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Review Article

The Impact of Floods on the Structure and Functional Processes of Floodplain Ecosystems

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1. Abstract

Floodplains are among the most endangered ecosystems in the modern landscape. Due to changes in land-use and river regulations, about 10 % of their global original area has left. The increasing magnitude and frequency of river flash floods caused by global climatic changes represent a further and significant disturbance factor that affects the remaining riverine ecosystems. However, floodplains play important beneficial socio-economic and ecological functions in the landscape and they deserve protection and restoration. This contribution provides a short review of our knowledge about river floodplains, their distribution, and structure and ecosystem services. Special attention is given to the negative impacts of river regulation on the biodiversity, structure and functions of river floodplain ecosystems. The effects of inundation stress and flood disturbances on riverine floodplains at various structural and functional ecosystem levels, such as vegetation, plant metapopulations and plant physiology and properties of floodplain sediments, their pollution loads and soil microbial activities are also shortly summarized. The contamination of floodplain sediments by conventional and modern types of pollutants represents a serious threat not only for edaphon and animal compartment of riverside ecosystems but also for sustainable utilisation of the floodplains by local riverine human populations. A better understanding of floodplains in the context of current environmental conditions can be utilised to develop new protection and rescue programmes to enhance the ecological stability of landscapes and mitigate and adapt to the effects of climate change.

2. Keywords

Ecosystem Structure and Functions; Floods; Floodplain Ecology; Flood Sediment Characteristics; Plant and Soil Biology

3. Introduction

The frequency and magnitude of floods have been increasing as a consequence of global climatic changes. According to the EM-DAT International Disaster Database, floods were the most frequent (43%) type of disasters worldwide between 1994 and 2013. Floods affected 55% of the population impacted by disasters, and represented 12% of all disaster-related deaths. The average annual direct flood costs in Australia from 1967-2005 were estimated at $377 million (2008 Australian dollars), and the increasing magnitude and frequency of floods has led to recent cost increases. Besides the unprecedented loss of human lives and damage to property, flash floods have damaged large areas along the lower reaches of big rivers. Technocratic (hard engineering) and/or ecological protective solutions are some of the currently considered promising solutions [1,2]. In order to maintain safe and sustainably exploitable landscapes along rivers, reliable data about the effects of irregular flash flood disturbances on abiotic and biotic environmental compounds and their interactions in the landscape are critical.

The banks of rivers consist of riverside wetland ecosystems that are adapted to annual and occasional extreme floods. Due to river regulation and changes in land use, however, the areas of original floodplains have shrunk, become fragmented or have even disappeared and been replaced by substitute ecosystems. The effects of flash floods on riverside ecosystems depend on the magnitude and frequency of the floods and the resistance and resilience of the affected ecosystems. Some answers associated with questions about the expected impacts of the extreme floods on remaining wetlands may be provided by floodplain ecology [3]. Many flood effects on landscape compartments have been obtained by studying past floods or in controlled laboratory experiments. However, our understanding is still limited. For example, flood sediments are an important constituent of floodplain ecosystems, but the impacts of flood sediment characteristics on wetland ecosystems, in particular their vegetation compartment, have been rather ignored by flood ecologists. The current frequent occurrence of extreme flooding episodes provides a unique opportunity to investigate the impacts of floods on riverside ecosystems at various organizational and functional ecological levels and in various geographical and climatic areas. Deeper insights and knowledge in this field is needed in order to formulate and implement policy-relevant strategies and effective socio-economic and environmental governance in areas endangered by floods. It is well known that wetlands provide many ecological services beneficial for riverine human populations, such as biomass production, soil formation, water regulation and cleaning, food and drinking water supply, recreation, etc., [4]. Extreme and frequent floods can negatively impact nearly every wetland ecosystem service. Wetlands are internationally protected and a search is underway for suitable techniques for floodplain restoration, decreasing the harmful impacts of extreme floods and improving decision-making that restricts floods to small controlled events that are beneficial for the riverside wetland ecosystems.

The goal of this contribution is to review the current knowledge of the effects of floods on floodplain ecosystems and illustrate the techniques used for floodplain ecosystem investigations. Many studies have dealt with this topic from the partial points-of view of hydrology, climatology, geomorphology, economics, biodiversity, etc. This review deals with floodplain ecosystems more in the context of historical river management, climatic change, the complex impact of floods on floodplain ecosystem compartments including vegetation and soil covers, the need to retain floodplain ecosystem services and floodplain ecosystem restoration. However, it is clear that the restoration of floodplains in the present systems of land tenure, maintenance and use will be a difficult issue. Moreover, floodplain ecosystem functions in restored floodplains are never fully re-established due to the lack of more complex data about the roles and interactions of individual ecosystem components and/or climatic change effects. This review provides information about the current knowledge of the structure and functions of river floodplain ecosystems and the impacts of anthropogenic and climatic factors on floodplain ecosystems, and points out knowledge gaps that need to be filled.

4. Ecosystems and their Benefits

4.1. The formation and distribution of riverine wetlands

Recent relative climatic stability caused a regular regime of water cycling and pulses of river flow rates within individual Earth climatic zones [5]. Irregular deviations in precipitation amounts can appear in the landscape and initiate extremes such as dry periods or large flash floods, thought increased deviations from the normal tend to occur with decreasing probability [6]. Based on long-term annual, decimal, vicennial, secular or five hundred year peaks in flow rates (from Q1 to Q500 flood magnitudes), the range of flooded zones along rivers are known from the historical experience of local populations or can be assessed through models, and the predicted flood lines depicted in maps.

