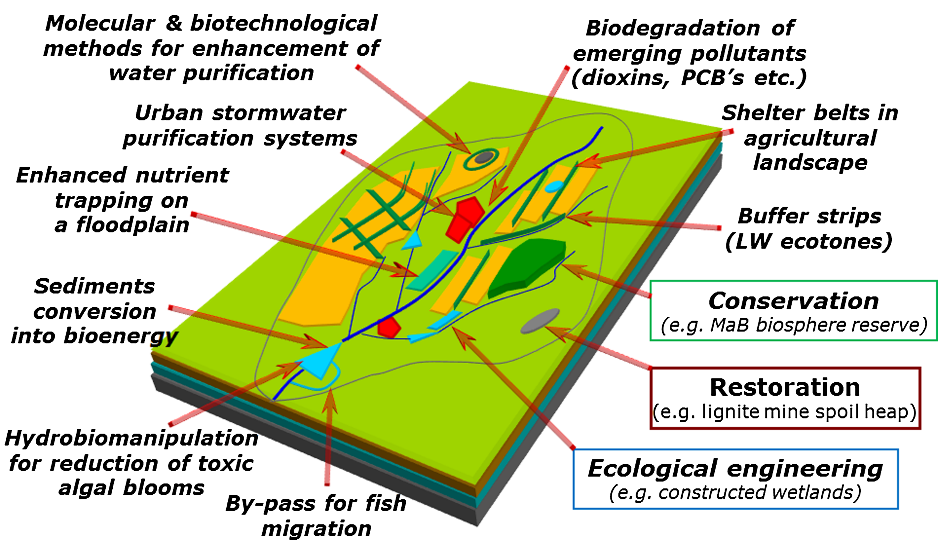

Fig. 5. Third principle of ecohydrology; using biota to control hydrological processes and vice versa, using hydrology to regulate biota, integrated with conservation, restoration, and ecological engineering measures, and hydrotechnical infrastructure at a basin scale (reproduced from Zalewski 2013, with permission from the European Regional Center for Ecohydrology of the Polish Academy of Sciences)

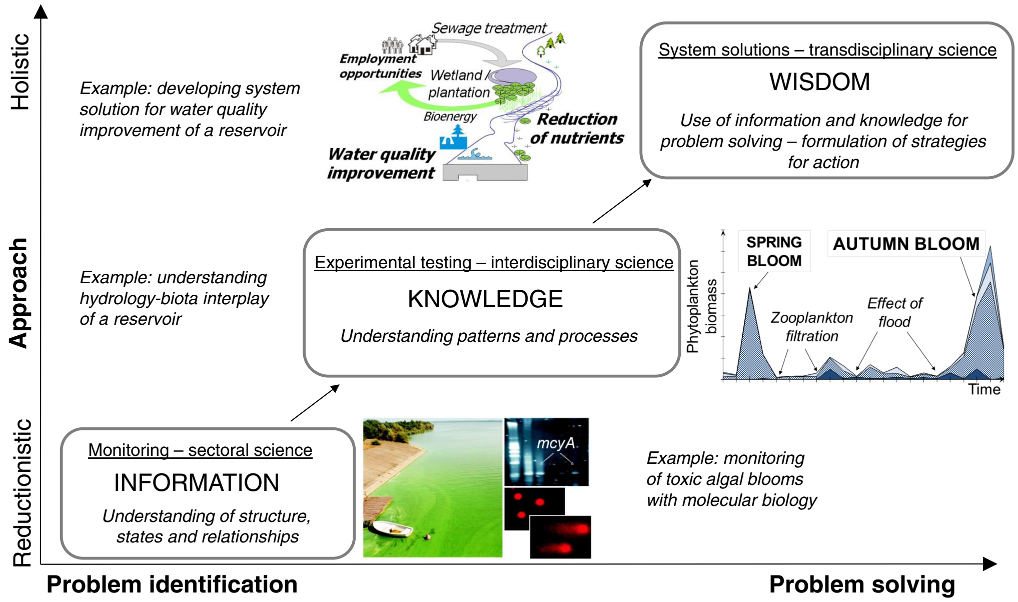

Fig. 6. Methodological background of ecohydrology as a problem solving science; from information through knowledge to wisdom to develop a transdisciplinary system solution, a template for three principles of ecohydrology [drawing based on the concepts described in Zalewski (2000), (2002a, b); graph based on the concepts described in Zalewski (1999); images based on the concepts and data from Zalewski (1999), Mankiewicz-Boczek et al. (2002), and Mankiewicz-Boczek et al. (2006); figure adapted from Zalewski (2011), with permission from ICE Publishing]

decision support systems should be seen as useful tools to test alternative scenarios and implementation of the EH methodology for sustainable water use, ecosystems, and societies (Fig. 6). Mathematical and GIS-supported modeling are cross verified with field experiments. Such interdisciplinary analysis creates a background for integration of the social and economic processes occurring in the catchment into the problem-solving exercise, which creates a background for transition from multidisciplinary and interdisciplinary to transdisciplinary science.

