Frontiers in Flood Research / Le point de la recherche sur les crues
(IAHS Publ. 305, 2006).

Flood pulses and river ecosystem robustness

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Abstract From the functional ecology perspective, rivers have been considered as "open" ecosystems. This means that a river's dynamics, in the sense of its mass balance, is dependent on a permanent supply from the terrestrial ecosystems. On the other hand, its water quality and biodiversity is mainly the function of the flood pulses, which in turn depend on the climate, geomorphology of the basin, ecosystem characteristics, the catchment's development, emission of pollutants, and river valley modification. Understanding the specifics of the interplay between these components is fundamental for sustainable water resources and "ecosystem services" for societies. Among the most potent tools for water management, though little used until now, are the ecosystems of flood plains. They possess great adaptive ability which can be used to increase the carrying capacity of the river basin. The adaptive potential of the flood plain biocoenosis is an inherent property of the system as a flood plain forms a temporary ecosystem for a broad range of early ecological succession stages. Early, and especially intermediate succession stages of ecosystems are characterized by intensive uptake of nutrients and pollutants. Those stages, change from year to year depending on the strength of hydrological pulses. The systems approach of ecohydrology provides a conceptual background regarding how to use those ecosystem properties, e.g. the hydrology and biocoenosis interplay ("dual regulation") of the flood plain, to optimize flood plain functioning towards self purification enhancement, and converting excess nutrients into biomass/bioenergy.

Key words flood pulses; functional ecology; "open" ecosystems; sustainable water resources

Les impulsions de crue et la robustesse des écosystèmes fluviaux

Résumé Du point de vue de l'écologie fonctionnelle, les rivières sont considérées comme des systèmes "ouverts". Cela signifie que leur dynamique en matière de bilan de matière dépend d'un apport continu en provenance des écosystèmes terrestres. D'un autre côté la qualité de l'eau et la biodiversité dépendent principalement des impulsions des crues, qui à leur tour dépendent du climat, de la géomorphologie du bassin, du caractère de l'écosystème, du développement du bassin, du rejet de polluants et de l'aménagement de la vallée. La compréhension de l'interaction entre ces composantes est fondamentale pour que les sociétés bénéficient de ressources en eau et de "services écosystémiques" durables. L'un des outils les plus puissants pour la gestion de l'eau, peu utilisé jusqu'à présent, est le potentiel de l'écosystème de la plaine d'inondation. Les plaines d'inondation possèdent de grandes facultés d'adaptation qui peuvent être utilisées pour accroître la capacité de transfert des bassins fluviaux. Le potentiel adaptatif de l'écosystème de plaine d'inondation repose sur ses propriétés propres puisque la plaine d'inondation a été l'écosystème traversant toute la gamme des premières successions d'états écologiques. Les états primitifs et plus encore intermédiaires des écosystèmes se caractérisent par un intense prélèvement de nutriments et de polluants, ces états changeant d'année en année en fonction de la puissance des impulsions hydrologiques. En tant qu'approche systémique, l'écohydrologie fournit un cadre conceptuel permettant d'utiliser les propriétés de l'écosystème, l'interaction entre hydrologie et biocénose dans la plaine d'inondation par exemple, pour optimiser ses fonctions en vue d'une de l'amélioration de l'autoépuration transformant les nutriments en excès en biomasse et/ou en bioénergie.

Mots clefs impulsions des crues; écologie fonctionnelle; systèmes "ouverts" ressources en eau durables