In riparian habitats that have not been significantly anthropogenically altered, distinguishable belts of vegetation types or "shifting vegetation mosaics" corresponding with water levels can be seen along rivers. Ecosystems from ranging from the watercourse (lotic) through riverside wetlands (lentic, paludal) can be recognized, extending from the river bed towards elevated terrestrial sites with floodplain vegetation resulting from only occasional or "no" floods. Specific ecosystems have historically developed along rivers that adapt to or can tolerate the given regimes of ground and flood water fluctuations, which depends on the distance from the river. The similar morphological appearance of riverside vegetation zones commonly assembled from various taxonomic groups of vegetation (plant species, plant communities) is a common scenario reflecting the regime of regular flooding as a dominant environmental factor (concept of water/flood pulses formulated by WJ Junk and his colleagues at the end of the 1980s) in individual climatic zones of all continents. This phenomenon used to be called the "epharmonic convergence" in the beginnings of adaptation ecology. According to newer functional ecology concepts the riverine vegetation developed similar convergent morphologic structures (life-forms, functional or ecophysiological groups) enabling them to survive the effects of the water level gradient and flood pulses as the main ecological factor operating along all-natural rivers [7,8].

The concept of C-S-R plant strategies by Grime from the 1960s/1970s explains the species composition of vegetation structure as a result of the colonisation of an area affected by flood stress (e.g., inundation) and flood disturbance (e.g., mechanical damage) only by those species that have developed suitable life strategies to survive the given stress and/or disturbance loads [9]. In the present literature, hard and soft adaptive or functional "traits" (e.g., architectonical, physiological, biochemical, phenological, etc.) are used to describe species adaptation abilities to survive in given ecological niches [10,11]. The structure and function of natural river floodplain ecosystems in various climatic zones have been generally well described in many publications [12-14].

The virgin Amazonian catchment system has provided a rare opportunity to study tropical floodplain forests of high species richness and very complex relationships among ecosystem components during both the flood and dry seasons. Numerous study cases and specific interactions between biotic and abiotic factors operating during regular Amazon River floods have been found and documented [15-17].

On the other hand, in Arctic-alpine regions only very narrow and irregular riverine vegetation zones of small biodiversity appear along the upper parts of rivers, mainly due to the strong mechanical disturbance effects of waterflow on river banks and short vegetation seasons for vegetation recovery [18,19].

Floodplain ecosystems are traditionally looked at as a transition zone between local fluvial and terrestrial biomes, called an ecotone. The ecotone concept generally supposes increased biodiversity in this interface zone because it can provide a habitat suitable for many species that occur in neighbouring ecosystems. However, another approach the idea of a distinguishable transition zone between the "dryer" and "wetter" zones of a river valley is rejected, rather emphasising the spatiotemporal fluctuation of the water level and the continual gradient of decreasing water potential in soil covers with distance away from a river bed (a water content continuum concept). Hence there cannot be any discrete transitional zone along the fluent water gradient and so no reason to find a peak of significantly increased species diversity anywhere along this gradient [20,21]. The power of modern methods of ecological gradient transect analyses could help resolve this issue.

Figure 1 shows typical vegetational zonation along large river floodplains in central and Western Europe caused by the local water level regime and modified by historical land use.

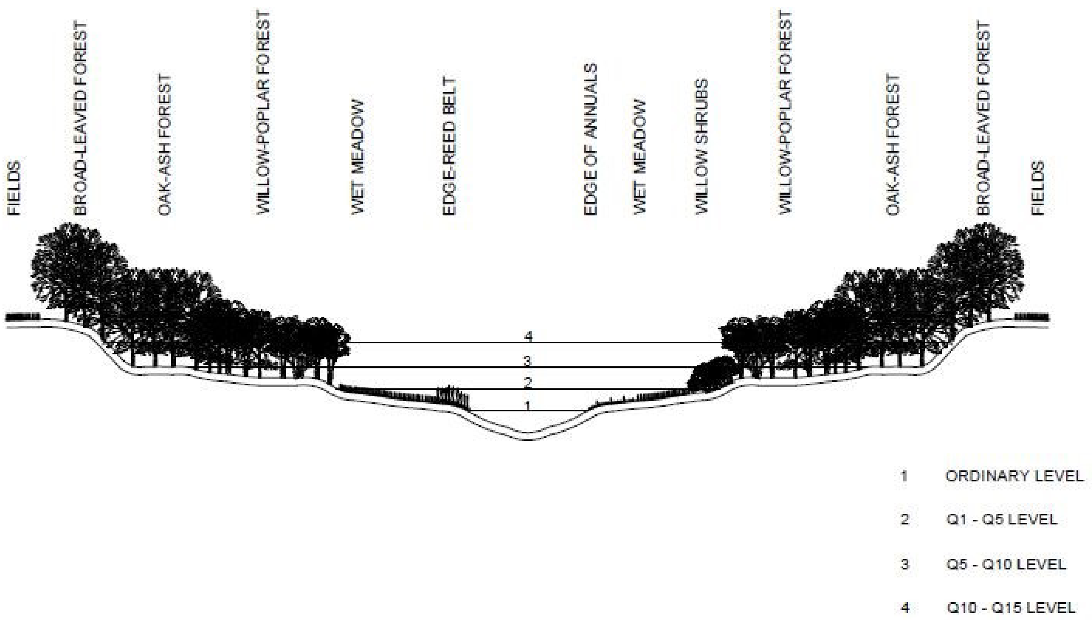

Figure 1: The diagram of riverside vegetation zones along big rivers in central and Western Europe reflecting the water gradient and flood regimes with the increasing elevation (distance from the river): pioneer, usually annual bank vegetation; sedge and reed vegetation; anthropogenic wet meadows; remaining softwood and hardwood forests and economic forest or fields.

4.2. Beneficial functions of floodplain ecosystems

Floodplains play many socio-economic and ecological functions that are directly or indirectly beneficial for the local human population and the landscape. Particularly in the present time, when the landscape suffers from undue exploitation and the impacts of global climate change, wetlands play an irreplaceable role in landscape ecological stability. Since the 1990s these beneficial functions have been frequently called "ecosystem services" [22]. The riverside vegetation cover can serve as a buffer zone, for example, slowing storm water runoff, attenuating flood pulses, the aggradation of eroded materials, improving water quality by filtering and nutrient uptake, stabilising river banks and soil cover against water erosion, preventing excessive water surface evaporation and air temperature amplitudes via shading, and accumulation of organic carbon (carbon sequestration). Each ecosystem service can be quantitatively measured and valued by relevant indicators, for example, soil cover protection by the volume of retained soil covers or improvement of water quality by achieved chemical parameters of water.

