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Sustainable floodplain management for flood prevention and water quality improvement

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Abstract Although it is not possible to completely eliminate flooding in an era of climate change and intensification of extreme weather events, effective flood prevention and management in river floodplains may make a significant contribution. The land use characteristics of a catchment and river valley determine, to a great extent, the functioning of a river floodplain, as well as the quantity and size of the flood pulses in the river. The paper is focused on the role played by ecohydrology in flood risk management and water quality. From the ecohydrological perspective, river floodplains are extremely important and capacious ecosystems which, being periodically flooded, absorb flood and pollutant peaks and may minimise the danger of flooding. Increased natural water retention capacity in floodplain areas and the whole basin in the face of progressive climate change is possible through three routes: the modelling of the hydrological budget of the catchment towards the sustainable ecohydrological management of floodplains, the optimal use of existing hydrotechnical infrastructure and the implementation of ecohydrological biotechnologies. Furthermore, with such a holistic perspective, the role of river floodplains is one that also enhances the resilience of the river basin against climate and anthropogenic change, as well as increasing flood safety, improving water quality and increasing its ecosystem services for society.

Keywords Climate change · Flood · River floodplain · Ecohydrology · Flood prevention · Water quality improvement

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1 Introduction

Progress in integrative environmental sciences provides a background for the integration of, among others, two domains of water resources management: flood risk management and sustainable floodplain management. According to Schanze (2006), flood risk management can be defined as a combination of comprehensive and continuous societal analysis, assessment and interventions for reduction in flood risk. Evidence suggests that over the past 8 years, the exposure of people and assets to disasters has been rising (Lavell 2009; IPCC 2012; UNISDR 2013). There is an increasing risk of losses in social progress, health, well-being, employment opportunities, security, water quality and economic development. Public institutions, scientists and business entities alike need to move towards a more comprehensive approach to flood risk management (UNISDR 2013). Sustainable floodplain management is aimed at restoring the natural floodplain areas in the river valleys, as well as developing mechanisms for increasing the retentiveness of water and matter in the landscape, which contributes to the correct functioning of floodplain ecosystems in a catchment. The integration of management strategies could be based on a holistic strategy incorporating the principles of Ecohydrology (EH), which encompasses all the elements of the environment which would need management. Its elaboration should be preceded by a cooperative analysis of the processes involved, as the approach combines a range of scientific and applied disciplines including natural sciences, such as Meteorology, Hydrology, Ecology, Ecohydrology and GIS analysis, social sciences such as Politics, Economics, Psychology and cultural heritage and engineering disciplines such as Hydraulics and Hydrotechnics. Recognition of the complexity of the interactions between the above disciplines is fundamental for the efficiency and efficacy of the decision-making process.

Floodplains are a very important integral part of river systems and play an essential role in the exchange of water masses and matter between river and terrestrial ecosystems (Junk et al. 1989; Tockner et al. 1999; Kiedrzyńska et al. 2008a, b; Mitsch et al. 2008), thus influencing water quality. In these ecosystems, surface and ground water act as a connector between various abiotic (soil) and biotic (vegetation) elements of an ecosystem, and at the same time as a spatial connector between the valley and riverbed along the river continuum (Kiedrzyńska et al. 2008b). These connections, operating at various scales and on many planes, are crucial for maintaining the function and integrity of floodplain-river systems (Tockner et al. 1999; Thoms 2003). These systems act as interfaces of terrestrial and aquatic biodiversity in the catchment landscape within the mosaic of plant communities and its spatio-temporal dynamics (Zalewski 2008; Zalewski and Kiedrzyńska 2010).

Climate change and the increasing frequency and intensity of extreme weather events, such as floods, tornadoes, droughts and the drying of streams and rivers (IPCC 2012), as well as the major environmental degradation observed in many catchments and floodplains, have led to a reduction in the carrying capacity of the global system. According to Freudenberger et al. (2012), Hobson and Ibisch (2010), Rosen (2009), Ryan et al. (2007), the anthropogenic degradation of ecosystems on the global scale leads to a shift from an evolved state of self-ordering complexity towards a state where conditions reflect more simple structures and functions that are less efficient. In consequence, the simplification of ecosystems leads to a reduction in the internal complexity of ecosystems and their carrying capacities (e.g. Wagendorp et al. 2001; Ryan et al. 2007; Zhang et al. 2014; Zalewski 2014a, b), with a loss of biodiversity and ultimate dysfunction in systems (e.g. Hassan 2005; Hirsch 2010). According to global analyses of the functionality of terrestrial ecosystems conducted by Freudenberger et al. (2012) and Zhao and Running (2010), the ecosystems in the southern hemisphere have been characterised by drought-induced net primary production (NPP) loss rates between 2000 and 2010, which are related to global climate change, among other things. Although areas with high ecosystem functionality index (EFI) values, but also with high NPP losses, are distributed worldwide, they have been identified mainly in South America, parts of southern Africa, South-East Asia and central Eurasia (Freudenberger et al. 2012).

Nowadays, "many climate change adaptation efforts aim to address the implications of potential changes in the frequency, intensity and duration of weather and climate events that affect the risk of extreme impacts on human society" (IPCC 2012). However, it is important to understand that risk is determined not only by the climate and weather events, i.e. the hazards, but also by the exposure and vulnerability to hazards which have been induced by human activity (IPCC 2012). Therefore, effective adaptation and disaster risk management strategies and practices also depend on a rigorous understanding of the dimensions of exposure and vulnerability, as well as a proper assessment of changes in those dimensions (IPCC 2012). Under intensive global changes, it is not enough to protect ecosystems against increasing human populations, energy and water consumption and growing aspirations. It is necessary to regulate ecosystem structure and processes towards increasing the 'carrying capacity' of the global ecosystem, which may be defined as the maximal load of the environment, while preserving the ecological equilibrium and functionality of the ecosystem. It demands, among other things, the improvement of water quality, restoration of biodiversity, provision of greater ecosystem services for society and the improvement of river ecosystem resilience (Zalewski 2011). Understanding the role of vegetation in water cycling processes is of crucial importance (Rodrigues-Iturbe 2000; Vorosmarty and Sahagian 2000; Gaberščik and Murlis 2011). Arguably, on this basis, the following questions represent important goals for the science of the twenty-first century: how can the dramatic progressive degradation of river floodplains be reversed in order to reduce the consequences of flood events and achieve a sustainable use of its resources in the face of global climate change, and how can the valley-floodplain-river systems be managed to preserve their hydrological, ecological, biological, social and cultural values?