INTRODUCTION

There is an increasing amount of evidence that in recent decades, Man's activities have become the major driver of the functioning the Earth's biosphere (Crutzen & Stoermer, 2000). The major phenomenon supporting this assumption is that 80% of the Earth's surface has already been changed by Man (Bidwell & Goering, 2004), and this process has been dramatically accelerating. An effect of the human "civilization progress" of the last few centuries has been to "increase the species extinction rate by as much as 1000 times over background rates typical for the planet's history" (Millennium Ecosystem Assessment, MEA). This has been mostly due to the high acceleration of the process of land conversion into the cultivated systems which now cover 25% of the terrestrial area. A consequence of the full range of Man's activities on Earth is that "novel ecosystems" emerge, which are characterized by new combinations of species and functions (Hobbs *et al.*, 2006). The ecosystems that are especially exposed to high anthropogenic stress, according to Meybeck (2003), are rivers. This is because they are situated in depressions of the landscape, to which all of the range of catchment anthropogenic modifications and impacts are transferred and cumulate, e.g. chemical pollution, microbial contamination, eutrophication, sediments and nutrient imbalance. Those dramatically progressing phenomena are often negatively amplified by impoundments and channelization, have been degrading the integrity of fluvial ecosystems and flood plains at an increasing rate, which are the important sources of water and ecosystem goods and services for societies. The question is how to reverse these dramatic processes, especially in the perspective of the global change which increases the stochastic nature of flood events and uncertainties of flood management (Kaczmarek, 2005). As long as population growth and aspirations continue, reactive measures will not be enough. There is an urgent need to formulate the scientific background of the new vision for constructive and pro-active policy, which will lead toward sustainable water resources and ecosystems. To define the scope of the action, it is necessary to recognize that there exist two different forms of impacts. Firstly, the emission of pollutants, the reduction of which is dependent on progress in technology and its implementation. Second, and much more complicated to control, is the understanding of the various pathways of degradation of the hydrological, biogeochemical cycles and biotic structure and interactions at the full range of scales up to the basin. As far as the second depends to a great extent on the complexity of hydrological, biological and socioeconomic interactions, there is no doubt that the efficient solution has to be based on integrative science, a systems approach.

In this context, the flood plain habitats which appear at the aquatic/terrestrial interface, due the high spatial and temporal dynamics of the hydrological and biological processes there, should be considered not only as the key element for river ecosystem restoration, but also as the starting point for implementation of the new way of thinking about sustainable water and ecosystem services at the river basin scale. The key to such a new approach is the necessity to use "ecosystem processes as a management tool" in water management (Zalewski, 2000) by regulation of the ecological processes based on integrative understanding of the hydrology–biocoenosis interplay, from the molecular to the catchment scale (Zalewski *et al.*, 1997). To reverse the accelerating degradation of water resources and ecosystems at the global scale, progress in the integrative sciences for the development of interdisciplinary methodologies for ecosystem-scale control, and transdisciplinary for basin-scale process regulation, is urgently needed. It is especially urgent in the case of all those types of catchments where highly modified "novel ecosystems" appear.

Considering the above for the formulation of the ecohydrology (EH) concept, in the framework of UNESCO IHP, the question: what is the hierarchy of factors which regulate ecological processes (implicitly water quality), in rivers of different sizes in different climatic zones (Zalewski & Naiman, 1985), was the starting point. This question, valid for both ecologists and hydrologists, allows definition of the three principles of EH:

– Hydrological: the hydrological cycle at the basin-scale should be considered as the template for quantification of both impact and opportunities relevant to the biological performance of the ecosystem.
– Ecological: freshwater ecosystem robustness can be enhanced on the basis of understanding the evolutionary established resistance and resilience of the ecosystems.
– Ecological engineering: enhancement of ecosystem resistance/resilience can be achieved by "dual regulation"—biocoenosis by hydrology, and *vice versa*. Thus by shaping the biota, the hydrology—mostly water quality—can be improved.

ECOHYDROLOGY FOR ENHANCEMENT OF FLOOD PLAIN ROBUSTNESS

Considering the protection of the river and its flood plain from the holistic catchment perspective, the terrestrial phase of the hydrological cycle has an advanced scientific background, especially regarding aspects such as the restoration and management of land water ecotones (Naiman & Decamps, 1990; Zalewski *et al.*, 2001), the restoration of water storage in the plant/soil system by enhancing the biomass and diversity of native plant species (Bird & Wilby, 1999), and shaping of the mosaic character of the landscape (Ryszkowski & Kędziora, 1987; Eagelson, 1982; Kędziora *et al.*, 1989; Rodriguez Iturbe, 2000; Vorosmarty & Sahagian, 2000; Zalewski, 2002).