Plant species inventories have revealed significant plant species diversity in natural floodplain ecosystems. Many plant species found in floodplains are very rare and endangered in the given regions or even globally. Other species bound, for example trophically, to these rare wetland species are also restricted in their occurrence to such biotopes (refugia). Searching for biological interactions of such rare species (mutualism, commensalism, amensalism, parasitism) can provide new data and mainly help in the preparation of programs for the conservation of these rare species [23-25].

Besides the positive hydrological, biogeochemical, ecological and microclimatological effects, riverside wetlands can also provide economic and social services, for example as possible sources of water, wood or fodder, and recreation, cultural and educational purposes [26,27]. The dollar value (1997) of wetlands worldwide was estimated to be $14.9 trillion [26]. However, it should be cautioned that the unsustainable use of these ecosystem services or increasing negative environmental factors can result in new pressures on these wetland ecosystems. Table 1 shows how selected environmental pressures can likely impact floodplain ecological services.

Ecosystem services	Flow modifications	Diffuse and point pollution	Groundwater salinization	Erosion Brownification	Hydrpmorphological alterations	Alien species
Provisioning						
Water for drinking	●	●	●	●	◐	○
Raw (biotic) materials	◐	●	○	◐	●	●
Water for non-drinking purposes	●	●	●	●	◐	○
Raw materials for energy	●	●	○	○	●	◐
Regulation and maintenance						
Water purification	●	●	◐	●	●	◐
Air quality regulation	●	●	○	○	◐	○
Erosion prevention	●	○	○	○	●	◐
Flood protection	●	○	○	○	●	◐
Maintaining populations and habitats	●	●	○	◐	●	●
Pest and disease control	●	●	○	◐	●	●
Soil formation	●	◐	○	●	●	○
Carbon sequestration	◐	○	○	◐	●	◐
Microclimate regulation	●	○	○	○	●	○
Cultural						
Recreation	●	●	○	●	●	◐
Intellectual and aesthetic appreciation	●	●	●	●	●	●
Spiritual and symbolic appreciation	●	●	●	●	●	●

Legend. Expected impact: ●high, ◐ medium, ○ low.

Table 1: Expected impact of selected environmental pressures on floodplain ecosystem services [28].

5. Control of the Watercourse and River Floodplains

Big rivers have historically served as important transportation routes and fruitful floodplains along lower reaches, and have been intensively exploited, mainly for farming [29]. It is no wonder that the landscape along river valleys have been most affected by urbanization, industrialization and farming. Most riverside habitats in densely populated areas have been gradually changed by drying, logging, grazing and ploughing [30,31].

5.1. Positive impacts of river regulation

Attempts to control river water levels were historically intended to protect the lives of riverine human populations and properties, and advance local socioeconomic conditions [1,2]. For example, the deepening of river beds and the construction and elevation of embankments were done to protect areas from regular or unforeseen flooding episodes and to make shipping easier. However, the parallel enlargement of deforested and ploughed areas in catchments even far from the watercourse triggered the acceleration of rain water outflows from the landscape and increased flood magnitudes in river valleys. The increased negative economic impact of river floods initiated the further elevation of embankments and the deepening and channelization of river beds to cope with these floods. The advanced building technologies at the beginning of the 20th Century enabled the building of river dam cascades to retain significant amounts of flood waters and mitigate downstream flood damages. At present, nearly all big rivers including, for example, the Mississippi, Indus, Mekong, and Yagtze are regulated, and the remaining, such as the Amazon or Congo are planned to be dammed for electric power production and water supply. It has been estimated that about 84,000 river dams have been built in US alone [32]. The regulation of flow induces significant hydrological changes on downstream river and floodplain ecosystems. The impacts of the major hydrological changes on floodplain areas are shown in figure 2.

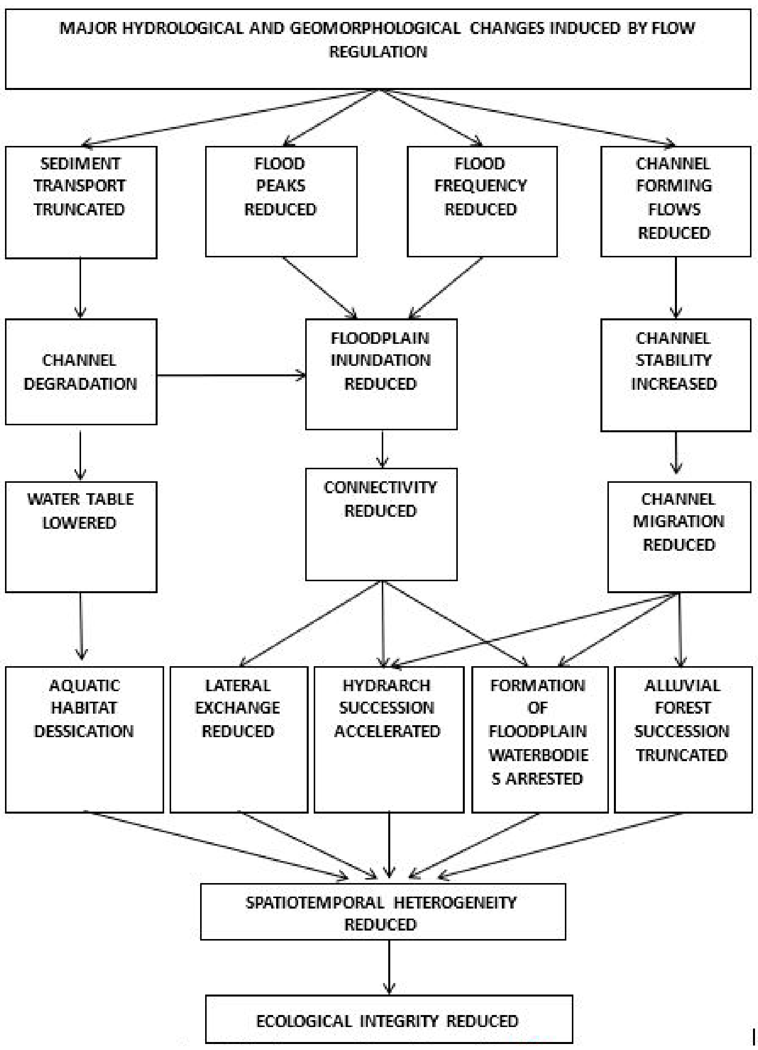

Figure 2: The downstream effects of flow regulation [33].