Case Studies of Implementation

Water Quality Management: Applying Synergy between Ecohydrological Biotechnologies and Hydrological Engineering Measures

Until now the problem of pollution and its reduction has been focused on point sources, which can be easily dealt with advanced technological solutions. However, dispersed sources of pollution might constitute over 50% of the nutrient loads to reservoirs and costal zones delivered through rivers (Zalewski 2009) and uncontrolled runoff from urbanized areas. In this case, only widely applied, low-cost and efficient solutions (Statzner and Sperling 1993), e.g., ecohydrological biotechnologies, will be capable enough to handle the problem. For example, microbial activity enhanced by carbon addition to enhance denitrification processes for nitrogen polluted groundwater (Bednarek et al. 2010), or regulation of excessive nutrients allocation in aquatic trophy pyramid through hydrobiomanipulation (Zalewski et al. 1990; Wojtal-Frankiewicz and Frankiewicz 2010; Izydorczyk et al. 2013). For example, widespread biochemical processes, like conversion of phosphates PO_4^{3-} transported with groundwater into plant biomass or nitrate NO_3^- into gaseous nitrogen N_2 by bacteria through denitrification occurs in the root zone of the riparian buffers. These processes applied deliberately have been described as landscape scale biotechnology, where biotechnology was defined (Zalewski and Wiśniewski 1997) as converting matter from one form into another using living organisms (classic example is converting sugar into alcohol by yeasts). The fundamental knowledge to apply such biotechnologies in the framework of ecohydrology stems from the understanding of the dynamics of surface runoff in relation to reservoir, lake, or river level oscillations, and plant or bacterial potentials for converting the mineral forms of nutrients into biomass or gas. Such natural resource management applications can be called ecohydrological biotechnologies.

The ecohydrology concept embraces the entire hydrological cycle, including its atmospheric, terrestrial, and aquatic phases, and in the entire cycle biological components of the environment play an important role as moderators of water quality and quantity. In the terrestrial phase vegetation moderates water quantity and quality, its availability for plants [water-soil-plants interactions, per Baird and Wilby (1999)] and dynamics in the atmosphere (Vorosmarty and Sahagian 2000). In the aquatic phase, aquatic and riparian vegetation can modify nutrient fluxes, allocation, and circulation affecting water quality and the related symptoms of eutrophication (e.g., toxic algal blooms) as well as surface water hydrological dynamics (Zalewski et al. 1990; Zalewski 2000). In this case aquatic ecohydrology (AEH) will investigate how water biota can modify nutrient loads into aquatic ecosystems.

Reduction of nutrient loads (stimuli of eutrophication and toxic algal blooms in reservoirs, lakes, and coastal zones) from a catchment is one of the key challenges in implementing the European Union (EU) water framework directive (WFD). In Poland over 60% of the phosphorus and almost 70% of the nitrogen load to the Baltic Sea originates from diffuse (nonpoint) source pollution. Also in Europe agricultural land covers up to 70% of the landscape. Creation of land-water ecotones has proven to be an effective tool for reducing the impacts of nutrients originating from a landscape on freshwater ecosystems. However, very often shoreline zones are too narrow for these ecotones to work effectively. That is why the goal of the EU-funded EKOROB (2011) project was defined to as reduction of diffused pollution using enhanced ecotone zones to reduce nitrogen and phosphorus fluxes into reservoirs and the