The most important part of the aquatic phase of the hydrological cycle is at the productive "interface" flood plain ecosystem which possesses great potential for adaptation of its biological structure and productivity to the intensity of flood pulses. On the other hand, the connectivity between the river channel and its flood plain may considerably improve water quality and moderate the hydrograph pattern (Hein *et al.*, 2003). Consequently, in anthropogenically modified river valleys, use of the flood plain to increase river robustness and the restoration and management of the plant communities should be an important element of "ecohydrological dual regulation"

(Zalewski, 2000, 2002a,b). This means regulation of the hydrology in some situations (e.g. highly degraded areas) and even shaping the geomorphology towards optimization of biological processes such as deposition, nutrient uptake and biomass conversion; adjusting and shaping the biological structure of flood plain plant communities to the geomorphology and fluvial patterns. There is increasing evidence that such "dual regulation" of ecological processes can enhance water and ecosystem goods and services such as: river self purification, nutrient and pollutant trapping; biomass, animal fodder, bioenergy plantations; aesthetic value, recreation potential of the area.

The primary question is: To what extent is there the possibility of regulating the intensity and quality of flood pulses? There is some empirical evidence that important dams are potential tools for management and regulation of the process of flood pulse formation (Timchenko & Oksiyuk, 2002). The impoundment of rivers doubled from the 1960s, despite the associated significant change to their ecological status. However, in most of cases, an increase of water retention is necessary to maintain and increase food production, because 70% of withdrawals are for agricultural needs. Given that most of the river courses of the world are already controlled by dams—the amount of impounded water quadrupled since 1960 and is three to six times as much as in natural rivers (MEA)—the question is how to regulate their operation for restoration and optimization the flood plain function.

REGULATION OF HYDROLOGICAL PATTERNS

The dynamics of the river ecosystem are dependent on matter supplied from the adjacent ecosystems. The flood pulse formation processes determine the delivery mode of mineral organic matter, nutrients, pollutants, and also fluxes of genetic information in the form of seeds of plants, eggs of fish, invertebrates and other colonizing organisms, into the flood plain (Junk *et al.*, 1989). It is dependent on the climate, the catchment's geomorphology, the forms and intensity of its use, the plant cover, and river network character. On the other hand, the macrophytes of a riparian wetland may influence water level and flood dynamics (Trepel & Kieckbusch, 2005).

Streams are fluvial habitats that are an order or even orders of magnitude more intensively supplied by water and nutrients from the valley and catchments, through the ecotone transition zone, than large rivers. This is due to the bank length:water volume ratio. Consequently, reduction of the land/water ecotone diversity (e.g. stream channelization), changes the allochtonous (terrestrial origin) organic matter supply, which in a natural stream is converted in a spiral process (primary production, food chain and decomposition) determining the productivity and biodiversity of the stream that in turn also influence the self purification process (Zalewski *et al.*, 1994). This has recently also been confirmed by Alexander *et al.* (2000) who demonstrate that natural streams transform significantly more nutrients per unit of surface than large rivers. As a consequence, flood plains supplied by channelized and natural networks of streams differ with respect to the temporal patterns of delivery and also the composition of mineral and organic matter, nutrients and pollutants, and the diversity of organisms. Following down along the river continuum, flood plains, due to biological transformation processes are the source of organic carbon (Thoms, 2003) and organic matter to the river ecosystem. Despite much evidence highlighting the role of the flood plain as a trapping system for pollutants (Magnuszewski *et al*., 2005; Mitsch *et al*., 2005), the processes of the qualitative conversion which appear at flood plain biocoenosis, are still not well understood, mostly due to the large abiotic geomorphic heterogeneity of the ecosystems (Martin *et al*., 2005).

The second major determinant of flood pulse patterns and magnitude at the river basin scale are impoundments—efficient traps for sediments, nutrients and pollutants. Unfortunately, they often disturb the processes of river channel formation below (lateral channel migration downstream) increasing soil erosion, and reducing organic matter deposition. This has a dramatic effect on soil fertility and in consequence the full range of ecosystem services for society, e.g. reduction of crop production, impact on fisheries at delta/coastal zones, toxic algal bloom appearances in tourist regions (Chicharo, 2001).