Nevertheless, dams and levees were not able to protect, for example, the surroundings of the lower reaches of Central European rivers from catastrophic flash floods in 2002 and 2013 [34]. Projects intended to prevent small floods may make big floods worse. Upstream dams can also reduce flow rates downstream and cause water scarcities [35].

5.2. Negative impacts of river regulation

In spite of the many beneficial socioeconomic effects of river regulations and the construction of dams (e.g. drinking or irrigation water store, water flow control, clean power production, fish breeding, recreation) many adverse ecological effects of such regulation and the building of flow barriers on remaining riverine ecosystems have been noted.

For example, the disappearance of the regular inundations and gradual drying of river valleys has caused the degradation or extinction of original riverine floodplains and their replacement by substitutive ecosystems or pastures and fields [36]. River regulation and the lowering of ground water levels have considerably decreased the vitality of floodplain ecosystems and shrunk their area. It is estimated that the original worldwide floodplain area has been reduced to about one tenth (Figure 3), and riverine floodplains show a similar trend. Many harmful impacts of river regulations on riverside ecosystems observed, for example fragmentation and isolation, decreased connectivity, limited transfer of seed and propagules (gene flow), and decreasing biodiversity. Besides ecological damages (decreasing biodiversity, diminishing the ecological stability of the landscape), floodplains altered by river regulation show decreased ecological services, which indirectly affect the socioeconomic conditions of local populations. What is more, the remaining woody vegetation in river valleys has often been considered to be an undesirable barrier for potential flood discharge and hence has been regularly removed [37].

More details about effects of river regulation on riverine ecosystems are available in the relevant literature [39-41].

At the present time, the world is facing a water resource crisis and, in parallel, the risk of extinction of many species and ecosystems. Respecting the socioeconomic and known landscape ecological aspects is necessary to make strategic decisions on whether to dam or not to dam [42-45].

6. Protection and Restoration of Floodplains

6.1. Floodplain protection

As mentioned in section 4.2 and documented in figure 3, floodplain areas have been dramatically decreased. Temporal changes in the area and distribution of floodplains can be observed in more detail using remote sensing inventories.

Figure 3: Time course of decreasing worldwide global wetland area [38].

The remaining riverine floodplains cover about 2×10^6 km^2 of the world's land surface [46]. The primary direct cause of floodplain disappearance is the deliberate utilisation or alteration of floodplains for farming or urbanization (drainage, woodcutting, burning, grazing and ploughing, building of dwellings, industrial buildings, roads, etc.).

The second reason for the shrinking of river floodplain areas is the limited water supply of the floodplain ecosystem due to defending the riverside areas against inundation and drying former floodplains as a consequence of technocratic river management as mentioned in section 5. Lastly, floodplains are being affected by current climatic change, for example, by increased water evapotranspiration and by serious disruptions to the local spatiotemporal precipitation regime. These remaining floodplains are also being affected by local socioeconomic exploitation (ecosystem services, section 4.2) and local and long-range pollution transport.

Since floodplains play important beneficial social, cultural, economic and ecological functions (the so-called services mentioned above) it is desirable to protect the remnants of these floodplains. The current international endeavour to conserve the considerable ecological value and worth of these unique parts of landscapes that exceed local and territorial importance resulted in the Ramsar Convention on Wetlands [47]. The Ramsar Convention justifies the need to protect wetlands using the following ten wetland ecological services: Flood control, Groundwater replenishment, Shoreline stabilisation and storm protection, Sediment and nutrient retention and export, Water purification, Reservoirs of biodiversity, Wetland products, Cultural values, Recreation and tourism, and Climate change mitigation and adaptation. The mission of the convention is to protect biodiversity and encourage the wise and sustainable utilisation of floodplains all over the world. In addition, valuable wetlands site across Europe have been protected by several EU directives, e.g. Water framework directive WFD 2000/60/EC [48], Birds Directive 2009/147/EC [49] and Habitats Directive 92/43/EEC [50]. The most valuable and threatened wetlands in Europe were encompassed in Natura 2000, the network of protected sites in Europe.

6.2. Floodplain restoration and adaptation to climate

The shrinking, fragmentation, degradation and disappearing of floodplains has compelled landscape ecologists to search for ways for the effective protection of valuable floodplains, the revitalisation of damaged floodplains, and the renewal of disappeared floodplains. Supporting arguments for mitigation and adaptation projects have included the decreased landscape ecological stability, ecosystem services, and later, the international convention on wetlands. Currently, various national and regional programmes of climate change adaptation strategies have been emerging, in which wetlands could play significant role. Besides the protection of biodiversity, wetland remediation projects aim to increase ecosystem services such as the natural water storage capacity of the landscape, biologically clean water, nutrient retention, carbon sequestration, and buffering the impacts of drought and flood episodes [51].

