UDK/*UDC*: 502.1:556.166(410.111)(282.242)
Prejeto/*Received:* 22.11.2024
Pregledni znanstveni članek – *Review scientific paper*
Sprejeto/*Accepted:* 09.01.2025
DOI: 10.15292/acta.hydro.2024.07
Objavljeno na spletu/*Published online:* 10.02.2025

FLOODS: EMERGING CONCEPTS AND PERSISTING CHALLENGES

POPLAVE: NOVI KONCEPTI IN TRAJNI IZZIVI

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Abstract

Historically, floods have posed significant risks to human society and the environment, resulting in substantial humanitarian, environmental, and economic losses. In recent decades, global flood events appear to have increased in frequency. Modern approaches to flood risk management include infrastructure protection, resource-efficient management, and insurance programs. However, these protective mechanisms are only effective when based on robust scientific methods and fostered through interdisciplinary collaboration. Effective decision-making requires diverse and comprehensive data, which is often lacking. Paradoxically, some protective measures can be counterproductive, occasionally resulting in more damage than if the floodwaters had been left to follow their natural pathways. This paper provides an in-depth analysis of floodplain management and levee systems in controlling flood risks. It also examines approaches such as "space for the river" concepts, nature-based solutions, and river restoration initiatives to mitigate flood impacts. Additionally, the Jubilee Bypass Channel, an artificial river designed to protect parts of London from flooding, is presented as a case study. Ultimately, this paper concludes that a fully risk-free flood protection system is an unattainable goal. However, floods offer ecological benefits, notably in enhancing biodiversity and soil fertility. As such, this study reviews various flood control strategies, innovative concepts, and international initiatives dedicated to minimizing flood damage and prioritizing the protection of human life.

Keywords: flood, floodplain, levee, flood control, concept space for the river, Jubilee River.

Izvleček

Poplave že od nekdaj predstavljajo resno tveganje za človeško družbo in okolje ter povzročajo veliko humanitarno, okoljsko in gospodarsko škodo. V zadnjih desetletjih se je pogostost poplavnih dogodkov po svetu znatno povečala. Sodobni pristopi k obvladovanju poplavnih tveganj vključujejo zaščito infrastrukture, učinkovito upravljanje virov in zavarovalniške sheme. Vendar pa so zaščitni mehanizmi učinkoviti le, če temeljijo na zanesljivih znanstvenih metodah in interdisciplinarnem sodelovanju. Učinkovito odločanje zahteva raznolike in celovite podatke, ki pa pogosto niso na voljo. Paradoksalno je, da imajo lahko nekateri

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zaščitni ukrepi nasprotni učinek, saj včasih povzročijo več škode, kot če bi poplavnim vodam pustili slediti naravnim potem. Članek ponuja poglobljeno analizo upravljanja poplavnih ravnic in sistemov nasipov pri obvladovanju poplavnih tveganj. Obravnava tudi pristope, kot so koncepti »prostor za reko«, naravne rešitve in pobude za obnovo rek za zmanjšanje posledic poplav. Kot študija primera je predstavljen Jubilee Bypass Channel, umetna reka, zasnovana za zaščito delov Londona pred poplavami. Na koncu članek ugotavlja, da poplavni zaščitni sistem, ki bi bil popolnoma brez tveganja, ni dosegljiv cilj. Kljub temu poplave prinašajo ekološke koristi, zlasti v smislu izboljšanja biotske raznovrstnosti in rodovitnosti tal. Študija ponuja pregled različnih strategij za nadzor poplav, inovativnih konceptov in mednarodnih pobud za zmanjšanje škode zaradi poplav in zaščito človeških življenj.

Ključne besede: poplava, poplavna ravnica, nasip, nadzor poplav, koncept »prostor za reko«, reka Jubilee.

1. Introduction

Throughout history, floods have caused immense suffering and the loss of millions of lives, while simultaneously playing a crucial role in the development of civilization. Today, floods remain the most frequent and devastating natural disaster, affecting countless lives and causing massive damage (Willner et al., 2018). In recent decades, there appears to be an unexplained increase in the frequency of floods and the damage they cause worldwide (Bonacci, 2017, Kunzdewicz et al., 2013; Burn and Whitfield, 2016; Burne et al., 2016; Curry et al., 2019; Mohanty and Simonovic, 2021; Rodell and Li, 2023; Grigg, 2024). One of the most significant impacts of climate change is its influence on the unpredictability of floods, particularly flash floods.

There are numerous definitions of floods, which are more or less similar but highlight differences in understanding. Different disciplines define and analyze floods in unique ways. These variations influence approaches to addressing this increasingly dangerous natural phenomenon. The complexity of floods and their diverse spatial and temporal manifestations make it challenging to find effective mitigation measures, underscoring the need for an interdisciplinary and holistic approach to this complex issue. Recognizing the weaknesses of existing flood defense systems is of critical importance.