An example of the effect of large-scale, long-term catchment processes on the character of a river flood plain is introduced by Starkel (1990), who presents evidence that the recent characteristics of the Vistula flood plain have been determined mostly by deforestation of Carpathian Mountains in the 17th century. However, the pattern of deposition of heavy metals is related to industrial development of the Silesia region during the 20th century (Zober & Magnuszewski, 1998).

The early, and especially the intermediate succession stages of ecosystems, are characterized by intensive uptake of nutrients and also pollutants due to high biomass incrementation. Because the flood plain is such a temporary ecosystem presenting the whole range of early and intermediate ecological succession stages, it has a high adaptive potential which provides crucial ecosystem services and goods for societies: groundwater recharge, water quality improvement, biodiversity, erosion reduction, maintaining river flow during dry periods, recreation, cultural and aesthetic values. However, the intensity of those processes changes from year to year depending on the strength of hydrological pulses. When the range of hydrological pulses declines due to dam construction, the flood plain functioning shifts from being a sink to a source of nutrients and pollutants (Shield *et al.*, 2000; Pinay *et al*., 2002).

The general idea, which should be considered as the starting point for defining the criteria for regulation of flood pulses, is provided by ecological theory, i.e. the Intermediate Disturbance Hypothesis (Connell, 1978), which has been tested and confirmed in numerous publications dealing with different types of ecosystems. The general body of theory suggests that the maintenance of the ecosystem in the optimal dynamic equilibrium state with high biodiversity and productivity is ensured by the intermediate strength of the abiotic disturbances. Catastrophic disturbances may lead to profound degradation of the biotic structure of ecosystems due to the long time required for regeneration (secondary succession) and the long period of reduced biodiversity and productivity, which is usually translated as a decline of ecosystem goods and services for society. On the other hand, the stabilization of abiotic factors beyond the natural level, e.g. stabilization of river hydrology due to dam development, leads to similar effects as far as the lack of flood plain inundation, decline of river connectivity, degradation of flood tolerant plant communities, but first and foremost, the reduced access of fish to spawning and rearing grounds (Agostinho & Zalewski, 1996).

Access to the river adjacent habitats, such as flood plains, oxbows lakes and small tributaries, determines to a great extent the river's genetic and species diversity. Bouvet & Patte (1991), comparing individual genotypes of roach, *Rutilus rutilus* L., from different habitats of the highly modified French Upper Rhone system, emphasize that genetic diversity is greater in river margins (backwaters, tributaries and neighbouring lakes) than in the channel. They concluded that "empirical data confirm the general opinion that the environment diversity is accompanied by genetic diversity".

In the case of the Parana River (South America) before dam building, the natural reproduction of fish in the flood plain usually appeared every third year, and this was enough to maintain sustainable fisheries (Agostinho *et al*., 2001). Since reduction of the flood peaks by the Porto Prima Vera Dam, the access of fish to spawning and rearing grounds has been so seriously limited that the fisheries have declined dramatically; the decline was seriously amplified by deforestation of the flood plain for cattle breeding and land cultivation for alternative protein production. This generates erosion, nutrient supply and accelerated eutrophication (toxic algal blooms) at the Itaipu Reservoir downstream. The proposed ecohydrological solution recommends restoration of high flood peaks during the short periods of fish reproduction. The deforestation could be stopped and reversed by successful restoration of the fisheries, and thus progress towards sustainable water and ecosystem resources would be achieved.

Another case of application of the regulation of water release by dams to protect ecosystem services and prevent the oxygen deficit for fish in river flood plain and delta areas, has been already successfully applied at the Dniepr reservoir, Ukraine (Timchenko & Oksiyuk, 2002).

The biological structure of the natural flood plain is organized according to the intensity of floods. Although usually a flood plain is a mosaic of various habitats, there is the tendency, at the areas near the river channel, for early succession stages of plant communities to appear, while farther from the channel ecosystems are more advanced containing higher and more stable biomass. Given that the different vegetation succession stages possess different resistance to flood hydraulic forces, and also have different potential for nutrient uptake and conversion to biomass, understanding of the spatial plant distribution pattern is important for management.