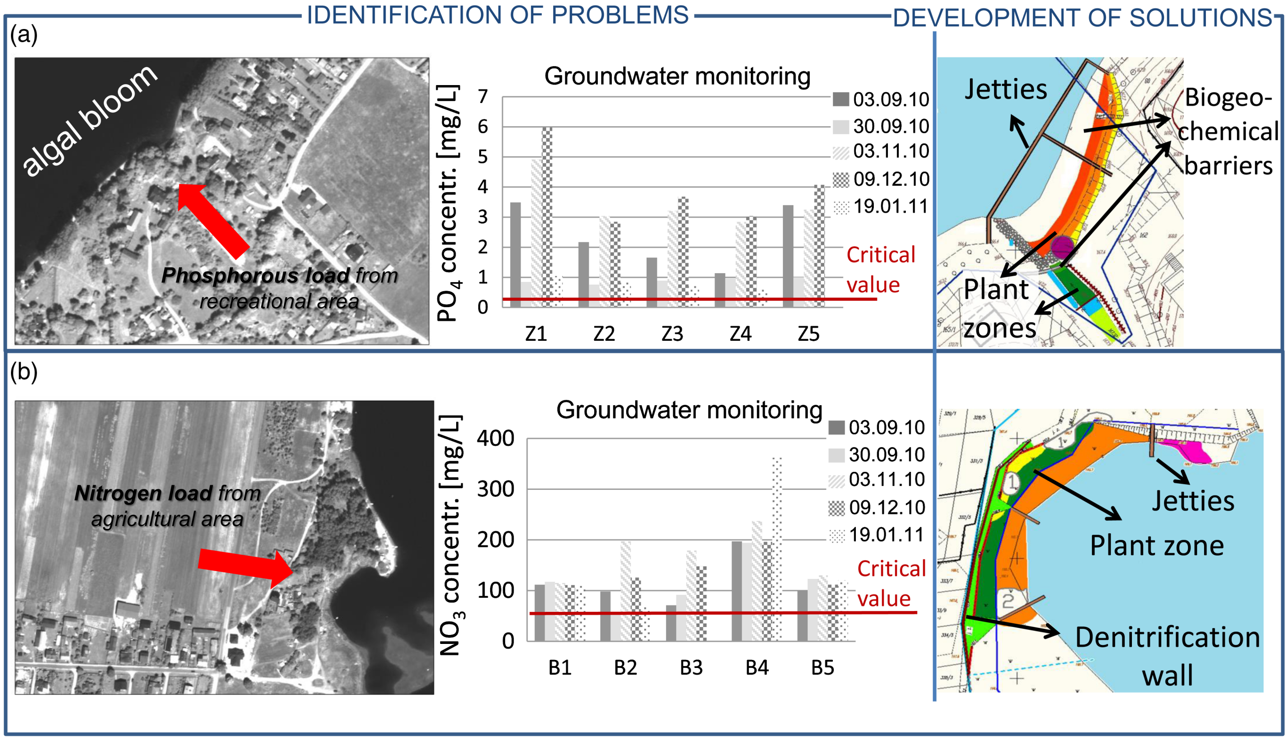

Fig. 7. (a) Reduction of phosphorus pollution, which generates toxic cyanobacteria blooms (visible on the photo as lighter stripe along the shoreline), from groundwater in the recreational neighborhood with plant buffering zones and biogeochemical and denitrification barriers, Zarzęcin, Poland; (b) reduction of nitrogen pollution generated from agriculture area by plant buffering zones enhanced with denitrification walls, Barkowice, Poland [satellite images DigitalGlobe/European Space Imaging, distributor SmallGIS; data for nutrients concentrations and developed solutions from EKOROB LIFE08 ENV/PL/000519 (2011) project by the European Regional Center for Ecohydrology of Polish Academy of Sciences]

Baltic Sea (Fig. 7; Izydorczyk et al. 2013). This project provides also an important step towards complying with WFD in achieving good ecological status and reversing the eutrophication of inland waters and the coastal zone.

Urban Storm Water Management: Low-Cost Advanced-Technology Approaches

The classic civil engineering paradigm concerning urban storm water management is to transfer the runoff water out of the city as soon as possible to avoid local floods. However, during the last decade development of best management practices for storm water management underlines the necessity for reducing impermeable space and increasing infiltration within urban green areas. Research which was conducted within the framework of another two EU-funded projects, i.e., (1) the Sustainable Water Management Improves Tomorrow's Cities' Health (SWITCH) project, and (2) the Polish Operational Programme: Innovative Economy (POIG) project "Innovative resources and effective methods of safety improvement and durability of buildings and transport infrastructure in the sustainable development," in the city of Łódź expanded this approach by analyzing the possibility of upgrading the quality of the postindustrial city landscape, primarily by purifying the water and increasing the retentiveness of the landscape.

The first goal was achieved by construction of a cascade of small impoundments along an urban river (Sokolowka River) valley for retention and purification of storm water. The major challenge to implement this idea was a limited space for construction of a purifying wetland in the valley, a typical ecological engineering solution. Thanks to the understanding of the self-purification processes in natural rivers, such as importance of light and availability of calcium compounds in water (Zalewski et al. 1998), it was possible to conceive an innovative prototype of a sequential biofiltration system (SBS; Fig. 8).

Sequential biofiltration systems consisting of (1) sedimentation zone, (2) geotextiles for stabilization, and (3) biogeochemical and constructed wetland zones enhanced by bed regeneration system, reduced concentrations of total nitrogen and phosphorus by over 50% during the first experimental year of operation. Stabilization of the river flows by constructing a detention basin upstream of the system further reduced the stochastic character of the process. Additional work included shaping of the wetland plant structure, introducing biodegradable geotextiles, and monitoring of microbial activity. In the last case, the genetic method, i.e., trinucleotide repeat sequences/polymerase chain reaction (TRS-PCR) using the common presence of TRS in the microbial genomes (Wojtasik et al. 2012; Adamus-Bialek et al. 2009) combined with partial sequencing of 16S recombinant deoxyribonucleic acid (rDNA) genes, showed qualitative dynamic changes in the microbial population in each zone. This demonstrated the diversity of purification processes at each stage. Analyzing these results relative to the hydrological dynamics of the system provided a baseline for further enhancing the purification efficiency by ecohydrological regulation of flows.

