Chapter

Ecohydrology: An Integrative Sustainability Science

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Abstract

The dynamic of the water cycle in catchments is determined by climate, geology, geomorphology, plant cover ad modified by agriculture, urbanisation, industrial development and hydroengineering infrastructure. Up until the end of the 20th century, water management was dominated by a mechanistic approach, focused on the elimination of threats such as floods and droughts and providing resources for the society with little to no regard for the impact this approach had on the ecosystem. Highlighting of water as a key driver of ecosystem dynamics, and further ecohydrology which highlights water/biota interactions from molecular to catchment scale provide a new perspective, new tools and new systemic solutions for enhancement of catchment sustainability potential WBSRCE (consisting of 5 elements: Water, Biodiversity, Ecosystem Services for Society, Resilience and Culture and Education).

Keywords: ecohydrology, sustainability potential, engineering harmony, water, management

1. Introduction: why ecohydrology becoming one of the key for sustainable biosphere, water and food

"We are living in the Anthropocene Era when almost 80% of our usable ecosphere, has been conditioned, converted, and consumed by humans, usually without understanding the full consequences of our actions" [1].

There is an increasing the number of the scientific evidences from molecular, ecosystem up to global scale, that the exponential growth of human population and acceleration of consumption in Anthropocene resulted in the declining the ecological and regenerative potential of the planet Earth, expressed by the "ecological footprint", which recently is above 1.7 [2]. This accelerated changes of biosphere can be described in two dimensions: first cumulative - synergic amplification many impacts (deforestation +pollution+ river channelization ect.) The second one - long term slow changes e.g. catchment urbanisation, industrialisation, transport development, emission of pollutants. Both create dramatic consequences: reduces water retentiveness and increase stochastic character of water cycle – floods, droughts, landslides and interconnected degradation of biogeochemical cycles – carbon, nitrogen, phosphorus and as further consequence the loss of soil fertility. All above processes increase abiotic disturbances strength for biota and decline biological productivity and biodiversity in catchment scale, which in turn negatively effects water quantity and quality. If we continue such "business as usually" deadly spiralling of

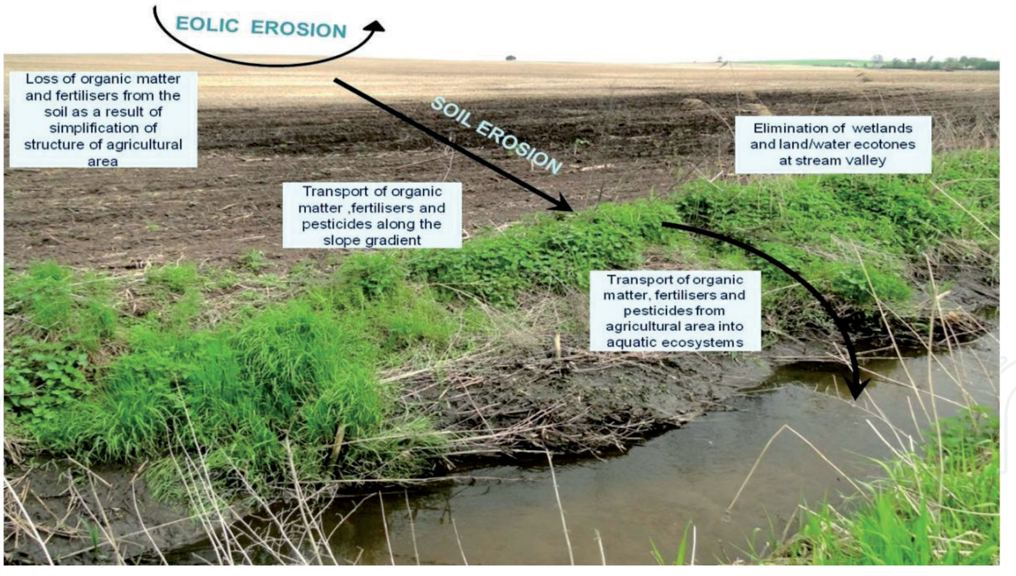

Figure 1.
Example of a drastic reduction in complexity of agricultural landscape – tree rows and land/water ecotone buffer zones, resulting in in soil drying, loss of organic matter due to aeolian erosion and surface flow.

the human impact, in which water is key driver, this can lead to decline and even extinction of civilisation due to mass migrations local, regional and global conflicts.