In order to establish new floodplain ecosystems, however, a thorough knowledge of the origin floodplain ecosystems is needed. In the 1980s, a new ecological discipline appeared called "restoration ecology", dealing with the renewal and restoration of degraded, damaged, or destroyed valuable ecosystems and habitats. The successful implementation of floodplain reclamation projects requires the close multidisciplinary cooperation of experts to deal with, for instance, water level fluctuations, sources and propagation of species pools, methods of reinstalling the vegetation cover (seed bank, plant cuttings, turfs), assembly and succession control, etc. The remnants of riverside floodplains has enabled researchers to study these ecosystems and acquire important missing data about ecosystem functioning. For the proper restoration of floodplains, not only is knowledge about alpha diversity (species assembly) important, but knowledge of the disturbance regime, effective methods of plant species propagation (transfer of seed banks, tissue cultures), manipulation succession use, water level control, etc., are critical as well. Several state, voluntary, and professional floodplain restoration programmes have been launched in the US, some European countries, Australia, New Zealand, China, Japan, and elsewhere. More details about the principles of floodplain restoration is provided in numerous literature [52-54]. However, the recovery or restoration of functioning floodplains seems to be a very complicated and long-term process. For example, Moreno-Mateos et al., [55] investigated 621 restored wetlands and found that the respective biological structure and biogeochemical functioning even after a century after restoration attempts remained on average 26% and 23% lower than in the reference stands. It may not be possible to completely restore floodplains, but at least the protection and improvement of floodplain ecosystems are achievable goals. However, climate change will continue to alter the development of the floodplain ecosystem.

7. Flash Floods as a New Phenomenon

In the recent past, seasonal river floods usually occurred in early spring in temperate climatic zones as a consequence of rapid snowmelt and the break-up of ice in river beds. However, historical accounts describe seldom and irregular floods during other parts of the year caused by long-term rainy periods. However, at present, due to climate change the warmed air can retain much more water vapour and climb higher than colder air. This means that a unit area above the earth can contain much more water in the atmosphere than in the past, and flash rain events can appear when deep low pressure forms above such an area. Since climate change has a global character, record-breaking rainfall amounts and intensities have been observed elsewhere as well [56-58]. Thus landscapes suffer from flash floods of increasing magnitude and frequency as a result of current global climatic change.

Hydrological databases have registered 3713 flood episodes between 1985 and 2010 [59]. The contemporary drainage systems in catchments are not able to absorb the significantly rising amounts of rainfall waters. Even the retention capacities of dams to trap rain outflows may be insufficient and are not able to prevent downstream flash floods, as has been documented in many cases [60,61]. Unprecedented hydrological power of flash floods causes enormous social, economic and environmental damages. In urbanised areas in particular such damage may be enormous (deaths, property damage, loss of critical infrastructures). However, flash floods have significant ecological impacts on the landscape, including riverine floodplain ecosystems. Although floodplains are affected by flash floods the areas where the flash floods originate are situated out of the affected floodplains, usually much upstream.

8. Impacts of Flash Floods on Riverine Floodplains

It is supposed that the high magnitude of flash floods and their increasing frequency must affect riverine floodplains in some way. One positive effect may be the inundation of remaining floodplains, which suffer from shortages of water as a consequence of river regulation. However, as explained earlier floodplain ecosystems adapted to "normal" seasonal flood pulses. The considerable hydromechanic power of "extreme" flash floods can totally deteriorate a floodplain area through the erosion or aggradation of thick layers of flood sediments. The recovery of affected ecosystems will depend on the limits of their resistance and resilience. Since we lack sufficient data about the effects of flash floods on floodplain ecosystems and their recovery, research dealing with this issue is highly desired. The following section provides a short review of our knowledge about the flood effects of "common" intensity on riverine floodplain ecosystems at various structural and functional levels (ecosystem, metapopulation and plant physiology).

8.1. The ecosystem level

The remnants of current river floodplain ecosystems are considerably vulnerable to the impacts of numerous anthropogenic and environmental factors. Since natural floodplain habitats have been adapted to regular seasonal flooding pulses, floods of common magnitudes may be beneficial for the recovery of remaining floodplain ecosystems. However, flash floods usually represent an "extreme" strong flood disturbance. Vegetation cover that is mechanically damaged and/or buried by flood sediments, together with long-term inundation stress, may cause irreversible changes to floodplain ecosystems. In order to easily evaluate the reactions of an ecosystem to a flood pulse the terms resistance (the impacted ecosystem remains untouched) and resilience (the ecosystem was changed by the impulse but it is able to return to the state before the impulse after some time) were introduced in ecology [62].

It is generally accepted by hydrobiologists that a floodplain ecosystem has the highest species richness if it has experienced long-term intermediate magnitudes of medium-term disturbances (i.e., former regular seasonal flood pulses). Long-term lower magnitudes of disturbances (e.g. controlled stable flow) or higher disturbance magnitudes (e.g. flash floods) significantly decrease species richness. Interdisciplinary investigations on the effects of flash floods on seed banks, nutrient content and their availability, plant-plant interactions during secondary succession at various scales, forecasting or modelling potential climax ecosystems, etc. may all be rewarding topics, building on present knowledge of the structure and functions of given riverine floodplain ecosystems in various climatic regions [63-67]. It is evident that if the intensity of a flood exceeds the resilience limit of the wetland, then irreversible changes in the affected ecosystem will be triggered. Due to the long-term recovery time of floodplain ecosystems, higher frequencies of floods of even lower magnitudes may initiate irreversible shifts in these ecosystems.

8.2. Plant populations

The area of riverside vegetation along channelled rivers have usually been decreased and fragmented. Since 1967 when the theory of island biogeography was formulated, this theory has been adopted to explain species richness on fragmented floodplain ecotopes, including the relationships between species richness and the area of floodplain sites with various mutual or one-way connectivity.

Floods are important downstream dispersals of seeds and vegetative propagules, such as rhizomes or stem fragments, from the catchment area, giving a rise to new ramets in downstream

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habitats. Due to a frequent clonal reproduction of hygrophyte metapopulations and their disconnected distribution along rivers the genotypic variation of local populations is usually low. This may be a threat for small populations of endangered species. For both general understanding and to increase the success of recovery projects, knowledge on the stand genotype variability in plant metapopulations, species genetic traits, genome spreading, minimum viable populations, inbreeding depression load, effective propagation methods for repatriation of rare plants, etc., is rewarding [68-70].