Flooding is a complex natural phenomenon that can be defined from various standpoints, with every definition capturing a different implication of flooding on society, ecosystems, and infrastructure. The commonly used definitions of flooding include various perspectives:

(1) An overflow of water onto typically dry land, resulting in the inundation of areas normally unaffected by water. This occurs due to rising levels in an existing waterway, such as a river, stream, or drainage ditch, or through water pooling at or near the location of rainfall. Flooding differs from flash flooding in duration; flooding is a longer-term event that may persist for days or even weeks (NOAA).

(2) The inundation of normally dry land by water that has overflowed or been released from its typical boundaries, including any lake, river, creek, or other natural watercourse—regardless of whether it has been altered or modified – as well as any reservoir, canal, or dam. In simple terms, flooding is the presence of water in areas where it is not desired (Geoscience Australia).

(3) Geologists define flooding as a natural process that occurs when the water level of a body rises sufficiently to overflow its natural banks or artificial levees, resulting in the submersion of typically dry areas. Flooding can occur annually along watercourses. Normally, high water flow is contained by natural banks or levees; however, when the volume of floodwaters exceeds the banks' or levees' capacity, the water spills into adjacent areas. The extent of flooding is influenced by several factors, including the volume of overflow, the velocity of water flow, and the topography of the surrounding land (Springer).

In addition to various definitions of floods, the literature presents several classifications and systematizations. It is important to emphasize that these classifications are not merely formal; each category of flood necessitates distinct theoretical and practical approaches for understanding and providing effective protection against their potentially dangerous consequences.

The most common types of floods can be divided into three categories: (1) river floods, (2) flash floods, and (3) coastal floods. River floods occur when sustained rainfall or snowmelt causes a river to exceed its capacity (Smith, 1993; Hoffius, 1997; Douben, 2006). Flash floods result from rapid and excessive rainfall, quickly raising water levels and potentially overtaking rivers, streams, channels, or roads (Bonacci et al., 2006; Wang et al., 2023). Coastal floods are typically caused by storm surges associated with tropical cyclones and tsunamis (Kralj et al., 2023).

Herchey (2002) identifies six flood categories: (1) riverine overbank flooding, (2) riverine gorge and canyon flooding, (3) flooding due to landslides or glacier blockages, (4) estuarine and deltaic flooding, (5) coastal flooding, and (6) volcanic flooding.

Mandych (2012) outlines three primary types of floods: (1) river floods, (2) inundation of seacoasts, and (3) floods occurring on inland seas and lakes. River floods can be further classified into eleven categories: (1) long-duration meltwater floods, (2) short-duration meltwater floods, (3) ice gorge floods, (4) ice jam floods, (5) long-duration rainwater floods, (6) monsoon rain floods, (7) flash floods, (8) dam break floods, (9) backwater floods, (10) mudflows, and (11) floods caused by icing. Inundation of seacoasts can result from three factors: (1) tides, (2) storm surges, and (3) tsunamis. Floods on inland seas and lakes can be caused by (1) tides, (2) wind surges, (3) seasonal flooding, and (4) seiches.

There are also many other types of floods caused by both natural and anthropogenic factors (Kershaw et al. 2005). Earthquakes that shift massive sheets of rock can significantly impact hydrological and hydrogeological processes, influencing groundwater levels and causing fluctuations in surface water in rivers, lakes, and reservoirs (Witman, 2017). The collapse of levees and dams can cause catastrophic floods (Müller-Salzburg 1987; Parolai et al. 2021).

Blöschl et al. (2015) highlighted the paradox that, while increased river flood runoff is a reality in certain locations, the socioeconomic conditions in many regions have changed even more drastically, leading to heightened flood damage.

The complexity of managing flood hazards and risks presents a global challenge, necessitating a comprehensive management approach. To develop more effective and innovative solutions, researchers must adopt holistic, integrated, and comprehensive strategies (Collins et al., 2014; Kunzdewicz et al., 2018; Awah et al., 2024).

The aim of this paper is to investigate the shortcomings of commonly used flood defense measures, highlighting their limitations and the realistic possibility that they may not achieve their intended purpose. The focus will be on the potential for revitalizing waterways and restoring flooded areas, as well as addressing the weaknesses associated with levees, which are the most frequently implemented flood protection measures.