The one of the major reasons of such decline local regional and global sustainability potential, is that the increasing strength and complexity of the of pressures and interactions between Man and the environment are still not sufficiently reduced and compensated by scientific, technological, progress as far as its translation best current knowledge into society environmental consciousness legal frameworks and policy.

The example of the negative consequences of the recent sociocentric/mechanistic paradigm and lack of understanding the complexity ecohydrological process in recent water management and agricultural policy, has been introduced on **Figure 1**. The Water Framework Directive of European Commission require the achievement the good ecological status by EU member countries however, the agricultural policy by providing the financial support proportional to area of cultivated land has been indirectly encouraging the farmers to maximise such area even by elimination of land/water ecotones and tree rows - shelter belts, which are important buffers reducing nutrients fluxes of agricultural origin [3, 4]. Additionally they are reducing of wind speed, improve soil moisture and agricultural yield [5]. Such simplified agricultural land dramatically increase loads of phosphorus and nitrogen from non-point source pollutions, which in case of the Baltic Sea create more than 40% of the load. Recent agricultural policy focused only on maximisation of yield also accelerate organic matter loss and necessity to compensate reduced soil fertility by more intensive artificial fertilisers use, both of which further intensify eutrophication of lakes, reservoirs and costal zones.

2. Technogarden vs. sustainable anthropobiosphere

When the regenerative potential of the Earth is much below its equilibrium stage, the fundamental question for Humanity is how to achieve desirable safe prosperous future and whether our goal should be a Sustainable Biosphere or we should reconstruct Earth System as Technogarden.

The key assumption of technogarden scenario is that the recent and further technological progress based on experience gained at spaceship expeditions will be sufficiently fast and efficient to create on Earth a technogarden where humanity or a fraction of humanity will persist. Unfortunately the unsuccessful experiments in creation of sustainable technogardens [6] indicate that to maintain homeostatic equilibrium even at the ecosystems level, which means provision of basic ecosystem services: water, food, health and social interactions there is nothing better than the natural or seminatural ecosystems within the catchment, which maintains, self-regulatory water/nutrients cycling thus bioproductivity and biodiversity, thus the positive future we want.

3. The urgent need of paradigm change from sociocentric/mechanistic to evolutionary/ecosystemic

Up to now the science and technology operating in framework of Sociocentric/Mechanistic paradigm has been used as a tools for the intensification of exploitation of natural resources. However recently to achieve sustainable future there is an urgent need to change such paradigm into Evolutionary/Ecosystemic. This new paradigm has to be based on a profound understanding of how evolution determines fundamental ecological processes, first and foremost cycling of water and nutrients and next the whole range of water-biota interplay in different ecosystems, which is a basic role of Ecohydrology. Secondly the above understanding has to be used to develop deductive and inductive models of processes which are based on integration of knowledge form various disciplines of environmental sciences. Testing of the above empirical models provide an opportunities for discovery of new, emerging properties of the systems, which in turn can be translated into innovative methods and systemic solutions [7]. The above idea becomes a background of the evolution/ecosystemic paradigm [8], where Man is a component of Nature and has to obey the roles determined by biological evolution to achieve suitability. This also means that to achieve sustainable future we have to stimulate to a greater extent the integrative, transdisciplinary, environmental science which has the potential not only to highlight the complexity and specifics of the Man –Environment interactions at different continents and various cultural contexts, but also by empirically testing the highly advanced models of ecohydrological processes, generate innovative methods and systemic solutions for enhancement of sustainability potential WBSRCE of catchments [7]. WBRSCE expresses the urgent need for proactive management in face of the crisis generated by degradation and overexploitation of Biosphere. The key assumption is that in the recent stage of Anthropocene, it is not enough to conserve the nature, but much more intensive action is necessary towards reversing degradation of biocenosis, not only by reduction of impact e.g. by circular economy but, also by the regulation of fundamental ecological process such as water nutrients cycling expressed by a plethora of feedbacks between water and biota. The profound understanding of those relations become background for parallel enhancement of key parameters which determine catchment sustainability –Water, Biodiversity, Services from ecosystems for society, Resilience to climate and various anthropogenic impacts and Culture and education - WBSRCE.