The second challenge has its roots in alterations of water cycle in urban areas. There, infiltration and evapotranspiration, which naturally make up about 50 and 40% of the rainfall, respectively, are reduced to less than 5 and 30%, respectively, in many cases. Most storm water (up to 80%) is drained from cities by surface runoff channels and via highly efficient drainage systems. This process has far-reaching consequences for city inhabitants. The urban heat island phenomenon, characterized by increased temperatures, decreased humidity, and high amounts of dust and pollution in

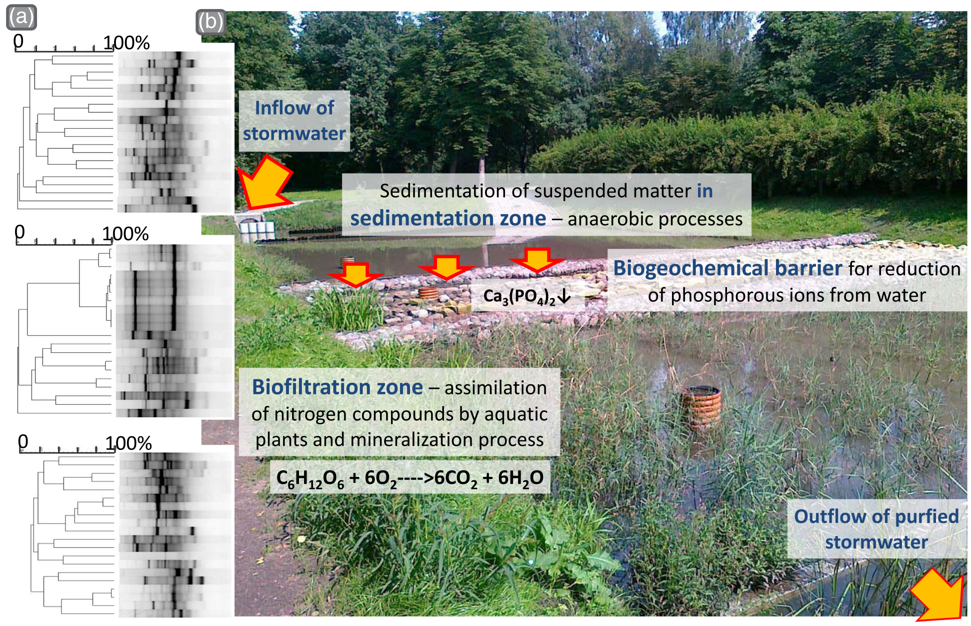

Fig. 8. Sequential biofiltration system as a background for experiments on further enhancement of storm water purification: (a) microbial diversity in different zones assessed by the TRS-PCR and partial 16S RNA gene sequencing; (b) arrangement of different zones in the biofiltration system [based on concepts and data from Zalewski et al. (2012); genetic analysis performed by Paweł Parniewski and the team of the Institute of Medical Biology of Polish Academy of Sciences; image by Maciej Zalewski]

the air of the densely urbanized areas, not only further affects precipitation, but also increases threefold occurrence of allergies and asthma compared to suburban areas (Kuprys-Lipinska et al. 2009). Declining comfort and growing health risks result in urban-suburban migrations, as humans are leaving cities in search for a better quality of life. In consequence, cities sprawl and force higher investments in development and maintenance of infrastructure. Daily commuting further increases traffic and the associated emission of pollutants.

In contrary, in the new paradigm, storm water is a valuable resource not a threat, and ought to be consciously retained after prior effective treatment, leading to the improvement of microclimate and groundwater recharge within the city landscape (Zalewski and Wagner 2005; Wagner and Zalewski 2009), promoting healthier lifestyles and a well-being of the population.

The development of efficient and innovative purification biotechnologies is a foundation for the urban spatial planning concept the blue-green network concept (BGNC; Fig. 9). The network of blue-green corridors of water related ecosystems is weaved into urban landscape, watered with purified storm water. It assumes that connected river valleys and green spaces create a network which not only reduces costs of storm water management infrastructures, but also improves microclimate, encourages healthy lifestyles, attracts developers, and make the city resilient to global climate change. This concept has been officially adopted by the city of Łódź as a part of its strategy for integrated development, Łódź 2020+.