In the face of advancing climate change and against the background of existing demographic trends, there is an urgent need for large-scale testing of integrative scientific solutions. One such solution, proposed by EH, is the requirement to enhance the carrying capacity of ecosystems. This in turn should provide a background for the formulation of a new vision of a constructive and proactive policy which would lead towards sustainable river and floodplain ecosystem development (Zalewski 2006, 2012). According to the International Council for Scientific Unions (ICSU), scientific efforts must be integrative for local, regional and global problem-solving and be oriented towards a common water policy. From the European Union perspective, the common water policy which relates to flooding is the Flood Directive (2007/60/EC). This directive requires EU countries to identify areas at risk of flooding by the end of 2011, draw up flood risk maps by 2013 and establish flood risk management plans by 2014. In flood risk management plans, the Member States shall take into consideration long-term climate change as well as sustainable land use in the flood risk areas. The aim of this paper was to present the ecohydrological assumptions needed for sustainable management of river floodplains and catchments to minimise flood hazards and solve the problem of water quality Therefore, both the subject of this paper and the concept of ecohydrologically sustainable floodplain management are highly relevant to the Flood Directive and its assumptions, statements and requirements.

2 Climate change: implications for global ecosystems

2.1 Climate change: the consequences for the hydrological cycle

Climate and water on the planet Earth are intimately linked, as water both influences, and is influenced by the climate. Every change in the climatic system induces a change in the water system, and vice versa (Kundzewicz 2008). Climate change is caused by the emission of "greenhouse" gases, which trap long wave radiation in the upper part of the atmosphere and thus raise atmospheric temperatures. Carbon dioxide is the main gas, the atmospheric concentration of which has dramatically increased since the industrial revolution, due to intensification of industrial production and fossil fuel combustion and large-scale land use changes (McCarthy et al. 2001; Nicholls and Klein 2005; Kundzewicz and Matczak 2012). According to Houghton et al. (2001), in 1800, the atmospheric concentration of carbon dioxide was near 280 parts per million (ppm), while today it amounts to 350 ppm and is steadily increasing; the concentrations of other greenhouse gases, methane and nitrous oxide are at similar levels. Scenarios for 2,100 assume an increase of carbon dioxide concentrations to the level of 540–970 ppm, with a range of uncertainty between 490 and 1,260 ppm (Houghton et al. 2001). Based on these projections, the Intergovernmental Panel on Climate Change (IPCC) expects an increase in globally averaged surface temperature between 1.4 and 5.8 °C over the period of 1990–2100. It is very likely that nearly all land areas will warm up more rapidly than the global average, particularly those at high latitudes in the cold season, including much of Europe (Houghton et al. 2001).

Climate change influences hydrological cycle change, and vice versa. According to Kundzewicz (2008), the hydrological cycle can be interpreted as "a set of water fluxes (hydrological processes), which transfer water between stores (reservoirs) in the geosphere (hydrosphere proper—oceans, seas, lakes, rivers, wetlands and marshes; cryosphere—ice and snow; lithosphere—groundwater, water in rocks and Earth crust; and atmosphere—clouds) and biosphere (water contained in living organisms, plants and animals)." Climate change, among other things, leads to the emergence of hot spots and changes in the hydrological cycle, which are manifested by an ongoing intensification of the water cycle, with increasing rates of evaporation and precipitation, and such consequent extreme events as catastrophic floods and droughts (Kundzewicz 2008).

2.2 Floods and droughts

Global mean sea level rose during the twentieth century at an average rate of 1.7 ± 0.5 mm $year^{-1}$ (Church and White 2006; Bindoff et al. 2007; Chust et al. 2009). However, other estimates of multi-decadal global rises indicate slightly lower rates (1.5 ± 0.4 mm $year^{-1}$) occurred between 1961 and 2003 (Domingues et al. 2008). According to Chust et al. (2010), global climate models predict a mean sea level rise of between 0.18 and 0.59 m by the end of the twenty-first century, with high regional variability. The two major causes of global sea level rise are thermal expansion of the waters of the oceans and the loss of land-based ice due to increased melting, both processes being driven by global warming (Bindoff et al. 2007; Chust et al. 2010). All these factors are already contributing to a range of problems, including increasing flood risk and coastal erosion. It is expected that future climate change will be greater than that experienced historically and that the frequency of storms and the intensity of river flood pulses may increase across northwest Europe. As evidenced by the above facts, global climate change is not fictional, but rather the cause of the increased frequency of catastrophic phenomena due to human activity. Even assuming a positive scenario, that the level of greenhouse gases will be reduced as a result of the restrictive policy of the European Commission (EC) and the efforts of the global community, the severity of catastrophic events such as transboundary floods, droughts, tornadoes and rising sea levels will increase until the end of the 21st century and beyond (Nicholls and Klein 2005; Chust et al. 2010; Botzen et al. 2010; Khan and Kelman 2012).

Floods are regarded as one of the most widespread disasters in both Europe and throughout the world, causing a large scale of losses (Glaser et al. 2010). Floods are very well-known extreme events, which have been described and reported since early historical times, such as the floods of the Nile in ancient Egypt and the flood events in ancient Greece and the Roman Empire, when human activities and human settlements were relatively limited (Ganoulis 2008). Today, the risk of flooding is a major concern in many catchments in Europe and throughout the world. During the assessment and analysis of flood risk, it is important to remember that floods are part of the natural hydrological cycle. The predictability of floods depends on the catchment characteristics, and while some floods, such as snow-dominated or highly regulated ones, can be highly predictable, others can sometimes be random and unpredictable (Stancalie et al. 2006). During the past 20 years, catastrophic flood events both in Europe (Vistula River, Oder River, Danube River, 2010; Danube River in Romania, 2006; Danube River and Elbe River, 2002; Vistula River and Odra River in Czech Republic, Poland Germany, 1997; Rhine River, 1995), the USA (Mississippi River, 1993, 2011) and Asia (Yangtze, Yellow and Songhua Rivers in China, 2010) and Australia (State of Queensland, 2011) have shown that human activities and traditional river engineering works may result in an increased frequency of floods and, most importantly, in negative economic consequences, such as loss of property, destruction of livelihood and loss of human life (Fendler 2008; Ganoulis 2008). In August 2002, an extreme flood event in Central Europe caused heavy damage and loss of human life in Austria, the Czech Republic and Southeast Germany. One hundred people lost their lives and about 100,000 were displaced. The total cost of the flood losses in August 2002 is estimated at €15–16 billion (Ganoulis 2008). The flood peak of the Elbe River in Dresden was classified as at least a 500-year-recurrence event. In Austria, it is estimated that the flood peak along the Danube River represented a 70–100-year-recurrence event, while in some tributary basins, floods occurred with a return period of about 1,000 years (Ganoulis 2008). Data from the European Environment Agency Report (2010) showed that between 1998 and 2009, Europe suffered 213 major floods, which caused 1,126 deaths, displaced half a million people and was responsible for insured losses of over € 52 billion.