4. Why water and its interplay with ecosystems? genesis of ecohydrology- dual and mutual nature

Ecohydrology emerged in the last decades of the XX Century as a result of the parallel efforts of hydrologists, hydrobiologists, botanists and plant physiologists. The roots of the aquatic phase of ecohydrology which integrates in the framework of physics laws, hydrology and ecology has to be considered in the Abiotic-Biotic

Regulatory Continuum (ABRC, **Figure 2**) [9, 10], which introduce changes of hierarchy of abiotic (hydrology, thermodynamics) vs. biotic drivers (competition, predation, adaptive life strategies) along the river continuum at different climatic regions. One of the inspirations to develop this model was the debate between ecologists on density dependent and density independent regulation factors of populations [11]. ABRC model indicates a gradient of density dependent and independent regulation, which in rivers depends on physics – Bernoullie's principle and temperature determinant of oxygen availability, energy flow, nutrients cycling and biological productivity.

The model also provides a predictive tool e.g. in the abioticaly regulated rivers of boreal zone, to enhance fish populations and stocking efficiency it is necessary to reduce hydraulic stress and energy expenditure in trophy limited ecosystems. On the other hand in biotical regulated tropical rivers there is a necessity to increase trophy potential to reduce competition for food and improve spatial diversity of habitat to reduce predator pressures. This model provided a framework for the FAO UN EIFAC programme Habitat Modification and Freshwater Fisheries. In the next important stage, the ABRC model supported the development of Ecohydrology UNESCO Intergovernmental Hydrological Programme. The expression of Ecohydrology underline that abiotic factors (hydrology, temperature) are primary drivers of ecosystem functioning as far as biota is filling the template created by abiotic factors [12]. An important step was the UNESCO MAB Programme "Role of the land/water ecotones in landscape management and restoration [3, 13] and further regulation of hydrological dynamics of reservoir for shaping the trophic cascade towards mitigation of eutrophication symptoms [14], the environmental flow in the face of global climate changes [15] and the Ecological Engineering idea [16, 17] were supportive to integrate the above puzzles in the international expert team involved in the framework of UNESCO International Hydrological Programme [18, 19] and especially for development of the key idea of **Ecohydrology** as a transdisciplinary sustainability science - **using ecosystem properties and processes as a tool for**