2. Floodplain and River Restoration

There are many definitions of a floodplain, such as: (1) a nearly flat plain along a river's course that is naturally prone to flooding; (2) a plain bordering a river that is subject to flooding; (3) a low-lying area adjacent to a river, primarily formed by river sediment and subject to flooding; (4) a flat land bordering a river, composed of alluvial deposits (sand, silt, and clay) from past floods; (5) a strip of land bordering a river, typically inundated during seasonal floods (Nanson & Croke, 1992; Bridge, 2003; Matella & Jagt, 2014; Nardi et al., 2019; Mohanty & Simonovic, 2022). A floodplain is intermittently but frequently covered with water during periods of high discharge from adjacent rivers. The European Environment Agency (EEA, 2016) describes a floodplain as intermittently inundated lands adjacent to riverbeds and channels. The extent of a floodplain depends on specific geomorphologic and vegetative characteristics (Dodov & Foufoula-Georgiou, 2006; Woznicki et al., 2019). Various methods and approaches are available for delineating floodplains (Ricard et al., 2022).

Wohl (2004) illustrates how human activities have degraded rivers, disrupting essential links between river ecosystems and surrounding environments. The prevailing human inclination to prevent or control flooding may not be the most sustainable long-term management approach. Many flood management measures can produce hydrological, morphological, and environmental impacts, which in turn have significant socioeconomic consequences.

Historically, floodplains have been central to socioeconomic activity, evidenced by the high density of human settlements along rivers worldwide. These fertile areas have been instrumental in the development of civilizations; in arid regions, floodplains serve as oases for agriculture, while in mountainous regions, they provide rare expanses of flat land suitable for cultivation and transport. Modern society places enormous demands on floodplains (Knox et al., 2022a).

For hydrologists, a floodplain is an area that experiences flooding at least once every 100 years, while ecologists view it as a zone subject to periodic inundation. From an ecological perspective, understanding the interactions between river ecosystems and their floodplains is of significant scientific and practical importance.

Historically, floodplains have served as sites of vibrant socioeconomic activity and dense human settlement for thousands of years. Communities that settled in these fertile areas have faced the constant challenge of flood protection since their inception. Over the past two centuries, humans have dramatically altered these natural systems in an effort to defend their land and assets from flooding. However, not only have these efforts failed to provide lasting protection, but they have also caused significant long-term damage to the natural environment.

In the past two decades, the issue has intensified considerably. The construction of levees has disrupted the natural functioning of floodplains, resulting in increased peak flows in flood hydrographs. Alongside levee construction, regulatory works, such as the channelization of river flows, have accelerated river currents. In recent decades, there have been attempts to protect and manage watercourses using radically different approaches, including efforts to restore flooded areas, which may endanger downstream regions (Boon et al., 2000). It has become evident that we must protect ourselves from floods whose increasing intensity has been influenced by our own interventions (Cigler, 2017).

Most of the world’s rivers have been significantly altered to meet societal demands for food production, flood protection, and economic development. River restoration is an approach focused on managing rivers to reinstate natural processes, aiming to restore biodiversity and deliver benefits to both people and wildlife. Over the past 6,000 years, human activities have heavily modified river corridors through over-engineering, pollution, resource over-abstraction, and ineffective management (Nienhuis & Leuven, 2001; Abhilash, 2021; El Hourani & Broll, 2023).

River restoration involves reestablishing natural physical processes, such as flow variation and sediment movement, and restoring features like sediment sizes, river shapes, and habitats, including submerged, bank, and floodplain areas (The River Restoration Centre, n.d.). In many cases, restoration efforts also include floodplain re-establishment.

Traditionally, floods have been managed with technical protection measures; however, Ferreira et al. (2022), Christopher et al. (2024), and others advocate for nature-based solutions (NbS) as viable alternatives for enhancing flood resilience. Rajib et al. (2023) emphasize that, despite growing support for improved floodplain protection and management, a comprehensive, global-scale assessment quantifying human-induced floodplain alterations remains lacking.

Flood risk studies utilize flood hazard maps to identify areas susceptible to potential flooding. Lindersson et al. (2021) suggest that hydrogeomorphic floodplain maps can serve as valuable tools for generating high-resolution maps of flood-prone areas, aiding riverine flood risk assessments. However, caution is advised when applying these maps in regions that are arid, steep, very flat, or near coastal zones.

Warner et al. (2013) remind us that the floods that occurred in the Netherlands at the end of 1993 and 1995 initially shocked the public and professionals alike, prompting a reevaluation of flood management strategies. They believe that, at that time, many in the country—scientists, politicians, and the public—were complacent, believing that flood issues had been permanently resolved once and for all in the best possible way. However, following this awakening, Dutch experts made a historic decision: instead of continuing to build levees along the rivers, it was crucial to restore the natural spaces that had been taken from them through extensive hydrotechnical and regulatory interventions. They identified the loss of natural floodplains, severed by levee construction, as a significant factor contributing to the increasing frequency and intensity of floods and various other ecological disasters. This concept was termed "space for the river."