Other major extreme events are long-term droughts leading to water deficits, which may affect more than 65 % of the global human population by the year 2025 (Momba 2010). Currently 40 % of the world's population does not have enough water, and according to a report by UNESCO, in the next 20 years, the amount of available water will be further reduced by about 30 % (UNESCO WWDR1 2003). It is estimated that only about 2.5 % of the world's water is fresh water and less than 1 % is drinking water (UNESCO WWDR4 2012). The limited supply of drinking water is very aptly summed up by the quote by the English poet Samuel Taylor Coleridge—"water, water everywhere, nor any drop to drink." These extreme events, like catastrophic floods and long-term droughts constitute a serious challenge to long-term management of catchment-floodplain-river systems (Nicholls 2002; Mee 2005; Nicholls and Klein 2005; Kundzewicz et al. 2008).

3 River floodplains as pulsing ecosystems

Every square inch of land on the Earth forms part of a catchment. River catchments with their river valleys, floodplain areas and rivers are crucial hydrosystems that sustain the global freshwater bodies. River floodplains are an integral part of valley-river systems. They often function as natural wetlands that are transitional 'dynamic spatial mosaics' (Amoros and Bornette 2002; Thoms 2003) between a terrestrial river valley and open river ecosystems. A fundamental role of floodplains is to exchange flood and ground water, as well as mineral and organic matter, nutrients and pollutants back and forth between river and terrestrial ecosystems (Junk et al. 1989; Naiman and Decamps 1990; Tockner et al. 1999; Magnuszewski et al. 2000; Kiedrzyńska et al. 2008a, b), along the river continuum.

Factors such as geomorphology and climate define the extent of floodplains and can influence floodwater retention. However, the foundation is the hydrological profile of an area (Junk et al. 1989), which affects its physiochemical environment, including the soil, which, together with the local hydrology, determines which part and how much of the biota, including the vegetation, is found in a given floodplain (Mitsch et al. 2009). According to Meybeck (2003), river catchments and river floodplains in particular are exposed to changes in land use and more pronounced anthropogenic transformation of water and biogeochemical cycles. Rivers and floodplains are situated in landscape depressions, into which a range of substances with anthropogenic modifications and impact are transferred and accumulated (Wagner et al. 2009; Kiedrzyńska et al. 2014a, b), e.g. sediments and nutrients (Altinakar et al. 2006; Magnuszewski et al. 2005, 2007; Kiedrzyńska et al. 2008a, b), dioxins (Urbaniak et al. 2012, 2014a, b) and microbial contamination (Mankiewicz-Boczek et al. 2006; Gągała et al. 2010). These dramatically progressing disturbances are often negatively amplified by changes in the hydrological cycle and the loss of integrity between fluvial ecosystems and floodplains, which result in drastically increased eutrophication and a reduction in biodiversity and ecosystem services for society.

4 Flood risk assessment and management

At present, the success of sustainable catchment management depends on a profound understanding of the whole range of two-dimensional processes involved (Zalewski and Wagner-Łotkowska 2004). The first dimension is temporal: spanning the time frame from past, paleohydrological, conditions till the present, with a due consideration of future, global change scenarios. The second dimension is spatial: understanding the dynamic role of river and floodplain biota over a range of scales, from the molecular to the valley scale. Both dimensions should serve as a reference system for enhancing the buffering capacity of floodplain wetlands as ecosystems playing a key role in water retention and flood protection, as well as the reduction in nutrients and other pollutants, which are transported by river to downstream water ecosystems by flood sedimentation and nutrient retention, contributing to the improvement of river water quality.

A key assumption in all river management schemes is that the area of natural floodplain should remain intact along the entire river from the source to the mouth. Natural floodplains act as safety valves during floods, where water can be poured without causing serious harm to the human economy. Recent floods have demonstrated the additional role played by different human factors and anthropogenic activities, such as intensive urbanisation (Gardiner et al. 1995). The flood risk is generated by changes in the land use of

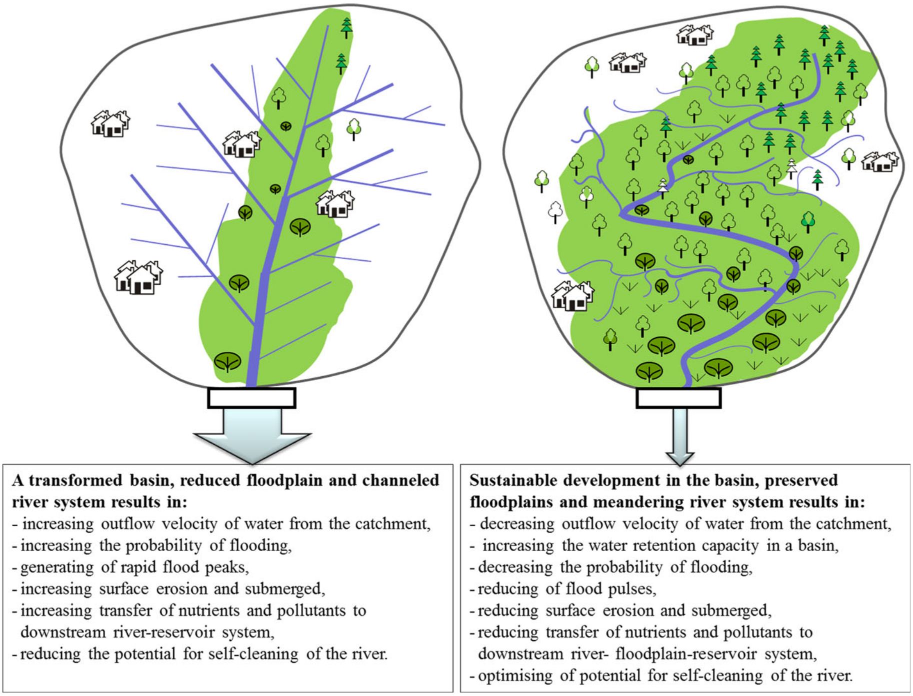

Fig. 1 The role of the character of the catchment-floodplain-river system in the probability of flooding, water quality improvement and good ecological status of the basin

catchments and multi-mosaic character of river floodplains (Fig. 1), which have caused the imbalance and transformation in their natural function as a storage and conveyance system for water, nutrients and sediments.