Flash floods can spread and mix plant seeds and propagules over much larger littoral areas (e.g. Q50-500) including potentially invasive species. The devastating effect of flash floods and dissemination of the propagules of invasive plant species can accelerate the invasion of such species into current floodplain ecosystems and into new remote sites of newly inundated areas. The spread of invasive plant populations along rivers has been frequently studied worldwide and invasion ecology is currently a highly topical discipline [71-73].

In addition, flash floods are also effective transmitters not only of water-borne and vector-borne communicative diseases but also infectious plant pathogens (viruses, bacteria, oomycetes, etc.). Due to climate change, new species of pathogens have quickly spread into colder climatic zones and endangered river bank woody species, for example, [74-76].

The species richness of floodplains strongly correlates with the water level regime and flood duration. Inundation is the main stress factor that plant species face during floods [63,77]. As an example, figure 4 documents the generalized effect of inundation time on the response ratio of seedling and adult plant survivals obtained from investigations of various plant species.

Field and laboratory studies have shown that inundation causes serious disorders in air supply to roots, nutrient uptake and affects other physiological processes, which may lead to growth retardation and plant dieback. Oxygen deprivation (hypoxia, anoxia) slows or stops aerobic reactions in plants and in sediments. Resulting effects include the microbial production of reduced forms of toxic metals and some toxic anions that damage plant roots, the production of toxic alkyl mercury, the down regulation of water uptake by roots, the decreased ability to release ATP energy for physiological and biochemical processes, the accumulation of toxic compounds from imperfect oxidation reactions, and role of phytohormones in plant responses [79-82]. The present state of knowledge of plant physiological reactions to inundation will be deepened with the assistance of new nano-technological methods.

Some plants have developed successful strategies (both resistance and avoidance) to survive inundation, such as special anatomical, morphological or metabolic mechanisms

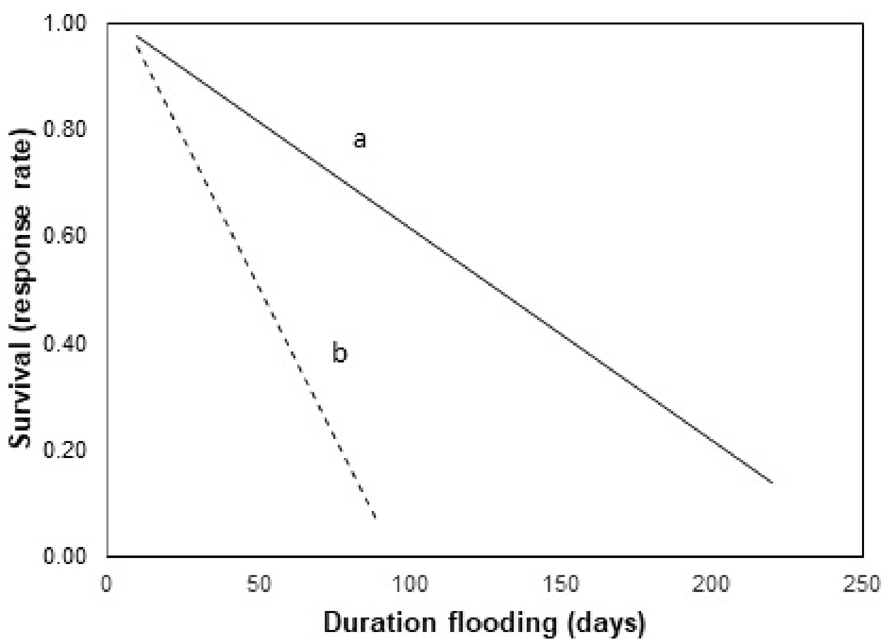

Figure 4: Effect of duration of flooding on response ratio of a) seedling (continuous line) and b) adult plant (dashed line) survivals, for respective 11 and 34 plant band seedling species [78].

including various types of aerenchym tissue, apoplastic barriers, adventive roots, pneumatophores (aerial roots), etc. [83,84]. However, genetic, biochemical and other adaptation mechanisms enabling resistant plants to survive long-term flooding are being intensively studied on the molecular scale to better understand the limits of plants species to stress and disturbance effects in floodplain habitats.

9. Floodplain Sediments

The area of river floodplains covers about 2.8% of the global continental area. Floodplain sediments are composed of skeleton (particles > 2.0 mm in diameter) and fine earth (< 2.0 mm) represented by sand, silt and clay grain size categories. The sorting and sedimentation of the grain size categories is controlled by the flood water flow speed. However, vertical and horizontal variability in sediment texture is generally considerable and temporally variable due to repeated floods and variable hydrological processes. What is more, sediments of various origins (geochemical properties) from large catchments are mixed across floodplains. However, the peripheral edges of river valleys usually contain the finest clay sediments, which most affect the soil structure and nutrient capacity of the plain soil cover. The development of soil on floodplain sediments is a slow process frequently interrupted by flood episodes. Several international and national soil classification systems distinguish a few types of floodplain soils, which are defined and called by different terms in parallel, such as Fluvisol, Inceptisol, Entisol, Gleysol, Planosol, Acrisol, Phaozem, Regosol, Ranker as well as several subhydric soil types in long-term inundated areas [85-87].

To make the results of sediment chemical analyses comparable, it is recommended to analyse some standardized grain size fraction of the sediment matrix (e.g. various clay particle sizes between < 63 and < 2 μm). However, for soil analyses the soil fractions 2.00 mm; 0.25 mm or others are frequently used. The presence of coarse sand particles comprised mainly from resistant quartz grains bearing chemical elements adsorbed merely on a thin coat of hydrated iron and aluminium oxides "dilute" the element content of analysed samples. In contrast, humus and other organic particles of high adsorption capacity, frequently present in flood sediments, contain considerable concentrations of organically bound and adsorbed nutrients and pollutants [88,89].