However, like many noble ideas, this one faced numerous theoretical and practical challenges. Before delving into a detailed examination of the issues related to creating space for rivers, it should be noted that the idea did not emerge in the early 1990s. Similar negative consequences of construction interventions had been observed decades earlier on rivers worldwide, particularly in developed countries where significant modifications to river systems were implemented as “final solutions” for flood control.

The vast majority of experts and laypeople agree that rivers should be given back their natural space. However, even at the theoretical level, disagreements arise, often insurmountable ones, regarding the best way to achieve this. Additional problems arise when moving from principles to concrete solutions. Each case is unique and necessitates the involvement of experts from various fields who represent a multitude of differing, often opposing interests. In the vast majority of cases, the cost of intervention becomes the ultimate criterion and/or dominant factor in decision-making regarding the measures to be implemented. While the costs of certain actions can be precisely quantified, quantifying the ecological benefits of proposed measures in economic terms poses significant challenges. Moreover, accurately estimating the long-term damages and benefits of an intervention can be nearly impossible. Consequently, final decision-making is often left to politicians; as the adage goes, “where science ends, politics begins.” This approach to problem-solving, prevalent in all social communities, generally proves to be ineffective in the long run.

Whol et al. (2005) indicate that the number of stream restoration projects in the United States is growing exponentially. Unfortunately, many of these interventions have proven unsuccessful (Williams et al., 1997; Phillips et al., 2022). Bernhardt et al. (2007) emphasize that many stream restoration projects in the United States have been implemented with minimal scientific support. They believe that the following aspects are particularly lacking: (1) a solid conceptual model of the river’s ecosystem, (2) a clearly articulated understanding of ecosystem processes, (3) recognition of the river's multiple interactive responses at various temporal and spatial scales, and (4) long-term monitoring of successful and unsuccessful responses to interventions.

Despite substantial scientific, technical, and financial investments, and the growth of a restoration industry, river ecosystems continue to degrade globally. Three main factors contribute to this ongoing decline. First, uncontrolled, poorly controlled, or falsely controlled anthropogenic activities continue intensely, with little or no regard for the health of open watercourses and their associated ecosystems. Short-term capital interests are generally prioritized and achieved. The second reason lies in the fact that the restoration and remediation work already carried out has not resulted in the planned improvements but has further worsened already unsatisfactory conditions. The third reason is that there are no scientifically based prerequisites for the concept of successful restoration. Simply put, not all scientific interactions within these highly complex and dynamic social systems and ecosystems have been understood to date.

2.1 River Jubilee Case (UK)

The Greater London area, including its center, has frequently suffered—and continues to suffer—damage from floods caused by the River Thames, which flows through this vast and one of the wealthiest, and most organized, cities in the world. This happens despite the fact that the city has been undertaking numerous and costly measures to protect itself from flooding for centuries (Gardiner, 1994). The largest Thames floods in the London area during the twentieth century occurred in 1947 (a 50-year flood) and in 1968, both characterized as flash floods caused by heavy rainfall in the watershed.

The Thames has been extensively modified through many long-term projects, resulting in a complete alteration of its natural morphological and hydrological regime. Based on the principles of "green construction" and with the goal of integratively managing the Thames's water resources, with an emphasis on flood protection and environmental preservation, the artificial Jubilee River was constructed in London's western suburbs. The intention was to protect an area of the Thames basin upstream from central London from flooding by constructing an artificial channel known as the Jubilee River. The description below will outline the project, highlighting both its positive aspects and some questionable points, dilemmas, and controversies regarding the implementation of the space for the river concept in practice (Warner, 2013).

This complex flood-protection system also aimed to meet sustainable ecological development goals. Figure 1 shows the layout of the Thames and the Jubilee River, designed and constructed by the Environment Agency. It is an 11.6-km-long bypass channel with a trapezoidal cross-section and an average width of 45 m. Its construction protects 3,000 properties in the area between Maidenhead and Datchet. The channel is designed to carry a maximum flow of 215 m³/s, which accounts for 42% of the Thames's flow for a 65-year return period.

A particularly strong incentive for building this system arose in 1990, when the town of Maidenhead suffered significant flood damage from the Thames. The final decision to proceed with the construction was made in 1995. Construction took place in the late 1990s, with the project being fully completed in the early 21st century. The construction cost amounted to £110 million. At the time of completion, it was the largest artificial river in the United Kingdom and the second largest in Europe.