At present, highly modified river catchments with intensive building development or whose areas have been sealed result in outflow acceleration and reduction in water retention time in a catchment, which, in the face of global climate change, result in frequent occurrences of catastrophic floods and drought (Fig. 2).

Many studies report that while, on the one hand, the main factors driving run-off decline in most river basins are human activity in river catchments and climate change, but on the other hand, specific meteorological and hydrological situations, and changes in catchment land use, also lead to accelerated run-off and catastrophic floods (Vorosmarty et al. 2000; Kundzewicz et al. 2007; Barnett et al. 2008; Yang and Tian 2009).

As the capacity of air to hold water vapour increases exponentially in a warming climate, water can be recycled at an accelerated rate (Huntington 2006), potentially causing more frequent extreme hydrological events (Chang and Jung 2010). River flow characteristics based on the local climate depend on individual catchment characteristics. Catchment geology, elevation and land use are first-order controls which modulate the response of the timing and magnitude of basin run-off to climate change most strongly. According to Chang and Jung (2010), if a drainage basin is located at a low elevation and is dominated by rainfall, run-off change is controlled more by changes in precipitation than temperature, while basins located in high elevations with snowmelt-dominated regimes are highly sensitive to temperature changes (Loukas et al. 2002; Hamlet and Lettenmaier

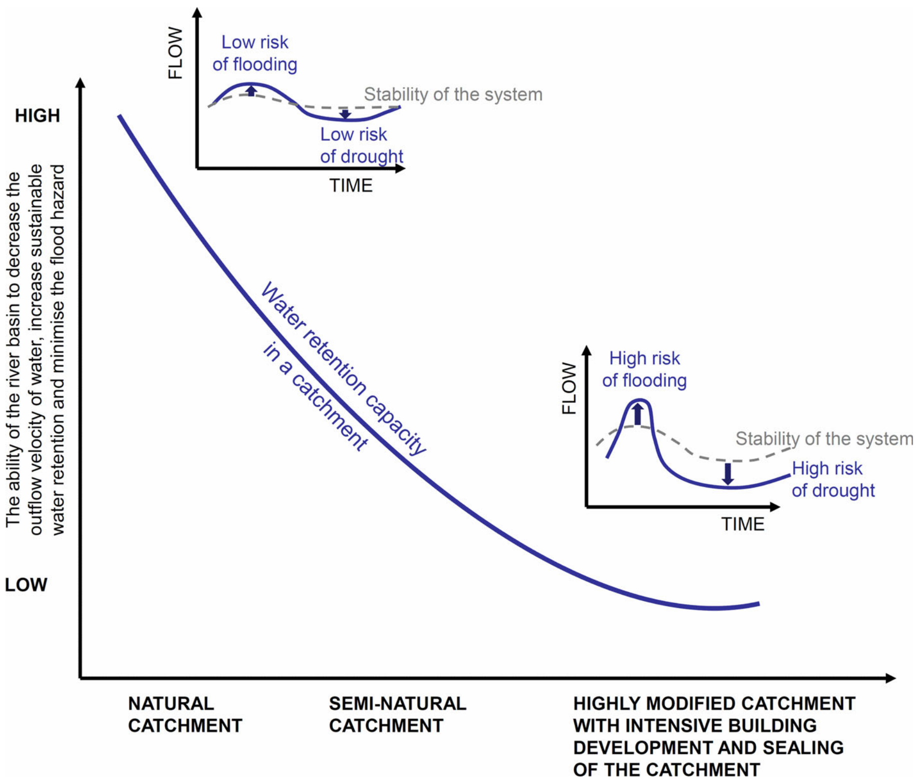

Fig. 2 Impact of catchment characteristics on the outflow velocity of water, water retention capacity and occurrence of catastrophic floods and drought

2007). However, a comparative modelling study in Oregon's Cascade Range between one basin that has a large component of groundwater and another basin that is run-off dominated indicates that basins in which a significant proportion of the streamflow comes from groundwater may be less sensitive to changes in climate (Tague et al. 2008; Chang and Jung 2010). An analysis of human-induced changes in the hydrology of the Western USA by Barnett et al. (2008) indicates that the hydrological cycle changed significantly over the last half of the 20th century. The results show that up to 60 % of the climate-related trends of river flow, winter air temperature and snow pack between 1950 and 1999 are human induced. Understanding the role played by human activity in shaping the land use in river catchments, as well as changes in the hydrological cycle made by spatial and temporal variations of run-off in the catchment, is especially important for water resource management and flood risk assessment.

Flood events with high magnitudes of flow represent a hazard. Most studies on the consequences of extreme flood events focus on the damage to buildings and infrastructure caused by water, without including the transport of pollutants: sediments, nutrients, micropollutants and bio-contaminants. Meanwhile, many hazardous substances bound to sediments are also deposited and represent a major threat to people, especially to children, as well as to livestock and wildlife, plants and soils. The contaminants transported by flood waves are observed to have negative effects, especially after the 2002 flood in the Elbe River basin (Geller et al. 2004) and in 2010 in the Vistula and Oder River basin.

Flood risk analysis should be based on hydrological and hydraulic models, which quantify such factors as the discharge, water level and flow velocity, among others. Their outputs should be and in most catchments are integrated with investigations on flood vulnerability and economic classifications of the damage. For example, in the USA, a new decision support system based on realistic two-dimensional flood simulations has been developed for integrated flood management within the framework of ArcGIS (Qi and Altinakar 2011). The authors argue that this system has the ability to interact with and use classified Remote Sensing (RS) image layers and other GIS feature layers like zoning layer, survey database and census block boundaries for flood damage calculations and loss of life estimations. According to Qi and Altinakar (2011), this new system provides a very versatile and reliable environment for estimating various types of flood damage and may greatly enhance the decision-making process in the future.

Risks are ultimately calculated as the likely damage for a certain time span, which can then be displayed on risk maps (Sauer et al. 2007). The management and mitigation of flood risk are very often perceived sectorally and mostly in technical terms. Standard management in a river valley aimed at minimising the flood hazard events include the pre-flood, flood emergency and flood recovery activities described below.