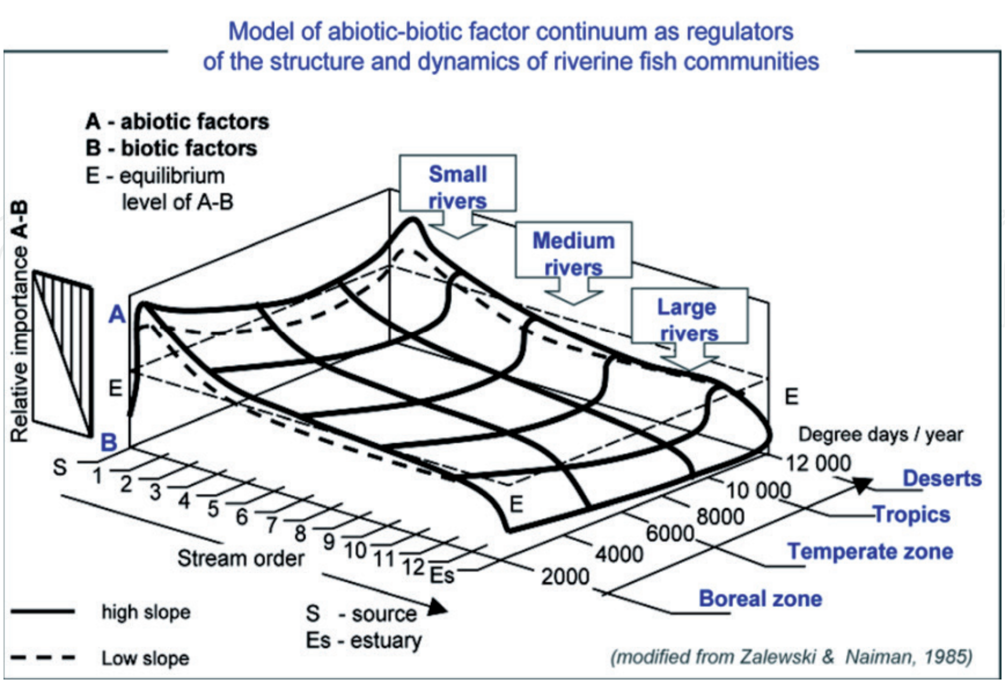

Figure 2.
Deductive model of changes in hierarchy of abiotic and biotic drivers along the river continuum and the temperature gradient: The stream order determines the hydrodynamics and energy demand for trophic processes (hydrology), whereas the temperature determines the metabolic rate, growth rate and bioproductivity (ecology). Water quality, bioproductivity and biodiversity depend on the nutrient spiralling rate, flood pulses and the relation of energy intake from food and the energy expense determined by the above processes.

holistic catchment management [19] and enhancement of sustainability potential WBSRC [20]. Independently the terrestrial phase of ecohydrology has been deepening our understanding of water/plants/soil interactions [21–24] - which is crucial for catchment management especially for shaping terrestrial ecosystems distribution and structures for concordant enhancement of resilience to climate change, reduction non-point source pollution, ecosystem services and biodiversity. The synthetic model which introduced dependence of terrestrial ecosystems bioproductivity and biodiversity and in consequence its sustainability status on the catchment water retentiveness and temperature was introduced in a model build on empirical data [25]: Water, Temperature, Bioproductivity and Biodiversity (WTBBS) (**Figure 3**). This model indicate that reduction of catchment retentiveness by reduction of forest cover, ecotone shelter belts between fields, elimination land-water ecotones and streams/rivers channelization (see **Figure 1**) not only reduce organic matter in soils due to water and wind erosion but generate eutrophication of inland and coastal waters and in situation of climate changes accelerating nutrient cycling indirectly reduce biodiversity and bioproductivity.

A further crucial step for implementation of Ecohydrology was developed on modelling large scale processes especially in costal zones and sea [26–29], analysis of the water biota interplay at different ecosystems [30, 31], employment of molecular