The traditional civil engineering approach for flood control is a combination of dams with simple "detention polders" that not only disturb river hydrology dynamics but reduce biodiversity (Okruszko *et al*., 2005). However, the restoration of flood plains to their pristine conditions often might be not acceptable for society. But if restoration processes, e.g. detention polders, are designed with consideration to multi-functional use—to stabilize hydrological processes, restore biodiversity by providing refuges at periodically flooded habitats for both aquatic and terrestrial organisms, moreover to provide required ecosystem goods and services for society, e.g. biomass/ bioenergy production, this might be positively received by society and incorporated in to local development plans. To maximize the robustness of such restored flood plains, the periodically flooded polder should be constructed as a system of different patches of terrestrial, semi aquatic and aquatic vegetation with periodical and sequentially cropped biomass/bioenergy of different succession stages. Such areas of limited access will also be important refuges for some organisms from terrestrial habitats during catastrophically dry periods, the frequency of which is increasing as a result of global climate changes.

PILICA FLOOD PLAIN CASE

An example of implementation of the ecohydrological approach for enhancement of the carrying capacity of the flood plain is the Pilica River case (Fig. 1; Kiedrzynska *et al.*, 2006). The Sulejów Reservoir, despite cyanobacterial toxic algal blooms, has for a long time been the source of water and recreation for the City of Lodz (a conurbation of one million people). To eliminate the danger for society and to achieve a good ecological status as required by the EU Water Framework Directive, an urgent reduction of the phosphorus load provided by river to the reservoir has been needed (Zalewski, 1994, 2000). This is because in the reservoir, 1 kg of P converts into 2 t of toxic algal blooms. The major load of organic matter and phosphorus to the reservoir is provided with floods (Wagner & Zalewski, 2000), thus use of the flood plain above the reservoir to reduce and convert this load into bioenergy, reducing phosphorus levels to below the level which promotes Cyanobacteria growth, should be ecologically relevant and socially acceptable. The question is to what extent, by shaping the plant communities on the flood plain and using mostly local species tolerant to periodic floods, it is possible to increase the trapping of phosphorus and bioenergy production so maintaining or even improving conditions for local biodiversity.

To provide an answer, an investigation of flood plain structure and dynamics, with consideration of conversion of part of the terrain into bioenergetic willow plantations, has been developed (Kiedrzyńska *et al.*, 2006). Due to the natural character of the Pilica River, river–flood plain connectivity appears along the whole course. Up to now, the major agricultural output, hay, was often lost due to periodic flooding. In the face of the increasing demand for renewable energy in Poland, the significantly more profitable yield would be the production of bioenergy by willow plantation resistant to periodic flooding. For the evaluation of the seasonal pattern of phosphorus accumulation in different plant species, maps of groundwater P concentrations, the location altitude map, a Digital Terrain Model, inundation model of the flood plain and a map of plant communities distribution (Fig. 2) were developed. On the basis of these maps the biological primary potential for P trapping was assessed as 255 kg. However, if the willow plantations were extended to cover 24% or 48% of the flood plain, phosphorus accumulation would increase to 332 and 399.4 kg, respectively. Moreover it can be expected that the sequential cropping of the willow (three areas, one cropped each year) in winter will disturb the ecosystem of the flood plain to a lesser extent than three hay cuts during the summer. The above interdisciplinary studies indicate that by changing the biological structure of the flood plain, the robustness of the river ecosystem can be significantly improved with associated social and economic benefits such as: reduction of the nutrient and pollutant load in the river, reduction of reservoir eutrophication, enhancement of flood plain biodiversity, and renewable energy gain.