1. According to Stancalie et al. (2006), prevention activities are as follows:
   - Establishment of evacuation routes, critical decision thresholds, public service and infrastructure requirements for emergency operations, among other things;
   - Construction and maintenance of technical flood defence infrastructure and implementation of forecasting and warning systems;
   - Land use planning and management within a catchment;
   - Public communication and education on the risk of flood and actions to be taken in a flood emergency;
2. Operational flood management includes (Stancalie et al. 2006):
   - Determination of the likelihood of a flood, tracing its development and forecast of future river flow conditions;
   - Issuing warnings to the appropriate authorities and the public on the extent, severity and timing of the flood;
3. The necessary activities after the flood are as follows:
   - Aid for the immediate needs and reconstruction of damaged buildings, infrastructure and flood defence, and recovery of economic activities in flooded areas;
   - Review of the flood management activities to improve the process and planning for future events in the area affected (Stancalie et al. 2006).

The range of options available to manage flood hazards is theoretically large. However, floods still bring devastating consequences, because of technical, political, economic, social and environmental constraints (UNISDR 2013). The knowledge of past catastrophic events can improve the flood risk mitigation policy through building adequate institutions, improving education and raising awareness against risk. A wealth of historical information is available in Europe and the USA from the past five centuries, and hydrologists can incorporate information on past floods into an adapted probabilistic framework (Coeur and Lang 2008). According to Coeur and Lang (2008), two suggested courses of action, already in use in many catchments, concern the use of historical information in education and promotion activities concerning flood risk management: (1) the development of a regional flood data base, with both historical and current data, in order to better evaluate recent events and to improve flood risk education and awareness; (2) obtaining the commitment for persistent and perennial management of a reference network of hydrometeorological observations for climate change studies.

According to Abbott (1996, 2007) and Vojinović and Abbott (2012), the socio-technical nature of water problems arises from the multiplicity of stakeholders and their diverse interests and attitudes. The authors emphasise that very often stakeholders are excluded from participation in the development of their water and flood protection infrastructure. Therefore, the authors recommend, among other things, the use of "hydroinformatics" as a holistic approach to the analysis of the problem of flood risk management (Abbott and Vojinovic 2014). In this approach, "hydroinformatics integrates knowledge from the social and technical domains to create so-called conjunctive knowledge, that is concerned with an understanding of how technical interventions have social consequences and how the resulting social changes in turn generate new technical developments" (Vojinović and Abbott 2012). This paradigm provides a completely transparent system of decision-making in matters of flood risk management and brings together all stakeholders.

Nowadays, a holistic, structural set of activities is required, approached in practice on several fronts with the appropriate institutional arrangements in place, to deliver the agreed standard services of the community at risk (Samuels 2004). We argue that a suitable holistic conceptual tool is Ecohydrology. Its hydrological, ecological and ecotechnological principles (Zalewski et al. 1997; Zalewski 2006) can be used to develop a sustainable approach aimed at minimising the flood risk in a given catchment and managing river floodplain systems. The introduction of ecohydrologically sustainable floodplain management is necessary for the restoration of natural floodplain areas in river valleys. In addition, it is important to implement mechanisms for increasing the retention of water and matter in the landscape and closing the nutrient and energy flow cycles, which determine the correct functioning of floodplain ecosystems in a catchment.

5 Ecohydrology for flood protection and management and water quality improvement

5.1 Ecohydrological background

Ecohydrology (EH) is a sub-discipline of Hydrology that focuses on the ecological processes occurring within the hydrological cycle and strives to utilise such processes for enhancing the environmental sustainability of terrestrial and aquatic ecosystems (Zalewski et al. 1997; Zalewski 2011; Zalewski 2014a, b). Ecohydrology provides a scientific understanding of the hydrology/biota interplay, and a systemic framework of how to use ecosystem processes as a tool for Integrated Water Resources Management (IWRM), complementary to ecological engineering and applied hydrotechnical solutions. The key questions posed by EH concern the hierarchy of factors regulating the dynamics of hydrological and biological interactions and the means by which EH can be used to solve environmental and societal problems with reference to Integrated Water Resources Management (IWRM) and in the scope of policies such as the European Water Framework Directive (WFD EC, 2000). The role of Ecohydrology in the implementation of the Sustainable Floodplain Management and the Water Framework Directive (WFD) is to facilitate to development of scientific methodologies, whose task is to achieve a "good ecological status" for catchment-river-floodplain ecosystems by stimulating progress in the environmental sciences and enabling a better understanding of their processes. Ecohydrology provides three principles which can be used as a framework for scientific investigation and implementing problem-solving strategies (Zalewski 2011). These can be adopted and used for sustainable management of river floodplain ecosystems, flood protection, water quality improvement and achievement of 'good' ecological status of catchment-floodplain-river systems.

1. *The hydrological principle* The quantification and integration of hydrological and biological processes at the basin scale is based on the assumption that abiotic factors are of primary importance and become stable and predictable when biotic interactions start to manifest themselves (Zalewski 2011, 2014b). The quantification of hydrological pulses along the river continuum (Vannote et al. 1980; Junk et al. 1989; Agostinho et al. 2004; Altinakar et al. 2006; Kaczorowski et al. 2006; Magnuszewski et al. 2007; Kiedrzyńska et al. 2008b) and monitoring of floods (Fendler 2008; Kiedrzyńska et al. 2008b; Glaser et al. 2010; van Pelt and Swart 2011) and threats (Mankiewicz-Boczek et al. 2006; Izydorczyk et al. 2008; Urbaniak et al. 2012, 2014a), such as point and non-point source pollution (Takeda et al. 1997; Borah and Bera 2003; Tian et al. 2010; Urbaniak et al. 2014b; Kiedrzyńska et al. 2014a, b), are necessary for optimal regulation of processes towards sustainable water and ecosystem management.
2. *The ecological principle* The ecological principle is based on the assumption that under intensive global changes, it is not enough to protect ecosystems against increasing human population, energy consumption and aspirations. It is necessary to regulate ecosystem structure and processes to increase the carrying capacity of ecosystems (Kyushik 1998; Kang and Xu 2010; Zhang et al. 2014; Wang et al. 2014), which is their evolutionarily established resistance and resilience, in order to reduce anthropogenic impacts (Zalewski 2002, 2009, 2011). This can be achieved by restoration of floodplain areas along the river continuum, retention of flood water in natural and constructed floodplains and regulation of the interplay between hydrology and biota. An analysis of the dynamic oscillations of an ecosystem and its productivity and succession, as reflected by flood water and nutrient/pollutant absorbing capacity versus human impacts, should be the basis for the regulation of processes (Kiedrzyńska et al. 2008b; Zalewski 2011).
3. *The ecotechnological principle* The use of ecosystem properties as a management tool is based on the first and second principles of EH and is related to ecological engineering. This principle comprises three steps of implementation: (a) 'dual regulation'—the regulation of biota by hydrology and, vice versa, the control of hydrology by shaping the biota or controlling interactions (b) the integration of various types of biological and hydrological regulations at the basin scale to achieve the synergy needed to increase the flood water retention in floodplains and improve water quality, biodiversity and freshwater resources (c) harmonisation of ecohydrological measures with such necessary hydrotechnical solutions as dams, irrigation systems or sewage treatment plants (Zalewski 2011).