Discussion

Ecohydrology: Paradigm for Sustainability

One of the potential pathways towards sustainability has been expressed by the growing interest in use of the potential for water/environment/society problem solving by scientific exploration of water-biota interactions. This has been confirmed by the exponential increase in the number of peer-reviewed journal articles using terms such as ecohydrology and hydroecology (Dunbar and Acreman 2001; Wood et al. 2007), and ecohydraulics (Leclerc et al. 1996; Statzner and Borchardt 1994). Efforts to integrate ecological knowledge and water sciences began in the mid-1990s, with several scientific teams working independently. During this starting period two major approaches related to the specifics of the hydrological cycle emerged. The terrestrial ecohydrology, focused on water-soil-plant interactions was primarily developed by botanists, soil scientists, and geophysicists (e.g., Wassen and Grootjans 1996; Baird and Wilby 1999; Eagelson 2002; Rodriguez-Iturbe 2000; Newman et al. 2006). The aquatic ecohydrology, initiated and developed by limnologists and hydrologists (e.g., Zalewski et al. 1997; Zalewski 2000, 2002a, b; Januer 2000; Chicharo et al. 2001; Wolanski et al. 2004; Timczenko and Oksiyuk 2002; Hehanussa et al. 2003) within the framework of the International Hydrological Program (IHP) of UNESCO (IHP-V to VIII) evolved as a subdiscipline of hydrology focused on biological aspects of hydrological cycle. Several years later, Dunbar and Acerman (2001) proposed the term hydroecology (HE) defined as "the linkage of the knowledge from hydrological, hydraulic, geomorphological and biological/ecological sciences to predict the response of freshwater biota and ecosystems to variation of abiotic factors over a range of spatial and temporal scales." This definition implies only one-way analysis of impact (abiotic to biotic) with the aim in the assessment of the impact of biota. The difference with ecohydrology lies in both directions analysis of water-biota interplay with the aim to regulate environmental processes (dual regulation).

Analysis of the similarities and differences between ecohydrology and hydroecology lead some researchers, e.g., Wood et al. (2007), to the conclusion that both disciplines are "remarkably poorly defined;" however, they underlined that "ecohydrology has been employed to describe wider hydro-ecology linkages." Such a brief interpretation gives the impression that the researchers missed the fact that the development and especially the integration of different scientific disciplines has been a continual process and