Figure 1: *Map of the Jubilee River (Channel).*

Slika 1: *Karta reke Jubilee (kanal).*

The Jubilee River's designers and builders aimed to mimic a natural watercourse in both appearance and function. Given its urban setting, the project required numerous flow control mechanisms, along with bridges, pedestrian crossings, and other public amenities. Along the river's course, five weirs were constructed. Today, the Jubilee River is a popular spot for nature lovers, runners, walkers, and cyclists. To make this artificial river function as naturally as possible, many natural habitats, mirroring those along the River Thames, were recreated along its banks and throughout the catchment area. Many of these habitats, which had been destroyed by 19th- and 20th-century regulatory works, were restored by planting 38 hectares of reed beds, 5 hectares of wet woodland, and 250,000 trees, which have attracted numerous bird species back to the area.

The Jubilee River system proved effective during the significant Thames flood of 2007, successfully protecting its designated areas. However, it introduced potential flood risks to downstream areas, necessitating controlled water discharge into the Jubilee River and subsequently into the Thames to avoid endangering downstream areas of London.

From the very start of the Jubilee River system's operation, during high flows in 2003, failures emerged on engineering structures. The channel could not carry the designed water volume but handled significantly less. Bank erosion and damage to some weirs occurred. Erosion resulted because bank stability was not secured by rigid structures but relied solely on vegetation that had not yet fully developed. Consequently, and to mitigate the risk of Thames flooding downstream from the Jubilee River's confluence, the maximum allowable flow through the channel was reduced to 144 m³/s, and bank and bed reinforcements were added, including stone riprap and sandbags. The damage and its repair costs amounted to over £5 million.

During the high waters of 2003, the area downstream from the confluence of the artificial river with the Thames was flooded, prompting authorities to take certain measures within the system and downstream on the Thames. In 2006, the Environment Agency sued the main contractors of the system. In early 2014, high water levels, surpassing even those of the catastrophic 1947 Thames flood, affected areas immediately downstream from the Jubilee River's confluence. The large floods and subsequent flooding events of 2003 and 2014, which occurred after the construction of the Jubilee River system, have led local residents to seriously question the system's effectiveness at flood protection, particularly downstream on the Thames.

This costly, scientifically advanced project was expected to protect an area from floods in a new, interdisciplinary way, respecting environmental demands while ensuring sustainable development. However, experience has shown that achieving this is very difficult. The Environment Agency concluded that any community vulnerable to flooding must accept a certain flood risk if it seeks to build a flood protection system that also meets environmental criteria. This example clearly demonstrates that floods cannot be entirely prevented. This simply means we must be as prepared as possible for extreme and dangerous situations to avoid casualties and reduce damage.

3. Levees, Embankments, or Dykes

Levees, embankments, or dykes are engineered to confine river flows within specific areas along a river, or to protect against coastal flooding from waves and tides. They are designed to resist hydrostatic pressure, erosion, piping failure, and seepage during floods. However, by constraining river flows, levees limit the natural floodplain area exposed to inundation, disrupting the lateral hydrological connectivity along river corridors. This restriction negatively impacts the ecological processes of both channels and floodplains.

It's important to recognize that levees cannot provide absolute flood protection. Modern understanding acknowledges that an extensive levee system alone cannot guarantee safety from floods. While reinforcements and levee height increases reduce flood frequency in protected areas, they can increase flood risks downstream. For example, Figure 2 illustrates the evolution of the Mississippi River levee system over time (CIRIA 2013). Despite significant enlargement and heightening, levees have not prevented flooding. In fact, recent floods in the Mississippi River basin have been more frequent and destructive. Higher levees have correlated with increased flood severity, underscoring the limitations of levee systems as standalone flood protections.

William Hammon Hall, California's first State Engineer, expressed this reality nearly 140 years ago: "There are two types of levees, those that have been overtopped by floodwaters, and those that will be."

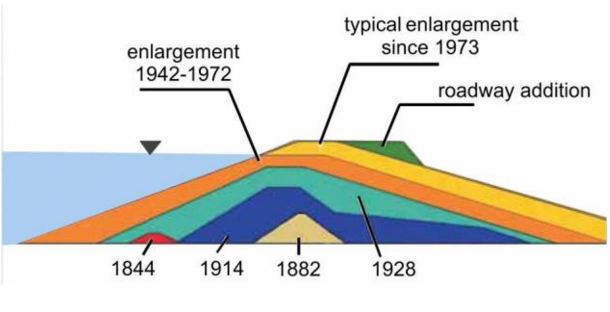

Figure 2: *Evolution of the Mississippi River levees from the beginning until today (CIRIA 2013).*

Slika 2: *Razvoj nasipov reke Mississippi od začetkov do danes (CIRIA 2013).*

There are three types of levees: (1) persistent, (2) transient, and (3) accidental. Persistent levees are designed for situations relevant over a period comparable to the design working life of the structure. Transient levees are intended for conditions that occur for a period much shorter than the structure's design life but have a high probability of occurrence. Accidental levees are constructed for scenarios involving exceptional conditions affecting the structure or its exposure, such as fire, explosion, or impact from local failure. For levees, accidental events may include occurrences like ship impacts or floodwater levels that exceed the established design return period. Levees are mainly constructed from soil, although recently, alternative materials and prefabricated structures are increasingly used to act as levees only during high-water wave events.