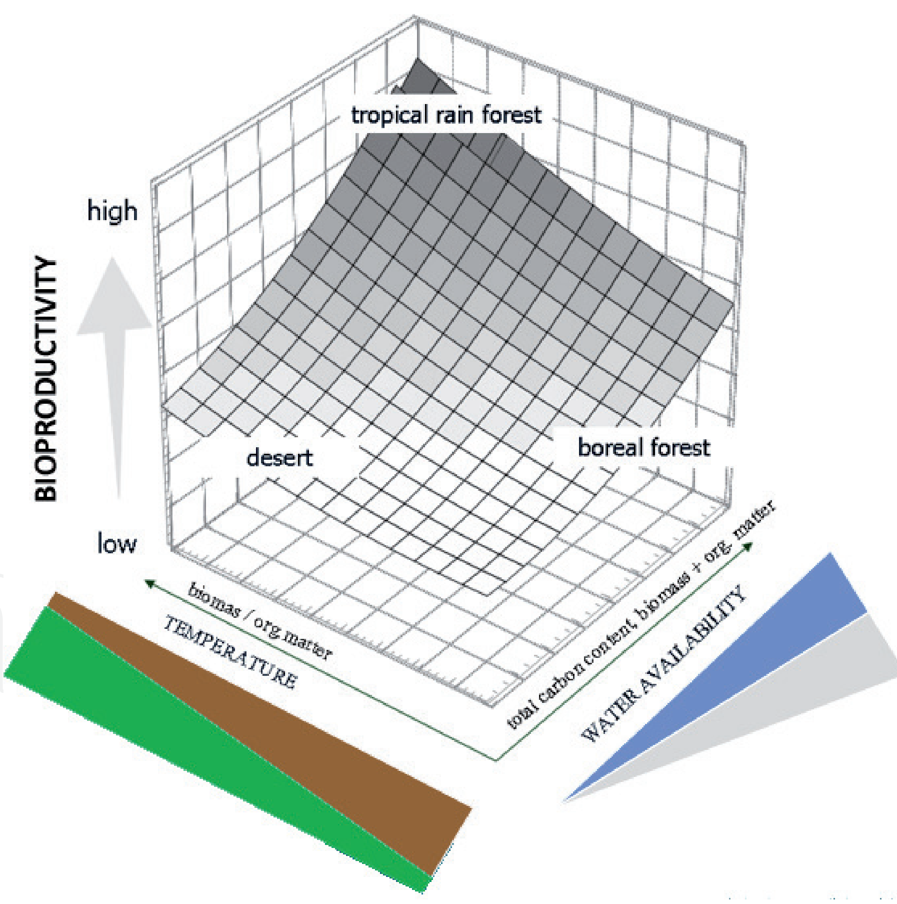

Figure 3.
A deductive model based on empirical data gathered worldwide. The amount of accessible water determines the ecosystem capability to accumulate organic carbon, whereas temperature determines carbon allocation between organic matter (in soil) and living tissues (plants). In low temperature zones most of the carbon is allocated in organic matter, because of low temperatures block decomposition processes and nutrient cycling. On the contrary, high temperatures, e.g. a tropical forest, most of the carbon is allocated in living tissues or organisms, because in such conditions favour high decomposition rate (bioproductivity). The model shows that in conditions of high water accessibility and high temperature, the recirculation rate allows a high bioproductivity and biodiversity. Worldwide long-term consequences of acceleration of river outflow which is occurring in the catchment because of deforestation and river canalization reduces accumulation of carbon, bioproductivity and biodiversity. Ecohydrology systemic solutions provide framework how to reverse these processes.

biology methods for freshwater ecosystem diagnosis [32] and next by translation of the integrative understanding of water biota interplay into ecosystemic biotechnologies [33–35] testing and development Ecohydrological Nature Based Solutions for Water in catchment scale [36]. Also the understanding of society priorities [37], becomes crucial for its involvement in reduction of dispersed impacts and broad range of activities improving WBSRCE. All above efforts especially developed in framework of UNESCO Man and Biosphere and International Hydrological Programme generate inspiration and provides certain prototype for development of the concept of Nature Based Solutions for Water [38].

The parallel step which has been deepening the understanding the various hierarchy of drivers and specific properties of the ecosystems vs. societies priorities was generated by the testing the best current Ecohydrological wisdom and biotechnologies into African conditions [39–41] and use indigenous knowledge in Ecohydrological solutions [42] and analysis of processes and versus human impacts in catchment perspective [43].