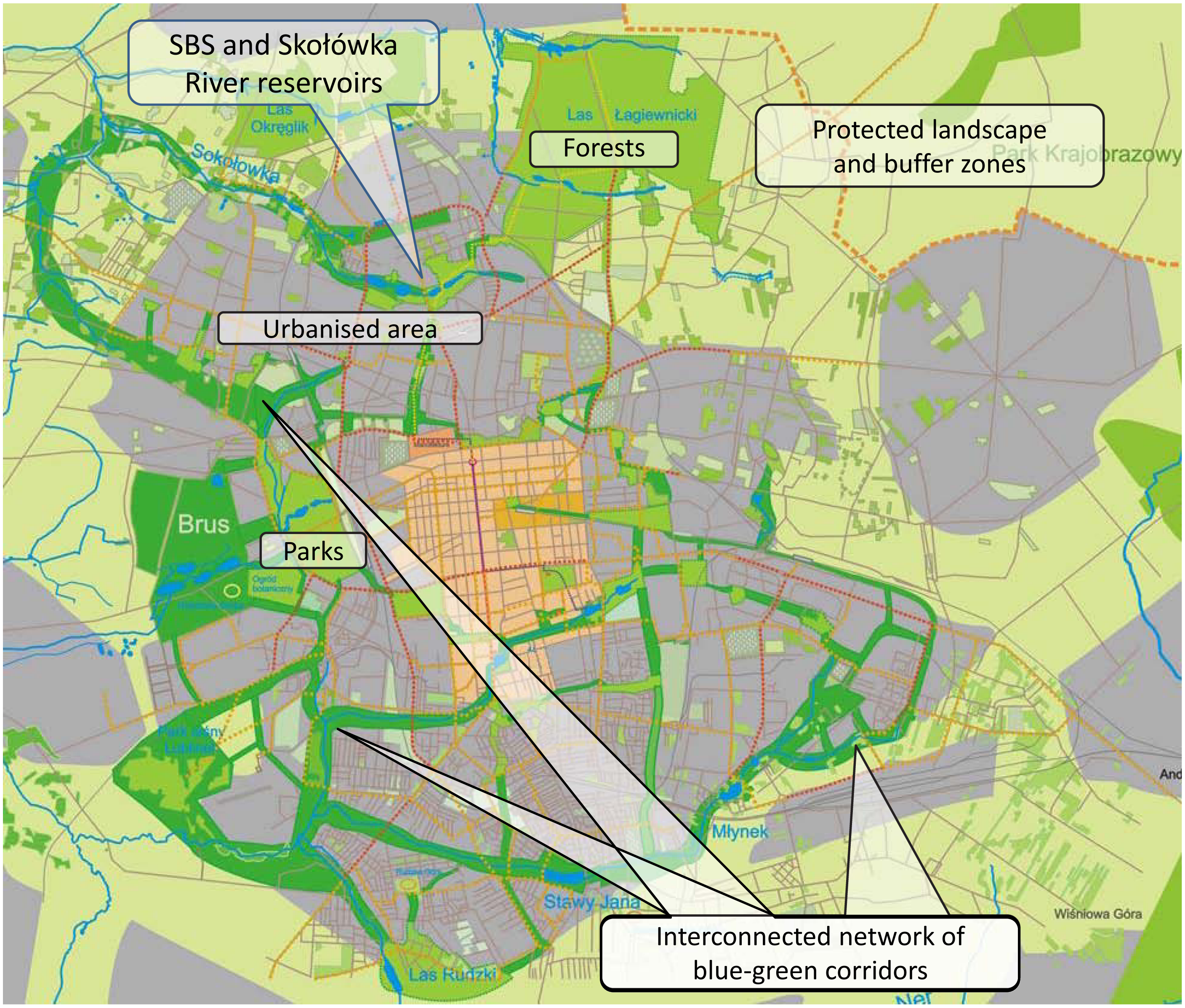

Fig. 9. Blue-green network concept; the framework for sustainable and restorative redevelopment of Łódź; the concept was described in Wagner and Zalewski (2009)

has taken several decades. In the case of ecology the first definitions were formulated by Elton (1927), Andrewatha and Birch (1954), Odum (1971), Krebs (1972), and Mitsch (1993) and still has been under evaluation towards sustainability science. Considering the previous discussion, probably the most important differences between EH and HE are in methodology. Ecohydrology is based on two elements, as follows: (1) the regulation of ecological systems based on evolutionarily established hierarchy of abiotic and biotic drivers, and (2) ecological engineering methodologies for enhancing carrying capacity, both inspired by Mitsch (1993), Straskraba et al. (1993), Straskraba and Tundisi (1999), and Mitsh and Jorgensen (2004).

On the other hand, hydroecological publications seem to be largely focused on ecohydraulics, which describes a range of dependencies of aquatic organisms on hydraulic conditions (Statzner et al. 1988) and environmental flow science, which answers the question of how to allocate water resources to different users while protecting ecosystem structure and functions (Bunn and Arlinghton 2002; Tharme 2003). The large number of empirical data and case studies of the initial phase determined the inductive character of such approaches. The relation between these two ways of thinking, i.e., (1) EH, and (2) HE, was expressed by Petts (2007); "ecohydrology . . . has created an environment of opportunity to embed hydroecological perspectives within water resources management." As a consequence, the EH approach implies the need to expand our strategies for sustainable environmental management, from one limited to conservation and restoration of patches of a catchment (Fig. 4), to a new one based upon understanding ecological and hydrological processes and their regulation. In the latter the water cycle in whole catchments and freshwater/costal ecosystems is functionally linked with society as a main determinant of biotic structure and dynamics.

Nevertheless, the ecohydrology paradigm appreciates the role of hydrology and hydroengineering sciences in controlling environmental threats and its demonstrated potential to increase the quality of life and underlines that, in perspective, by integration with ecology it may contribute to achieve sustainable use of biogeosphere. It proposes to reconcile the two previously independent pathways of resource use: (1) the one of engineering sciences, and (2) that of environmental sciences. These two approaches have to be harmonized in order to meet human needs through the use of ecosystem potential in the face of global change. This can be achieved by integrating engineering attempts to increase the efficiency of resource use and reduction in the emission of pollutants with environmental sciences engagement in defining areas for possible enhancement of ecosystem carrying capacity.

How Can Society Move This Modified Hydrological Cycle toward Sustainability?

As far as biota form an important regulator of the hydrological cycle, the key to reversing degradation is understanding the biodiversity and bioproductivity potential of water biota through utilizing ecohydrological succession. The challenge facing the classical abiotic-biotic model is that the changing hierarchies of drivers in different geographic zones limit the chance for using the same strategy to basin management in each location. Within this context, each basin becomes a Platonian superorganism (Zalewski 2000), implying a nonrepeatable combination of factors superimposed on society. Transdisciplinary environmental sciences can help researchers to understand the hierarchy of factors within different geographic zones and by blending in transdisciplinary education researchers can begin to formulate the site-specific solutions needed to address these global challenges at local levels.

Current actions aimed at limiting the threats are confined mainly to reduction of emissions and increasing efficiency of resource use. They neglect the fact that society's existence on Earth is desperately dependent on an ability to maintain and reestablish the integrity of fundamental ecological processes that have evolved over millions of years of biological evolution and ecological succession. Ecohydrological biotechnologies and the system approach have now reached such an advanced state that the understanding of interactions between water and biocenoses, and their translation into real solutions, allows researchers to start the dialog not only with hydrologists but also with hydrological engineers, and to begin to take on the challenge of shaping the engineering harmony between humanity and the biogeosphere.