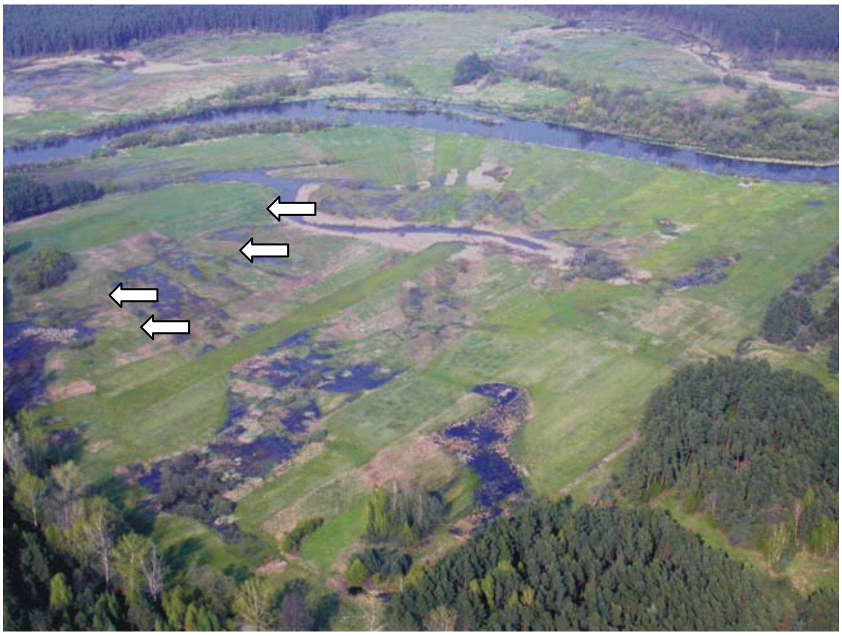

Fig. 1 The experimental flood plain of the Pilica River. The arrows indicate the experimental willow plantations (Photo I. Wagner).

DISCUSSION

Considering global patterns of plant diversity and the role of plants as one of the major ecohydrological regulatory factors, the question arises: to what extent is it possible to establish a universal pattern of ecohydrological management for the enhancement of the robustness of flood plains in the different climatic zones and continents?

According to Ricklefs (2005), global plant diversity is related primarily to climatic factors: temperature and precipitation, and next to evolutionary factors such as tolerance to freezing and high salt concentration: "*Competitive equivalence is maintained by variation in habitat breadth; the resulting demographic equivalence of species places the time scale of extinction on the same order as that for species production. Thus regional and historical factors shape the regional species pool …*" This statement leads to positive perspectives for development of a universal pattern of using plants as a management tool for different types of flood plains.

Flood plain plant communities, from a temporal perspective, are the most dynamic associations. According to Lite *et al*. (2005): "*flood disturbance and water availability both influence species richness of riparian plants in the flood plain of semiarid region rivers (Arizona) with the relative influence of each factor varying among plants group and over time*", and further "*richness and cover patterns also varied between years with different flood conditions*". Those findings are consistent with the Intermediate Disturbance Hypothesis (Connell, 1978) which predicts that the highest species number should appear at intermediate levels of disturbance and environmental stress.

The strategy for implementation of the Millennium Development Goals has to be realistic. That is why one of the fundamental questions is how to harmonize the hydrotechnical infrastructure, designed and operated mostly to ensure electricity supply and flood protection, with restoration and enhancement of flood plain robustness.