In some river sediment studies (successional sedimentation of individual layers in cores, sedimentation speed assessments, etc.) the dating of the given sediment material is needed. The age of deposited sediments is possible to assess by several available methods, for example, by annual rings of buried wood or through the activity determination of suitable radionuclides, such as ^{14}C, ^{137}Pb, $^{210}Pbex$, ^{238}Pu, $^{239+240}Pu$, ^{7}Be. Measurements of carbon and nitrogen stable isotope ratios (^{13}C:^{12}C; ^{15}N:^{14}N) can be used for identifying the origin of the organic matter in sediments [90-92].

Surprisingly, little is known about effect of sediment texture on the distribution of floodplain vegetation and the resistance of plant species to burying by aggravated sediments [93]. Much more data is available about the interactions of sediment texture and soil microbial communities [94,95].

Fertile river floodplain sediments have been drained and used for farming for millennia. The flood sediments contain washed out topsoil, humus particle and organic matter rich in nutrients from the catchments. Increased sediment humidity increases the speed of microbial decomposition of organic materials and the release of bioavailable species of nutrients, mainly nitrogen and phosphorus. Recently, enormous amounts of nitrogen and phosphorus have been introducing into river waters from municipal sewage and from washed off fertilizers from fields. Older sewage disposal plants are unable to remove macronutrients, mainly phosphorus, from sewage [96-98].

The increased concentrations of available nutrients, mainly nitrogen and phosphorus, in floodplains can cause an increase of plant species preferring soils rich in nutrients, e.g., by Ellenberg's rating of European plants to nutrient availability [99]. Plant production on fertile floodplains is generally not limited by the nitrogen supply. Nutrients from the water column and soil solution (pore water) are adsorbed by the plant cover, which takes part in the local element cycling. The floodplain ecosystems are significant sinks of nutrients, high productivity of these ecosystems. However, when suitable arranged and maintained (harvesting and disposal of biomass) riverside vegetation can be used as an inexpensive water quality control [100-102].

On the other hand, the anthropogenic eutrophication of river waters and sediments in oligotrophic regions has caused a diminishing of local rare oligotrophic stream and riverside ecosystems [103,104]. It has been well documented that along with drying, the increasing eutrophication of wetlands is the most harmful factor decreasing biodiversity and causing species extinction.

10. Contamination of Flood Sediments by Pollutants

Floodplain sediments of big rivers have long been anthropogenically contaminated by toxic elements, initially via mining activities and ore processing. At present, considerable amount and types of pollution with biological effects have been found in river water and sediments all over the world. Pollutants in floodplain sediments come from various sources, such as eroded topsoils and weathered rocks, mines and raw extraction pits, industrial factories, urban runoff, sewage discharge, and atmospheric deposition. Generally, the increased concentration of toxic pollutants in sediments is a higher threat to animal biota, including many types of soil microorganisms, than to vascular plants of the local riverside ecosystems.

10.1. Toxic and risk elements

Concerning inorganic contamination of the environment, only total concentrations of about 8-10 toxic elements are frequently determined (e.g. As, Cd, Co, Cr, Hg, Ni, Pb, Zn) because regional or national permissible limit concentrations have been adopted. However, biological availability and toxicity of these elements also depends on the element species. Concentrations of other risk elements (e.g. Be, Li, Sb, Sn Th and U) are less frequently monitored and the remaining element concentrations lack interest due to unknown their role in biota. This topic deserves more detailed investigations, as documented, for example, by the positive effects of rare earth elements on the growth of organisms, used to increase plant and animal production in agricultural practice [105]. For determining the age and sedimentation speed of deposited materials some radioisotope activities, usually ^{137}Cs and ^{210}Pb, are measured. Ratios of stable isotopes of other elements, for example, Cd, Hg, Pb, etc., can be used for tracking the sediment origin, such as local rock material, industrial pollution, soil from distant catchment areas, etc. [106].

An immense amount of papers have been published to document high contamination levels of river sediments by toxic elements [107-110]. Deeper insights into the methodology of normalisation of target elements, counting enrichment factors and processes associated with weathering, redox chemistry of elements, element bioavailability in river sediments, for example, are desired [111,112].

10.2. Persistent organic pollutants

Floodplain sediments are known as a significant sink of Persistent Organic Pollutants (POPs), a group of various hazardous organic compounds (e.g. polychlorinated biphenyls, polycyclic aromatic hydrocarbons, crude oil derivatives, DDT, etc.) that can persist in environmental compounds for a long time. POPs enter food chains and accumulating in the adipose tissue of organisms for their entire life. POPs may increase cancer and birth defects risks, as well as reproductive, immunological, neurological and genetic disorders, among others. Hence the Stockholm Convention on POPs (2001) ratified by more than 170 countries has restricted the production and use of POPs [113,114]. POPs compounds are poorly dissoluble in water and are mainly bound on fine organic and clay particles in river beds. The long-range transport of POPs bound on fine particles during floods is common, and downstream floodplain sediments usually show significant contamination by POPs [115-117]. Soil covers exceeding permissible POP limit concentrations should not be used for crop and fodder production. However, the uptake of POPs, particularly of larger molecules, by plant roots is limited, though plant surface contamination by soiling can be significant. Increased POPs concentrations in floodplain sediments are much less a risk for plants than for animals, especially carnivorous predators, and for the edaphon. On the other hand, soil microorganisms that can enzymatically degrade POPs have been under increased interest and may be suitable for remediation [118,119].

10.3. New pollutants

Unfortunately, many new types of pollutants with potentially harmful biological effects have appeared in industrial and municipal waste waters and subsequently in floodplain sediments. These include mineral and organo-halogen flame retarders, synthetic oestrogen from contraceptives, various compounds of antibiotics, beta blockers and further pharmaceuticals, illicit drugs and microplastics, as well as others [120-123]. Researchers generally pay increased attention to the harmful effects of these types of pollutants on human and animal compartments of floodplain ecosystems. However, there is insufficient knowledge of the biological effects of "cocktails" of these pollutants actually present in sediments.