5. Principles of ecohydrology as framework for action

Water is the common denominator and abiotic factors: hydrology and temperature are of primary importance in shaping the biological structure and processes within ecosystems for all types of climatic biogeochemical and ecological processes, thus water mezocycle within the catchment provides the best operational template for regulation of water-biota interplay towards enhancement of ecological potential and to achieve desirable status of the ecosystem and sustainable use of its resources. That is why the framework for elaboration and implementation of systemic approach for innovative Ecohydrological Nature Based Solutions (EH NBS) are three principles of Ecohydrology [25]:

I. **Hydrological principle** of Ecohydrology focus on: quantification of hydrological cycle with the special emphasis on the range and dynamics and its modifications due to human impacts, considering the geomorphological structure of the catchment, soil quality (flood, ground water recharge and drought vulnerability), erosion, identification and distribution of various forms of impact e.g. point sources pollution vs. non-point source pollution, urbanisation, transportation pathways. Moreover the timing of river pulses vs. water resources demand e.g. for agriculture and vulnerability to pollution during low flows periods (**Figure 4**.)

II. **Ecological principle** analysis the distribution and ecological potential (WBSR) of pristine – to be protected and novel [44] ecosystems, where novel are a result of the secondary succession and can be a subject of structure changes for processes regulation towards enhancement of carrying capacity (WBSR). **Figure 4.II**. introduce the forests distribution in upper Pilica River catchment, which is important for increasing water retentiveness and groundwater recharge. The enhancement of floodplain phosphorus absorbing capacity and biomass yield begins from analysis of floodplain plants community which combined with groundwater level provides opportunity to replace flooded meadow in 40% by bioenergy willow plantation doubling phosphorus absorbing capacity and profitability of agricultural yield of energy willow from floodplain [45].