The next fundamental step toward meeting these challenges should be an integration of the hydrological engineering into the ecohydrological framework for implementing and fine-tuning existing practices through adaptive assessment and management approach. As far as river basin management planning is concerned, a long-term high-cost enterprise and integration of engineering and ecology should be done with cross verification through application of socioeconomic and technological foresight methodologies. Foresight is not only a tool for prediction and planning of future developments but also an important tool for planning the required vision of the future (Martin 1995; Rogut and Pasecki 2011).

The unprecedented role in reaching sustainability lies in the system of education. This issue needs a few words of explanation. The traditional model of education provides a broad background knowledge at the primary levels of education and further undergoes process of specialization, resembling a pyramid-shape education model. It does not support a dialog between representatives of different disciplines. However, to achieve sustainability such a dialog is indispensable. To enable it the traditional model of education should be complemented by a subsequent phase of education broadening the understanding of various links of the main discipline to the related disciplines (Fig. 10). This model of education could be called the x-shaped model. In the context of this paper engineers need to understand the basic biological evolutionary mechanisms, particularly how water is shaping and regulating biotic processes and vice versa, how biota is shaping the water cycle. Ecologists, on the other hand, have to understand, for example, that when the landscape is

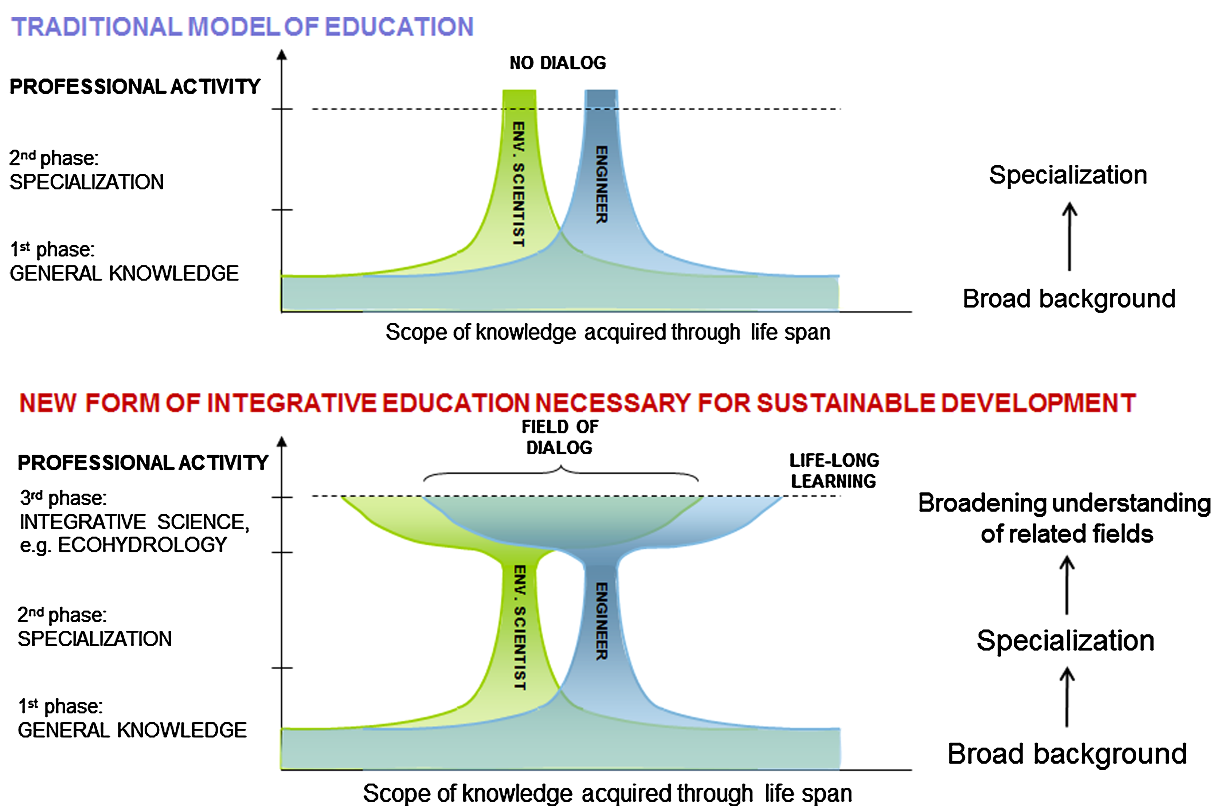

Fig. 10. Traditional and new integrative education model of environmental and sustainability scientists and engineers necessary for achieving sustainable development [based on concepts described in Zalewski (2013)]

modified for food production, urbanization, or transportation, its heat budget and hydrological cycle is also being modified making the landscape less water-retentive. That is why, for example, compensation of the water loss by increased evaporation and runoff can be achieved by construction of well-planned and properly designed reservoirs, integrated with ecohydrology of a catchment.