River and flood sediments accumulate radioactive elements from fallout or natural cosmogenic deposition loads. Man-made radionuclides with the long half-life (T1/2), such as ^{137}Cs (T1/2 = 30.2 y), ^{90}Sr (T1/2 = 28.6 y), ^{238}Pu (T1/2 = 87.7 y), ^{239}Pu (T1/2 = 24,110 y), ^{240}Pu (T1/2 = 6,561 y), ^{241}Am (T1/2 = 433 y) and others were released in the environment from the tests of nuclear weapons (1945-1970) and accidents of nuclear facilities (e.g. from nuclear plant Chernobyl in 1986 and Fukushima Dai-ichi in 2011 and others). These radionuclides are firmly bound to fine soil and humus particles on the soil surface and during floods they are transported to flood sediments with the eroded topsoil. Activities of these radionuclides in floodplain sediment cores can be used for estimations of the age and deposition speed of materials in a sediment layer (Section 9). In riverbed sediments downstream of nuclear power plants, activities of some special radionuclides (e.g. ^{3}H, ^{32}P, ^{55}Fe, ^{60}Co, ^{63}Ni) that may be present in liquid effluent releases may be monitored [124,125]. However, they could primarily contaminate submersed plants and water organisms in lotic ecosystems.

Since Cs and Sr are chemical analogues of K and Ca, biological systems treat the radionuclides ^{134}Cs, ^{137}Cs and ^{90}Sr in similar ways as the biogenic elements Ca and K. Even in floodplain areas outside of accidental radioactivity contamination, fruiting bodies of some fungi can accumulate radionuclides in dangerously high levels. Environmental radioecology (radiation biology) deals with the contamination of floodplain ecosystems by man-made radionuclides, their redistribution in these ecosystems and on the effects of low doses of ionizing radiation on biotic compounds of the ecosystems. Further data are needed about the accumulation of radionuclides in biota, their ecological half-lives, competition of some elements with radionuclides for root uptake, the protective role of mycorrhizal fungi in radionuclide uptake, bounding of radionuclides in clay minerals and humus particles, etc. in floodplains [126-128].

11. Floodplain Microbiology

One major interest of microbiologists after floods is in the finding of pathogens in wet and dry forms of sediments that might pose a health risk. Higher levels of *Escherichia coli, Enterococcus, Salmonella* and adenoviruses as a consequence of faecal contamination of flood sediments are regularly found [129].

Natural populations of microorganisms (bacteria, algae, diatoms, archaea, fungi) play important roles in floodplain ecosystems. Microbial activities are very dynamic in alternatively wet and dry sediments and due to variable nutrient pools and contamination loads. The key microbial role in floodplain ecosystems is in the transformation and demineralisation of macronutrients. Very active fields of investigation include the microbial decomposition of organic matter, and the purification of water and identification of water quality using compositions of microbial populations as water quality indicators [130,131]. Considerable functional heterogeneity of microorganisms has been observed in variable habitats across floodplains. The microbial activities usually significantly increase from young successional habitats (gravel deposits) to older habitats such as meadows and floodplain forests [132]. The bacterial populations can decompose organic matter, affect nitrogen, carbon and phosphorus cycling, support the formation of soil structure, support plant growth etc. Fixation of atmospheric nitrogen by cyanobacterial mats and its effects on trophic relationships within a floodplain ecosystem is a relatively new and important topic for investigators. Besides mycorrhizal fungi, some species of bacteria, e.g., plant growth-promoting rhizobacteria interact with plant roots and directly or indirectly positively affect the plant growth. Many new findings of mutually beneficial bacteria-root interactions are expected, for example, the protection of roots against pathogenic bacteria and pests [133-135]. However, activities of sediment microorganisms may also result in undesirable compounds, such as greenhouse gases. During long-term inundations of floodplains the microbial activities frequently run under anaerobic conditions. The slow decay of organic matter by particular bacteria is associated with the production of carbon dioxide, methane and nitrous oxide, greenhouse gasses that are widely studied due to climatic change [136]. The microbial alkylation of some toxic metals (e.g. arsenic and mercury) results in alkyl metal compounds that can be even more toxic than the original elements. Reduced forms of sulphates and some metal compounds (iron, manganese) arising from microbial activities [137-139] can be similarly toxic for plant roots.

On the other hand, as mentioned above microorganisms (bacteria, fungi) can decompose or disrupt some of the numerous modern pollutants. Many laboratory experiments have been performed to identify microorganisms that can decompose pollutants and utilise the microbial potential in remediation projects [140,141]. Modern microtechnology and molecular and genetic methods can significantly accelerate investigations and understanding the spatiotemporal distribution and functions of microbial populations in ecosystems affected by floods, including phylogenetic analyses, the roles of signal compounds in microbial exudates, microorganism-plant root interactions, and algal-bacterial linkages in flood sediments [142,143].

12. Conclusion

River floodplain ecosystems are among the biomes that are most endangered by current global climatic change and anthropogenic pressures. Although the importance of floodplain ecosystems for ecosystem services provision has long been recognized the area of worldwide floodplains has been reduced to about one tenth of their original area, and some experts are forecasting a near-term large-scale disappearance of river floodplain ecosystems. A considerable effort is being made to prevent permanent loss of floodplains and their resources. Various programmes for the protection and restoration of these beneficial ecosystems have been launched both on the national and international levels. However, some projects show that it is very difficult to restore fully functional floodplain ecosystems, and even in floodplains restored for decades full functions of the original ecosystems have not been re-established. This review shows that there are very complex interactions between floodplain compartments and environmental factors and some aspects of these relationships have not been fully known or understand. This indicates that deeper knowledge of riverine floodplain ecosystems is required in order to conserve and restore such unique ecosystems in the present landscape.

The remnants of natural riverine floodplains provide the last chance to investigate their very complex ecosystem structure and function, and relationships between these ecosystems and the environmental factors in various climatic zones. Use of modern technologies, such as remote sensing, nanotechnologies, automating of data collection and processing can bring new findings about function of floodplain ecosystems in more detail. The author urges the research community to study soil and plant biology of the disappearing near-natural floodplain habitats affected by flash floods and to publish new results in the relevant research journals.

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