"Dual regulation" is applied in the shaping and management of processes in river floodplain wetlands. It is used to increase the water retention capacity in a basin and flood water retention in a floodplain, as well as to improve purification and water quality, conserve biodiversity and develop ecosystem services for society. The biotic component of a floodplain ecosystem, i.e. the trees, shrubs, macrophytes, algae and bacteria within it can control and affect the chemical parameters of the water, and additionally, plants can control hydrologic and hydraulic processes by affecting the roughness of the substrate.

These relationships also occur in the opposite direction, that is, hydrology can be used in the regulation of biota (Zalewski 2006; Kiedrzyńska et al. 2008b; Zalewski and Kiedrzyńska 2010). The great potential of the knowledge which has been generated by the dynamic development of ecological engineering (Mitsch 1993; Jørgensen 1996; Chicharo et al. 2009), should, to a large extent, accelerate the implementation of the above concept.

Ecohydrological system solutions in a river valley based on these management methods, as well as the social and economic challenges and opportunities concerning water use, can contribute to better environmental quality, and also to the overall well-being of a region and its sustainability (Wagner et al. 2009; Kiedrzyńska et al. 2014b).

5.2 Ecohydrology for flood prevention and management

The development of Flood Prevention and Management (FPM) strategies, aimed at reducing the chance of flood events and improving water quality, is a long-term process that: (1) first—requires a change in thinking from the technical to the ecohydrological, and an appreciation of the value and capacity of natural ecosystems; (2) secondly—requires a change in the mode of action from a narrow to a multi-faceted sector, which uses the latest knowledge and high-performance digital technology.

Effective FPM will be made possible by several strategic activities and sustainable planning and management within the whole catchment in order to increase the water and pollutant carrying capacities in floodplain ecosystems:

1. An increase in the mosaic character of a catchment, in each of its upper, middle and lower parts;
2. Extension of ecotone buffer zones, which slow down the water run-off from a basin to river ecosystems and further restrict the transfer of pollutants through phytoremediation processes (phytoaccumulation, phytodegradation, phytostabilisation, rhizofiltration, rhizodegradation (Singh and Ward 2004; Bieniecki and Kiedrzyńska 2006; Bhandari et al. 2007; Sumorok and Kiedrzyńska 2007; Sumorok et al. 2008; Kiedrzyńska et al. 2008b; Skłodowski et al. 2014) that are especially intensive in ecotone zones;
3. The development of actions and technologies to increase the permeability of water catchments and to reduce its ability to retain water over large areas (e.g. the use of materials partially permeable to water for the construction of parking lots, the collection of rainwater in specially created reservoirs);
4. Increasing the water retention capacity throughout the whole area of the river catchment by the following activities: forestation, agrotechnology activities, river restoration, restoration of wetlands and creation of new ones and the use of water harvesting devices in rural areas, as well as by building cascade systems of flood reservoirs preceded by sequential biofiltering systems in urban areas;
5. Defining a restrictive limit for residential and economic development in river floodplains;
6. In many countries, a National Action Plan Against Flooding (NAPAF) for national catchments has been developed in case of local flooding. Furthermore, in the case of catastrophic floods covering many countries, a Transboundary Action Plan Against Flooding (TAPAF) exists for effective prevention and action. An example of such activities is the transboundary water management programme in the Danube River Basin, organised within the scope of the Convention on Cooperation for the Protection and Sustainable use of the Danube River (Danube River Protection Convention—DRPC), which was signed in 1994 in Sofia, Bulgaria by ministers of all Danube

countries. However, no Transboundary Action Plans Against Flooding exist for catchments of many transboundary rivers in locations such as Eastern Europe or Asia. It is important to note that flood responses are extensively integrated into the plans and include guidelines for operational management based on permanent monitoring of the meteorological and hydrological situation and estimating the likelihood of flood generation.

The methodological background for elaboration of an Action Plan for FPM, in order to minimise the flood hazard and to improve the water quality, includes the following five phases (Fig. 4):

1. *Monitoring of catchments* Understanding the structure, states and relationships, and quantifying any processes and threats by using knowledge derived from GIS information (Kiedrzyński et al. 2014a; Magnuszewski et al. 2014) for problem-solving.
2. *Ecohydrological evaluation of floodplains* Assessment of the ecohydrological state of a floodplain and the potential for flood water retention and water quality improvement.
3. *Carrying capacity and regulation of the process* Ecohydrological regulation and increasing the carrying capacity of floodplains for flood water and nutrient retention to reduce the risk of flooding and improve the water quality;
4. *Evaluation of the functioning of the system solutions* Evaluation of ecohydrological activities in floodplains and correction of solutions for their optimisation—adaptive assessment and management (Holling 2005). According to Holling (1978), Arrow et al. (1995), adaptive management views regional development policy and management as “experiments”, where interventions at several scales are made to achieve understanding, to produce social or economic products and to identify options.
5. *Ecohydrological sustainable management of floodplains* Preparing a plan for the Sustainable Ecohydrological Management (SEM) of river floodplains, which function in the optimal “dynamic equilibrium”, taking into account the constant adaptation to climate change and socio-economic development which takes place. Formulation of principles for future actions (Fig. 3).

Flood risk analysis and the assessment of hazards requires a multidisciplinary approach and the integration of many sources of information combining geomorphological and landscape-use analysis with meteorological and hydrological analysis, as well as the use of tools such as Satellite Images (SI) and Geographical Information Systems (GIS) to create models (Fig. 3).