III. **Ecological Engineering principle** focused on three types of solutions:

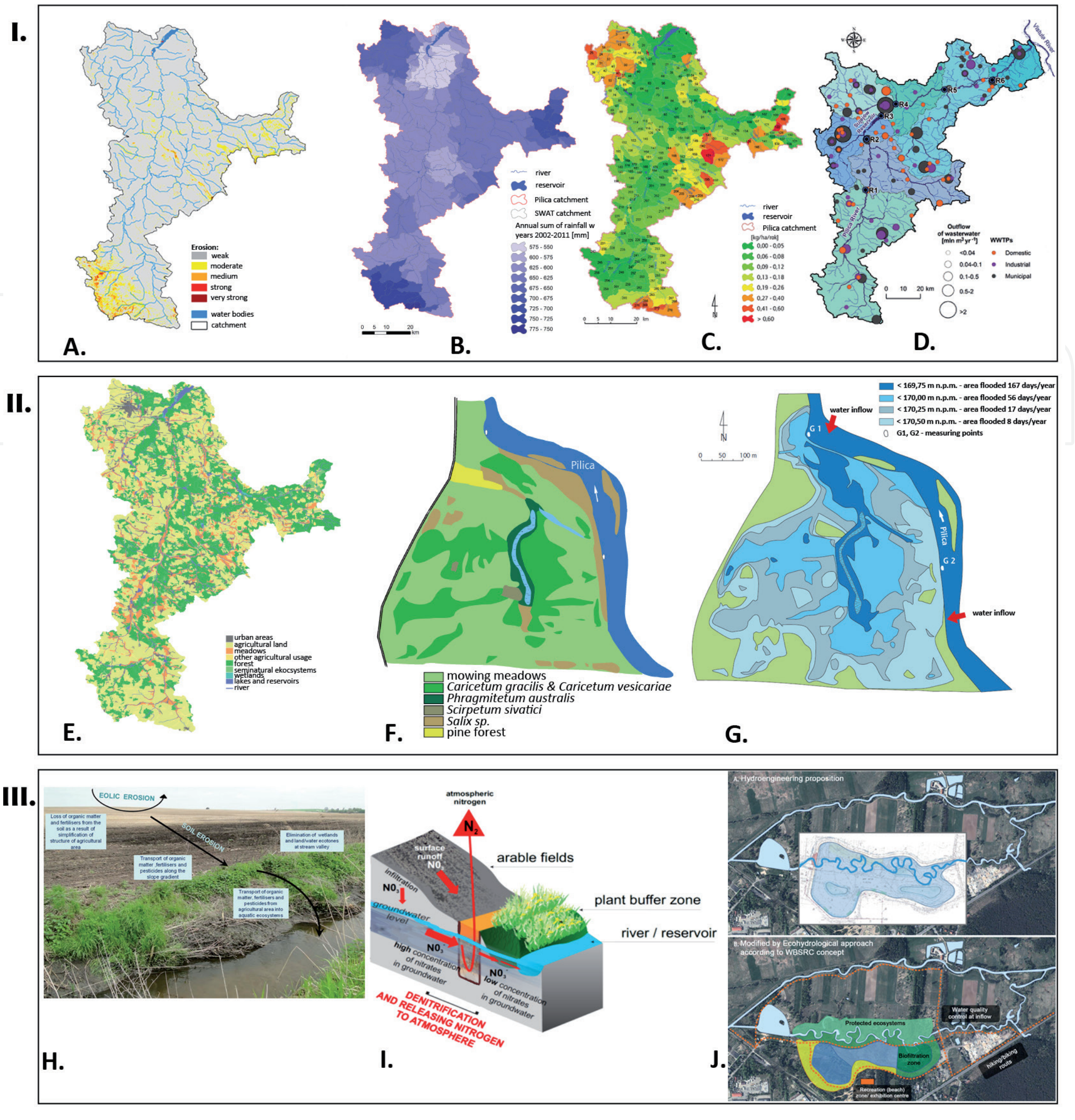

Figure 4.
Principles of Ecohydrology. I principle, hydrological: A. map of water erosion special distribution, describing geomorphological conditions. I.B. distribution of rainfall in the catchment. I.C. SWAT model of special distribution of phosphorus load from non-point source pollution. I.D. distribution of small treatment plants, contributing to total nutrient load in the catchment. II principle, ecological: E. distribution of various land use in the catchment. II. F. Distribution of plant cover on the floodplain corresponding with the time of flooding, allowing for bioenergy plantations of willows in the floodplain, allowing the absorption of phosphorus into plant tissues and increasing the self-purification efficiency by 40% (400 kg of P absorbed). II.G. water level and the time the floodplain stays underwater. III principle, ecological engineering: III. H. Example of a drastic reduction in complexity of agricultural landscape – Tree rows and land/water ecotone buffer zones, resulting in in soil drying, loss of organic matter due to aeolian erosion and surface flow. III. I. the high efficiency ecotone zone with a denitrification barrier for decreasing the nitrogen load from agricultural landscape into ground and surface water. III.J. Ecohydrological alternative solution to proposed by Hydroengieeners reservoir design which blocks the river continuum by eliminating a section of natural, meandering river of high biodiversity. Moreover observed periods of high concentration of phosphorus loads can stimulate toxic algal blooms and eliminate the recreational use of the reservoir. Proposed Ecohydrological approach maintaining the river continuum of the pristine, meandering river and enhancing the catchment sustainability potential by improvement of: W - water quality by eliminating toxic algal blooms, biodiversity, B – Biodiversity by increasing habitat diversity, S – Increasing recreation, R – Increasing river system resilience to climate change by increasing the river valley retentiveness, CE – Citizen science, sustainability consciousness and participation of society.

1. Development and implementation of innovative EHNBS tools with special emphasis on the"dual regulation" – regulation of water cycle/biota interaction from molecular to landscape scale, by shaping biota and regulating biotic processes and vice versa, enhancing biota by regulating hydrology [20, 46].

2. Harmonisation hydroengineering with EHNBS in to hybrid systems [35, 47].

3. Integration of EHNBS hydroengineering and hybrid solutions for synergy at catchment scale [19, 36].

An example of EHNBS construction is the high efficiency land/water ecotones at limited space (5 m strip) which contain denitrification barriers, plant buffer zone and possibility to incorporate geochemical barrier for phosphorus trapping [34] (**Figure 4.III.I**).