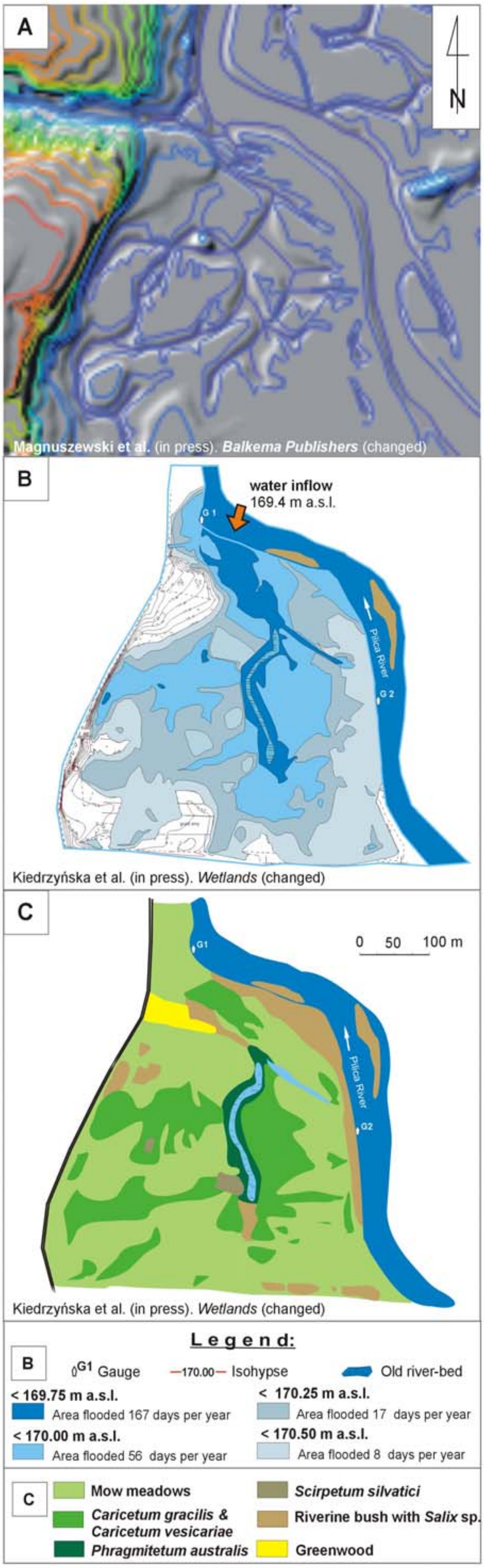

Fig. 2 Model of flooding and vegetation cover for the Pilica flood plain.

Considering the hydrotechnical infrastructure as one of the major factors degrading the flood plain biocoenosis and its functioning, many authors postulate the re-establishment of flood pulsing and interconnection as an essential step for restoration of flood plain wetlands because it determines the basic ecosystem functions: production, decomposition and consumption. However, to achieve this, some authors postulate the need for dam, levee and polder removal, and dechannelization. In some cases this type of action is possible and necessary. However, in highly populated areas it seems unrealistic because it might generate floods and drought. Instead, as an option towards achieving sustainable water and ecosystems, it is necessary to assess whether harmonization of the hydrological pattern with the full range of demands is an opportunity to develop instructions for multipurpose operation.

Ecohydrological principles provide the basis of the ecosystem approach, in the framework of IWRM (Zalewski *et al.*, 2002, 2004). However, the hierarchy and specifics of particular methods may be different for industrialized temperate countries and developing tropical and subtropical regions, similar to the differences in Water Management Strategies (Falkenmark *et al.*, 1987). Scientific interdisciplinary work on enhancement of the robustness of the flood plain should be considered as one of the key elements of the integrative ecohydrological measures for reversing the degradation of aquatic systems during the Anthropocene.

CONCLUSIONS

1. Flood plain biocoenosis is the self-organizing system through the process of the ecological succession (*sensu* Holling *et al.*, 1994) and the primary driving factor is hydrology. The worldwide progressive degradation of flood plains negatively effects river ecosystem biodiversity and productivity and, in consequence, the self-purification potential for water quality and all types of ecosystem goods and services.
2. For enhancement of the robustness of a flood plain as expressed by water, biodiversity and other ecosystem goods and services, ecohydrological “dual regulation” should be applied.
3. Harmonization of the hydrotechnical infrastructure with the spatial heterogeneity and temporal dynamics of flood plain ecosystems, to maintain an intermediate level of hydrological disturbances, should be key to achieving sustainable water and ecosystem goods and services for societies.
4. The integrative analysis of the specifics of the hydrological cycle and its anthropogenic modifications at the basin scale, with special emphasis on evaluation of the potential for elimination of point source pollution, restoration of land cover, use of land–water ecotones as buffers and harmonization of dams with the flood plain functioning, by formulation of multipurpose operation instructions, should be the starting point for the development of plans for the restoration and enhancement of the robustness of flood plains.
5. In the face global change, restored flood plains or detention polders, if created with consideration of the high patchiness of semi-terrestrial, and of the connectivity of periodically flooded wetlands and aquatic habitats, should be important measures for maintaining the whole catchment’s biodiversity, i.e. including aquatic and terrestrial organisms.

Acknowledgements Special thanks to Dr Cate Gardner for her help with improving the English.

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