The following info-layers are important components of any integrated GIS database: sub-catchment and catchment limits, a digital terrain model (DTM), the hydrographic network, the dyke and canal network, the hydrometric station network, the meteorological station network, the rain-gauging network, the transport infrastructure network (roads, railways, airports), localities, land cover and land use updated from a satellite and previous flood extents (Stancalie et al. 2006). Flood surveying, optical and radar can provide up to date geographical information. This information, integrated with the GIS data and with the information on flood generation, is helpful in determining the flood hazard and the raised water stage. The image enables the description of the land cover of the studied area under normal hydrological conditions and during flooding. Calibrated images provide information on inundated zones, flood map extent, flood evolution and the period after flooding: the satellite image indicates the flood’s effects, showing the affected areas, flood deposits and debris (Stancalie et al. 2006).

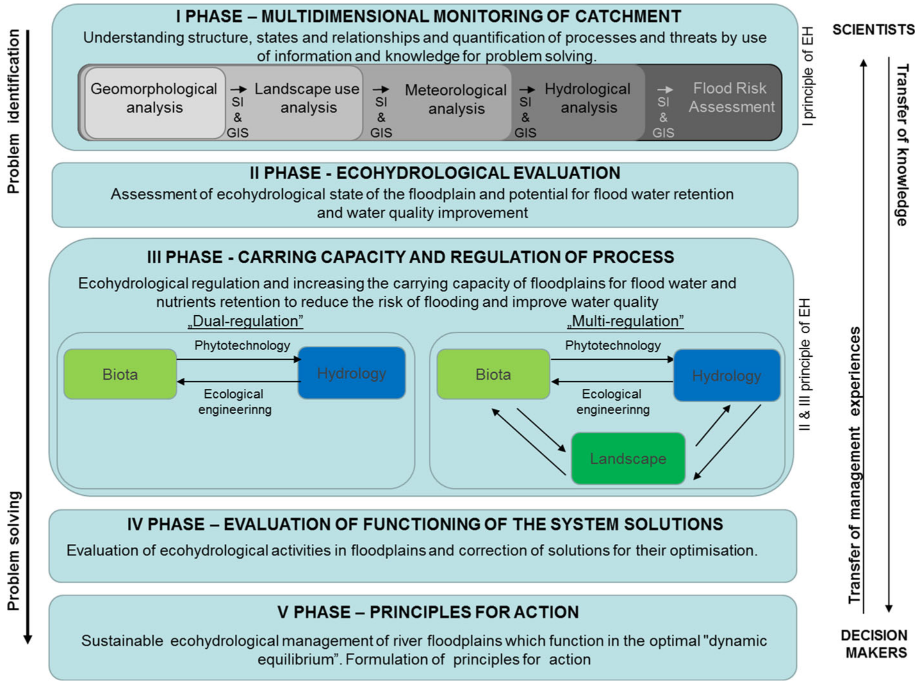

Fig. 3 Methodological background for flood prevention and adaptive management of floodplains and improve the water quality in river catchments

According to Brakenridge et al. (1998), the methodology for identification, determination and mapping of areas affected by floods is based on a range of classification procedures based on optical and radar SIs. Undoubtedly, a great advantage of using the high resolution optical satellite images is the possibility of selecting precise spatial information regarding a given area through merging images and to locate and define the flooded or flooding-risk areas through digital classifications. However, radar images can provide useful information on flooded areas, even during periods with abundant rainfall. Multi-temporal image analysis combined with land use and land cover information allow the identification of areas covered by water (e.g. permanent water bodies) and then flooded areas (Stancalie et al. 2006).

Specific methods for deriving satellite-based applications and products for flood risk mapping such as land cover/land use maps, thematic maps of flooded areas and affected zones and flooding-risk maps (Stancalie et al. 2006) have been under development for several years in the framework of NATO projects (e.g. Monitoring of extreme flood events in Romania and Hungary and other countries). Satellite-based applications will doubtlessly contribute to the prevention of extreme flood events by facilitating more judicious planning of land use development, by elaborating plans for flood mitigation, including infrastructure construction in flood-prone areas, and by optimising the facilities for the distribution of flood-related spatial information to end users. At the same time, it is important to provide the decision-makers with updated maps of land use/land cover and a hydrological network, and with more precise and accurate comprehensive thematic maps at various spatial scales with the limits of flooded areas and affected zones (Balint 2004; Stancalie et al. 2006).

Furthermore, the forecasting work performed by teams of experts following the foresight methodology (Zalewski 2008; Rogut and Piasecki 2011) is very important for enhancing sustainable floodplain development, as well as flood prevention and management. Foresight is defined as "a process of the discovery of a common space for open thinking on the future and the incubation of strategic approaches" (Popper 2008). Foresight methodology is an example of a system approach to evaluation of new trends, based on knowledge of environmental, sociological processes and technologies from the perspective of the economy, quality of life and sustainable development (Zalewski 2011).The exchange of knowledge, experience and views among scientists, representatives of industry and business and public officials (Fig. 3), systematises and integrates our awareness of the most important fields of science and the economy. The foresight methodology can be used for sustainable management of river floodplains and floods. In this context, foresight is based on a knowledge of environmental, sociological processes and technologies in terms of economy, quality of life and sustainable development. This will be possible through the following measures (Zalewski 2008, 2011):

1. Forecasting the future enables adaptive attempts to be undertaken, such as by expansion of the area and improvement of carrying capacity of floodplain ecosystems, preparation to be made for unpredictable events, and reduction in negative consequences of events that cannot be changed,
2. Management of the future involves proactive management of probable crises and positive management by goals,
3. Creation of the future involving the proactive creation of a necessary future vision.

Directly, Flood Directive (2007/60/EC) and, Water Framework Directive (2000/60/EC), and also indirectly Habitat Directive (92/43/EEC) and, Bird Directive (2009/147/EC) by protection of wetland areas, could use and introduce this proposed methodology for Flood Prevention and Adaptive Management of floodplains (Fig. 3) and improve the water quality in river catchments.

5.3 Floodplains for water quality improvement

The importance of natural river floodplains and ecotones for river self-purification and water quality improvement has been discussed by Bayley (1995), Zalewski (2006), Mitsch and Gosselink (2007), Kiedrzyńska et al. (2008a, b), Kiedrzyńska and Zalewski (2012), Skłodowski et al. (2014). River floodplains can absorb and retain sediment, nutrients and micropollutants such as dioxins during stable hydrological conditions, and especially when water retained during floods. Therefore, floodplains and ecotones can be considered as a tool for their reduction along the river continuum (Kiedrzyńska et al. 2008a, b; Urbaniak et al. 2012; Skłodowski et al. 2014). As the largest loads of pollutants transported by rivers usually occur during the rising water stages of floods, their redirection to floodplain areas upstream from a reservoir at the very initial stages of the flood would diminish the load on a reservoir.