Levee breaches are not uncommon. The primary causes include erosion and overtopping of the levee crest, though earthquakes can also trigger collapses. While all riverbanks are subject to erosion, the risk of levee failure depends on both location and the rate of erosion (Hossain et al., 2011). Nkagawa et al. (2019) documented examples of flood disasters in Japan caused by levee overtopping from river water, while Harada et al. (2024) described a case of river levee collapse triggered by an earthquake.

A major challenge is that levee failures remain difficult to predict with reliability, complicating timely responses to prevent them. Failures still occur relatively frequently despite advancements in levee construction technology and monitoring systems. Figure 3 shows a levee failure on the Sava River in Croatia.

Artificial levees constitute one of the major human modifications to river corridors. Despite this, there is no clear understanding of how artificial levees affect floodplain extent at regional and larger scales. The results of investigations by Knox et al. (2022b) indicate that artificial levees not only decrease floodplain extent but also alter the locations of floodplain connectivity. These levees cause complex changes in river-floodplain dynamics, increasing flooded areas in some rivers.

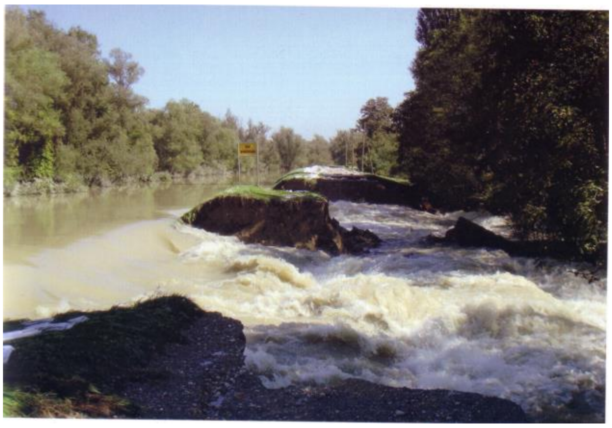

Figure 3: *Breakage of the Sava embankment at Sop Bukevski on 19 September 2010.*

Slika 3: *Prelom nasipa Save pri naselju Sop Bukevski, 19. septembra 2010.*

As part of river restoration efforts, the removal of levees is often undertaken. However, since a natural river corridor is a very complex system, this measure can frequently prove problematic and controversial. The WMO (2006) concluded that "there are no universal criteria to determine environmentally friendly flood management practices." It is crucial to adopt practices that suit the particular circumstances of a given hydro-climatic, topographical, and socioeconomic setting while following a rational and balanced approach to addressing environmental issues in flood management.

A comprehensive integrated approach is required for the removal of levees. In any given case, many factors must be taken into consideration, including the magnitude, frequency, and other flood characteristics, as well as the geographical and hydrogeological context and the region's socioeconomic background.

4. Discussion

Despite the fascinating developments achieved in many areas over the past few decades, the hazard of flooding has not been eradicated. In fact, recent floods appear to be more frequent and destructive in many regions of the globe, and projections for the future look bleak. This situation underscores the need to reevaluate strategies for flood preparedness (Kundzewicz 1998, 2013, 2018).

On 29 November 2024, deadly flash floods devastated Spain's eastern Valencia region, marking the worst natural disaster the area has faced in decades. An entire year's worth of rainfall fell in less than eight hours, sending torrents surging through riverbeds toward the Mediterranean, sweeping away cars and collapsing bridges. Over 200 lives were lost in this catastrophic event, which is not unprecedented. In October 1957, Valencia faced a similar deadly flood caused by the same seasonal weather phenomenon, Gota Fría, when the Turia River overflowed into urban districts, claiming dozens of lives. Despite significant investments in redirecting the river, these measures ultimately failed to prevent the catastrophic impact of the November 2024 flood.

The recent catastrophic floods in Spain's Valencia region exemplify several common challenges associated with flood events. Rapid urbanization, often lacking adequate drainage infrastructure, exacerbates flooding by increasing surface runoff and overwhelming existing systems. This urban expansion can lead to significant property damage, disrupt transportation networks, and strain emergency response efforts (AP News, 2024). Additionally, intense floods can have severe environmental consequences, including soil erosion, contamination of freshwater resources, and displacement of sediments, adversely affecting water quality and regional ecosystems (The Times, 2024). These events also pose public health risks, such as the spread of waterborne diseases and compromised access to clean water and essential services (The Sun, 2024). The severity of recent floods globally, including in Spain, underscores the urgent need for adaptive urban planning, investment in resilient infrastructure, and climate adaptation strategies to mitigate the growing flood risks in vulnerable areas.