The large scale of harmonisation hydroengineering with EH NBS by constructing reservoir on the floodplain and maintaining the river continuum is introduced at **Figure 4.III.J**. The key assumption was to guarantee good water quality - no toxic algal blooms for the recreational reservoir while still maintaining the river continuum. Therefore it was necessary to consider as a reference point the long term analysis of river pulses for identification of periods with good water quality to use for supply of reservoir in water low in suspended matter and phosphorus concentration [7].

Such concept of multifunctional reservoir based on three principles of ecohydrology improves: W - Water resources by increase the amount of water retained in the river valley and its quality by enhancement of biological self-purification process in biofiltration system and diversity of habitats; B - biodiversity by enhancement diversity of aquatic and wetlands habitats; S – services for society – bathing and fishing; R – resilience to climate of all river valley ecosystems by increase of retentiveness of river valley and ground water reserve; CE - culture and education by building the education centre for teaching on importance of river valley in cultural development in history and to develop citizens science.

6. Ecohydrology: summary and way forward

Water is key driver of the strategy to reverse the degradation of Biosphere Sustainability (Sustainable Development Goals, SDG of UN), especially in the face of increasing climate changes. The fundamental step in establishing holistic strategies and systemic solutions should be to understand the hydrological mezocycle, water/biota interplay and hierarchy of drivers. All of that enforced by knowledge and broad scope of environmental sciences with consideration of diverse economic, legal and societal interactions. Therefore for engineering harmony between environment and society, there is **a need to develop an integrative sustainability science**. The fundamental step for achieving this is translating accumulated scientific information into knowledge (understanding the processes, feedback and the hierarchy of regulatory mechanisms in these systems), and then to translate this knowledge into wisdom: the ability to solve sustainability problems by innovative NBS and technologies integrated in systemic solutions which are mitigating human impacts and also increase adaptive capacity and strengthen the ability to adapt society and professional skills to new Evolutionary/Ecosystemic paradigm and relevant technologies, thus changing the hierarchy of needs and situations.

For acceleration of achieving biosphere sustainability (SDG UN) the further steps based on Ecohydrology are necessary:

1. **Proactive Education of society** - coping with uncertainty in changing world and especially climate. There is an urgent need for shaping societal attitudes and understanding of Sustainability: **understanding the biosphere as a dynamic system where water, carbon, phosphorus and nitrogen cycling**

serve as the primary drivers of sustainability, and that these are influenced by each of us and in turn determine the amount and quality of the ecosystem services we need. This approach requires proactive education, which will stimulate a shift from a Sociocentric/Mechanistic to an Evolutionary/Ecosystemic paradigm based on three assumptions: 1/the unity of Man and Nature, 2/consciousness that happiness is not correlated with consumption but first and foremost, a fair and good relationship with other people, and with functioning in a healthy environment, 3/our positive mental status is to a great extent, defined by the quality of our environment. Such beliefs can to a great extent stimulate social capital – confidence and cooperation.

2. **Social capital as an important factor for translation of knowledge into wisdom and of innovations in catchment management**. The philosophy of the exchange of ideas and openness for controversial opinions has been broadening the holistic perception of the problems to be solved and generate most efficiently innovations. It is worth to underline that there appear to be many examples that both encouragement of team spirit but also respect for seniority and leadership towards achievement of strategic goals first and foremost reversing degradation of biosphere, synergies of both should also amplify the translation of Science into Technology.

3. **Socio-economic Foresight of the catchment as a tool for creating a desirable future**. Action without vision and strategies have typically resulted in a waste of human potential and resources. Hence, the primary tool used for the development of responsible vision and strategy in achieving SDG UN should be the foresight methodology, which should consider the circular economy, i.e. reduction of impact and bioeconomy production of commodities from renewable resources, and the enhancement of sustainability potential WBSRCE, where the water mezocycle has to be used as a framework for assessment, planning and management.

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