The ecohydrological research in central Poland on the Pilica River floodplain assessed the possibilities of enhancing this process, both through sedimentation (Altinakar et al. 2006; Magnuszewski et al. 2007; Kiedrzyńska et al. 2008a) and assimilation in the vegetation biomass (Kiedrzyńska et al. 2008b; Skłodowski et al. 2014). The research, based on DTM and hydraulic models, demonstrated that sedimentation of flood sediments in the floodplain essentially reduces their transport to the local lowland reservoir. Flood sediments were effectively deposited and phosphorus was retained in the 30-km section of the Pilica River natural floodplain. In the flooding area of 1,007 ha, fine grained flood sediments reached 500

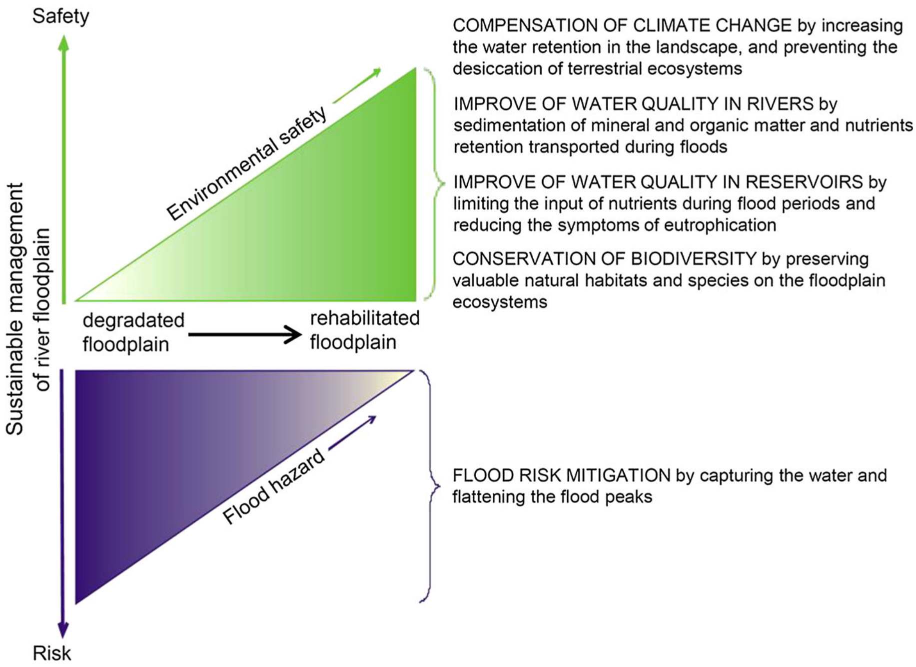

Fig. 4 Outputs of the sustainable floodplains management in the ongoing and expected changes of climatic conditions

t and the retention of P was 1.5 *t* (Kiedrzyńska and Zalewski 2012). An ecohydrological study conducted in relation to a hydroperiod showed that the efficiency of nutrient assimilation and biomass production by autochthonous plant communities, with a special emphasis on willow patches, was high. Vegetation in the Pilica River floodplain (26.6 ha) in summer accumulated 255 kg of phosphorus (P) year^{-1}; however, a conversion of 24 or 48 % of the area into willow patches can increase phosphorus retention up to 332 or 399 kg P year^{-1}, respectively (Kiedrzyńska et al. 2008b). Theoretically, 1 kg of P can lead to the accumulation of some 1–2 *t* of toxic algal biomass in a reservoir (Zalewski 2005). Based on these studies, and the literature, it can be said that floodplain wetlands are mostly enriched with riverine material and, at the same time, the river water is purified by its deposition. Therefore, river floodplains act as cleaning and biofiltering systems for reducing the concentrations of sediments, nutrients and other pollutants coming from the whole catchment area.

A more proactive approach to environmental river engineering and river floodplain rehabilitation and restoration would have many positive effects for the inhabitants, on both local and regional scales (Fig. 4), as would the management of river valleys and floodplains which preserve their potential for flood prevention, as well as their ecological and aesthetic functions.

6 Conclusions

1. As the management of flash floods is limited and risks severe consequences, flood prevention is a better course of action. A similar situation exists regarding water

quality. The process of river self-purification and water treatment in natural floodplains, where floodwaters are retained and treated, reduces the risk of flooding, and is preferable to incurring the very high costs resulting from eliminating the economic, ecological and bacteriological contamination resulting from flooding as well as its social effects.

2. The development of an action plan for flood prevention and management, and water quality improvement is a long-term process that requires:
   (a) A change from technical to ecohydrological thinking and an appreciation of the potential of natural floodplain ecosystems;
   (b) Restoration of river floodplains for minimising the flood risk from flash floods;
   (c) Restoration of floodplains to increase water capacity, and capacity for the retention and self-purification by retention of sediments, nutrients and other pollutants;
   (d) A change in the mode of action from a narrow to a multi-faceted sector, which uses the latest knowledge and high-performance digital technology.
3. Ecohydrology could increase the efficiency and effectiveness of measures taken for flood prevention and water quality improvement by the following steps:
   (a) The first concerns the hydrological principle of EH, a holistic catchment and a floodplain approach—quantification of hydrological patterns, flood pulses in the river continuum from source to estuary;—the quantification of nutrient and pollutant fluxes in different parts of a catchment with consideration of this distribution in various forms of impact (e.g. agricultural, urbanised, industrial).
   (b) The second relates to the ecological principle of EH—how ecosystems are distributed in a basin, especially high natural value ecosystems and 'novel ecosystems' developed through secondary succession, because this is important for the water basin budget and water and nutrient retention.
   (c) The third concerns the ecotechnological principle of EH. This refers to analyses of water resource distribution and the characteristics of floods in a basin with respect to human impact and 'novel ecosystems' that can be modified, the use of 'multi-regulation' methodology (Fig. 3) to increase the water retention in a basin, prevention of floods, upgrading the ecosystem potential and services, and achieving good ecological status of a catchment.
4. Long-term watershed management, where floodplains are ecosystem mosaics of high biodiversity and great biological value due to the scale and diversity of processes, has to be based on foresight methodology and a consideration of learning alliances, which encompasses cultural heritage protection and society's aspirations and is crucial for the development of bioeconomy supporting the sustainable future.
5. The exchange of knowledge, experience, and views among scientists, public officials and representatives of industry and business, systematises and integrates our awareness of sustainable watershed and floodplain management, and is necessary for the identification of problems related to floods and water quality, and their solutions.

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