Is It Enough to Just Expand the Paradigm in Environmental Sciences?

The harmonization of human needs with the biosphere potential is the primary challenge for a sustainable future of the global ecosystems and the society (Burdyuzha 2006; Zalewski 2006c; EcoSummit 2012). However, to achieve this goal there is an urgent need to change the ways of thinking not only about water and the environment but also in relation to the four areas of human activities: economy, engineering and technology development, environmental management and education.

Contemporary economic systems are based on the assumption that human beings have to constantly consume more and more services and goods to be happy. However, todays' society urgently needs to agree that the competition for resources has to be replaced by competition in their efficient use. The perception of the quality of life must be redefined and related to cultural values and societal relations rather than to the rate of consumption and material status.

Engineering and technology development, on the other hand, which in the nineteenth and twentieth centuries made a tremendous advances in securing safety and health for the human population, is now facing a declining availability of resources. What is more, many civil engineering solutions are oversized, using materials and energy too lavishly, showing a tendency to overengineering. This approach led to oversimplification of biological complexity of landscapes, e.g., by constructing urban areas as tidy and easy to maintain, and reducing the green spaces to green carpets instead of a biologically diversified blue-green network of high complexity. In human modified landscape "society should give chance to nature to do the job" (W. J. Mitsch, personal communication, 2013), which implies a spontaneous ecological succession. In accordance with the ecohydrology main goal to enhance the carrying capacity with WBSR in mind, society should additionally create adequate abiotic conditions, e.g., water content in the soil and groundwater level for creating the biologically productive, diversified, and resilient ecosystems/communities.

In ecology and environmental management there are still too many scientists and practitioners focused on species composition (structure) in ecosystems and thus tending to protect all organisms everywhere. However, in the current state of landscape modification, the classical conservation approach (relevant for pristine landscapes) and restoration approach (relevant for highly polluted/degraded environments), has to be expanded to ecohydrological processes regulation approach applicable primarily to highly modified agricultural and urban areas. The condition sine qua non for ecohydrological regulation is enhancement of biodiversity through applying EH dual regulation with water, hence ecological status should always be improved.

In education, both decision makers and the society are entering a phase of specialization. As a consequence, highly complex and broad environmental problems, which are compounded by the fact that every river basin is usually unique as a result of specific geomorphological, climatic, biological, cultural, demographic, and economic activities, are dealt with by highly specialized decision makers who lack broad multidisciplinary background/knowledge. For this reason, there is an urgent need to change the pattern of education to a phase in which specialization should be complemented with a new step focusing on broadening the understanding of the complexity of environmental processes. Parallel educational actions are needed to raise the consciousness of society about possible realistic scenarios for harmonization of societal needs with enhanced ecosystem potentials.

All in all, society cannot anymore consider themselves as passengers as humans all are members of the crew of the so-called spaceship Earth and humans all are responsible.

Acknowledgments

This paper is a result of brainstorming and discussions on several projects listed in this section. The author expresses his gratitude to Kamila Belka for inspiring questions and discussion, and for precise editing of the final version of the paper. The projects involved in the background of this work are the following:

- Innovative resources and effective methods of safety improvement and durability of buildings and transport infrastructure in the sustainable development; project financed from European Fund for Regional Development (EFRD) in the framework of the Polish Operational Program Innovative Economy, POIG.01.01.02-10-106/09, 2007–2013;
- Sustainable water management improves tomorrow's cities' health (SWITCH); European Union, 6 Framework Program, GOCE 018530, 2006–2011;
- Ecohydrological rehabilitation of recreational vessels, Arturówek (Lodz) as a model approach to urban reclamation tanks (EH-REK), LIFE08 ENV/PL/000517, 2010–2014;
- Ecotones for reduction of diffuse pollutions (EKOROB 2011), LIFE08 ENV/PL/000519, 2010–2014;
- Development of biodegadable biofilters for remediation of pollution resulting from nitrogen and phosphorus application on agricultural area, No. R14 0061 06/2009, 2009–2012;
- Microbial activators in denitrification deposits used for the treatment of nitrate pollution for the implementation of the Water Framework Directive and the Nitrates Directive (MIKRAZO), NCBiR No. PBS1/A8/5/2012, 2012–2015;
- Advisory and technical services, including development of dedicated solutions and concepts, for realization of project documentation for construction of dam and hydropower station across Vistula River below Włocławek (ARUP, Vistula Study), 2010–2012; and
- Implementation of ecohydrology, a transdisciplinary science, for integrated water management and sustainable development in Ethiopia, Polish Aid Program No. 62/2012 financed by Ministry of Foreign Affairs of the Republic of Poland.

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