On 11 September 2024, parts of Central Europe were hit by the storm (cyclone) Boris, which brought extreme rainfall and strong winds. The following day, the storm struck southern Poland, where some areas received 200 mm of rain in less than 24 hours, leading to floods in many cities. On 13 September, over 500 mm of rain fell in the northern Czech Republic, resulting in floods that caused immense damage to residential and industrial buildings, roads, and bridges. The next day, 14 September 2024, the storm reached Romania, where heavy rainfall of around 250 mm within 24 hours triggered flash floods that submerged numerous settlements, damaged approximately 5,000 homes, and destroyed two dams. It is estimated that at least 20 lives were lost: seven in Romania, five in Poland, four in the Czech Republic, three in Austria, and one in Italy. Boris was the latest and most devastating in a series of storms that have caused catastrophic flooding in Europe over the past 500 years.

In St. Pölten (Austria), a total of 350 mm of precipitation fell over three days, nearly doubling the 100-year precipitation amount. As a result, some smaller flash streams in Lower Austria experienced peak flows nearly three times higher than the estimated 100-year flows. This is exemplified by the Perschling, a small flash stream near St. Pölten, which recorded a peak flow of 276 m^3/s with a catchment area of only 55 km^2. Calculations determined its 100-year flow value to be 108 m^3/s, with the highest recorded flow to date at 102 m^3/s. The extreme rainfall caused dramatic flash flows, leading to significant damage.

The floods that occurred in 2024 as a result of Storm Boris and a cyclone in Spain's Valencia region highlighted the effectiveness of flood protection measures, such as retention in smaller streams and levees in larger ones. However, it is essential to understand that these measures only function up to a certain flow level; once floods exceed this level, evacuating residents becomes necessary.

Preparedness for flooding events is crucial, as studies indicate that climate change is resulting in more intense storms and flooding in certain European regions (Blöschl et al., 2019). Storm Boris, along with a cyclone over Spain, intensified due to exceptionally high sea surface temperatures in the Mediterranean. Additionally, northern Europe has seen increased flooding due to a shift northward in global precipitation patterns, driven by changes in pressure systems between the Arctic and the equator.

The summer of 2024 was one of the hottest recorded globally and in Europe, with the Mediterranean Sea reaching very high surface temperatures. This extreme heat played a critical role in fueling storms and altering atmospheric dynamics.. The rapid warming of the Arctic, caused by melting ice, has further intensified these shifts by reducing reflection and increasing solar radiation absorption, contributing to this trend.

Countries north of the Alps, including Austria, Germany, and France, have experienced an increase in flooding over the past 30 years. Blöschl et al. (2020) found that this period is one of the most affected by floods in Europe in the last 500 years. The devastating European floods of 2021 claimed more than 200 lives and caused enormous damage, underscoring the necessity of improving preparedness for their increasingly frequent and destructive occurrence.

The challenges of flood protection extend beyond traditional methods, such as reliance on return period-based designs. The limitations of this statistical approach, particularly in the context of extreme flood events, have been well documented (Kjeldsen et al., 2014; Bertola et al., 2023). For instance, flood protection measures, such as those targeting 100-year return period floods, may prove insufficient in the face of more extreme events. Notably, the Netherlands has adopted a 10,000-year return period for some critical infrastructures, reflecting an advanced approach to mitigating catastrophic risks (Rijkswaterstaat, 2017). The study by Kjeldsen et al. (2014) highlights that, although the scientific community widely acknowledges the value of historical records for flood analysis, their application in practical flood risk assessments remains limited. A comprehensive review of flood frequency estimation guidelines across various countries revealed a general recognition of historical data's importance; however, few practical methods exist for its systematic and routine inclusion in risk analysis. While historical event studies and national databases compiling such information were noted in many countries, significant potential still exists for improving flood risk assessments by incorporating the valuable insights provided by historical extreme event data.

Bertola et al. (2023) emphasize that effective flood management requires a combination of approaches that include analyzing natural processes, utilizing statistical methods, and assessing historical flood data. Their study points out that more intensive cross-border exchanges of flood experiences could be crucial for European countries seeking to improve preparedness and develop more effective responses to increasingly extreme weather conditions. The analyses presented in this article reveal that 95.5% of historical mega-floods could be predicted based on past occurrences in similar regions. The study highlights that while mega-floods may be rare in certain countries, they are more common across Europe. This indicates that such local floods can be expected even in areas where they have not previously occurred.

The concept of maximum possible flooding (MPF) also deserves greater attention. This criterion, widely recognized in protecting nuclear power plants, involves calculating the uppermost theoretical flood level, enabling better comprehension of potential disaster magnitudes. Although MPF is well defined technically, its practical implementation remains limited. Historical examples highlight the implications of such oversight: the Drina River's 1896 flood wave and the Drava River's 2012 event illustrate how human intervention, including reservoir mismanagement and regulatory constraints like Natura 2000, can exacerbate flood severity. These instances underscore the necessity of accounting for extreme flood events in planning and regulation.

The modern approach to flood risk assessment and management, incorporating risk and uncertainty analysis, introduces innovative concepts and methods in hydraulic and hydrologic modeling, model calibration and validation, as well as flood mitigation measures and their cost-effectiveness. Scarcity of observational data on extreme flood events remains a significant challenge in flood risk management. Over the past few decades, numerous new methods, concepts, initiatives, and organizations have emerged at national, regional, and international levels (UNESCO/WMO, 1991;

Johnson et al., 2007; Brils and Harris, 2009; Warner et al., 2013). However, a key conclusion about many of these efforts in flood attenuation and river restoration is that, despite their good intentions, they have not significantly advanced flood management. It appears that these valuable initiatives have fallen short of their goals partly because the developed world is generally more resilient to flooding (Balmforth, 2008).

A multidisciplinary and integrated approach to flood mitigation decision-making aims to optimize society's response to flood hazards, covering both preparatory actions and post-event mitigation efforts. Recently, flood perception has been recognized as an essential element in flood mitigation and management (Brilly and Polič, 2005).

There is no single paradigm that is equally applicable to all the different conditions that occur in the real world (Biswas 2004).

5. Concluding Remarks

Based on the previous discussions, it can be concluded that future solutions to river management issues should be grounded in complex, sophisticated, and continuous interdisciplinary research efforts. It is essential to integrate ecological aspects of the problem with engineering considerations while also taking into account the social dimensions of open waterways. It is evident that this is a complex issue that cannot be resolved quickly, with absolute certainty, or simply.

The need for a holistic approach is frequently emphasized. Achieving this requires collaboration among experts with diverse backgrounds who are willing to engage in reasoned discussions. The primary obstacle to such cooperation does not stem from a lack of willingness among individuals or groups to collaborate. Instead, it arises from two main factors: first, our insufficient understanding of the analyzed river system, and second, the inadequately educated decision-makers who cannot ensure equal opportunities for dialogue. Engineers often lack ecological training, while ecologists typically do not possess sufficient engineering knowledge.

It is also important to recognize that science has yet to fully comprehend the complexity of interdisciplinary issues and is therefore unable to provide satisfactory and reliable answers at present. Acquiring new knowledge about the relationship between river morphology and ecology—specifically the distribution of organisms and the development of ecological processes under varying hydrological conditions in rivers, floodplains, and the broader river corridor—is fundamental for implementing appropriate engineering interventions and measures that meet the demands of sustainable development and flood protection. Clearly, significant and intensive efforts will need to continue for some time to address this issue.

The concepts of space for the river and nature-based solutions have brought us back to the beginning, to a time before humans began "taming" open waterways and realization that floods are nothing more than a part of natural hydrological variations.

It has been recognized that many existing flood defense systems inadequately address, or even completely neglect, the ecological aspects of river corridors and watersheds. The consequences of this oversight not only lead to drastic environmental degradation and a dangerous decline in biodiversity but also undermine the effectiveness of flood defense systems. Such repercussions often destabilize social balance, with floods occurring more frequently and with greater intensity, causing increasing damage in areas where the most complex flood defense systems have been constructed. It is evident that humanity must accept UNESCO's concept of "living with floods," which acknowledges that floods cannot be absolutely prevented but rather that the number of human casualties and the damage that they cause must be minimized. At the same time, it is necessary to recognize and better utilize the positive effects that floods have on the environment.

In the past, when flood defense measures were undertaken, it was largely forgotten that floods play a crucial role in supporting biological productivity and diversity in floodplains and, through them, in the broader watershed area. Floods significantly contribute to soil fertility, habitat formation, and the transport and exchange of nutrients and organisms.

The sediment transported during floods does not only represent dead matter but also fertile components, nutrients, and biological organisms. New concepts are attempting to find new and more effective solutions. It should be kept in mind that science is still far from providing reliable answers.

For effective flood management, there is no one-size-fits-all solution that would apply in a heterogeneous environment with varying climatic, geophysical, social, economic, and environmental conditions, different institutional, technical, and managerial capacities, diverse institutional and legal frameworks, and divergent levels of development and available technology.

While the study of flood management is making steady progress, much work still remains to be done.

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