Gábor Ungvári

The role and potential of flood risk management in shaping land use

Flood-peak polders of the Tisza River from the perspective of integrated planning challenges.

CORVINUS UNIVERSITY OF BUDAPEST

Doctoral School of Business and Management

Sustainability Management Specialization

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Doctoral Dissertation

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Budapest, 2023

PREFACE

The dissertation follows an article-based PhD structure. The summary text contextualizes and synthesizes the three articles of my PhD dissertation. These articles cover the scientific approach and results of separate project-based work carried out along the Tisza River in recent years. I have been involved in these projects as a project leader and analyst. These works are listed at the end of chapter 2.2.

At the Tisza River, the development of flood-peak polders (in line with the Further Development of the Vásárhelyi Plan Program – or VTT according to the Hungarian acronym) was a significant initiative in terms of flood management and rural development in the period 2000-2020, but the assessment of its results from a policy implementation perspective is not unanimous. The aim of the thesis is, among other things, to describe the scientific context of these partly successful (flood management) and partially unsuccessful (rural development, land-use change) results. I believe that without a coherent interpretation, no further progress can be expected in the related policy field, although the reasons for the partial failure will be key issues in the implementation of any climate policy goal requiring territorial adaptation.

For this interpretation, I address the development process of the Tisza flood-peak polders through the perspective of Spatial Flood Risk Management (SFRM), an emerging approach. The thesis reflects on the issues that gave rise to this approach, its characteristics, and why and how it can be used to support the implementation of flood risk management projects that require the involvement of private land. This is the mainstream of the work. Another source of added value of the PhD thesis is that it contributes to understanding the economics of the approach by building on the articles.

The synthesis part of the dissertation begins by explaining my interest in the topic (Chapter 1, Motivation).

Chapter 2, Context, presents the policy-making challenge facing the water policy scene, both in general and specifically in the area of flood defense.

Chapter 3 presents the questions that structure the PhD thesis.

Chapter 4 reviews the state-of-the-art development and characteristics of the Spatial Flood Risk Management approach and the quantified flood risk assessment methodology.

Chapter 5 links the SFRM approach and the analyses presented in the three articles of the thesis. It contains a description of the further development of the SFRM approach and incorporates the results of analyses relevant to the train of thought in this synthesis text.

In Chapter 6, I draw lessons, raise discussion topics, make recommendations, and identify the most promising issues for further investigation in terms of the application of the SFRM approach to nature-based solutions.

The second part consists of the articles that provide the background for the synthesis and the summary of the work.

The first paper, Reducing flood risk by effective use of flood-peak polders: A case study of the Tisza River (Ungvári & Kis, 2022b), presents the methodological development and results of a flood-risk calculation-based economic support system for the management of the Tisza River flood-peak polders. The second, Combining Flood Risk Mitigation and Carbon Sequestration to Optimize Sustainable Land Management Schemes: Experiences from the Middle-Section of Hungary's Tisza River (Ungvári, 2022), presents the results of cost-benefit analyses that support the multi-criteria utilization of land suitable for flood-risk mitigation. The third article, Social, economic, and legal aspects of polder implementation for flood risk management in Poland and Hungary (Warachowska et al., 2023), compares the regulatory approaches underlying the operation of flood-peak polders on the Tisza River and the Warta River in Poland.

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ACKNOWLEDGMENTS

Regarding the accomplishment of this work, I would like to express my gratitude to those who supported and inspired me. To my family, who have forgiven me for having my mind elsewhere, and to my late grandma, who always wanted a man of science in the family.

Also, to individuals associated with my official and unofficial background institution, REKK, and my colleagues who created the solid background for implementing the programs that created the basis for the PhD-related work; and especially thanks to my friend and colleague András Kis, with whom I have endeavored to gather knowledge and improve insights into water, nature, and economics. I am also grateful to my colleagues at the Middle-Tisza Water Directorate, with whom I developed the knowledge that makes up the backbone of the work and who patiently answered our never-ending queue of questions aimed at obtaining deeper insight. Thanks especially to water director Attila Lovas, whose exceptional conviction about the need to support practice on the ground with economic facts gave us the opportunity to elaborate an approach that few deem essential. Last but not least, I would also like to thank Tamara Keszey and Gabriella Szajkó for their support and trust.

Water is an immensely complex natural feature. I am extremely thankful to those who shared with me the essential gaps in the knowledge that enriched and completed my holistic but economics-aligned view.

In nature, we trust. / *Hiszünk a természet szeretetében.*

1 MOTIVATION

I have been analyzing various water-related issues and problems and exploring their possible solutions for over two decades. In Hungary, we are primarily confronted with the failure of water policy initiatives that ignore the potential of economic instruments (adequate tariff-setting for infrastructure maintenance and the incentive-based pricing of constrained infrastructure capacities and scarce water resources), while elsewhere, we find successful but primarily unscalable solutions. To put it mildly, it is not popular for economists to propose economics-based solutions to environmental problems. However, I am convinced that without them and the correct use of economic policy instruments, the various water and climate adaptation efforts will not produce affordable, truly sustainable results. However, this situation offers economists an opportunity to play a positive role. I would like to highlight this niche in the field of water economics, especially flood risk management, as info-technology developments have recently created the conditions for the appropriate application of basic economic methodologies such as a cost-benefit analysis. My aim is to help water find a place in the landscape again, not just in a few economically unsustainable pilot projects lurking in the field.

Adopting the economic and spatial approach to domestic flood management practices extends beyond the latter's remit. It can open up real and economic space for ecosystem services that can also mitigate other water extremes. This is important because the most significant water-damage-prevention challenge in the Carpathian Basin is not flooding but the lack of water in the landscape and the problem of increasing aridity. The social impacts of the latter process cannot yet be modeled with the same spatial accuracy as flooding, but the space for the water needed to mitigate aridity will have to be generated using policy methods similar to those used to deal with flooding. Even in the case of flooding, however, we are not yet exploiting the new opportunities that technology has opened up to attach a service value to the flood-modifying capacity of specific pieces of land in the river basin. I would like to push these processes forward by demonstrating the added value of taking an economic approach and underscoring the applicability of economic tools to this unpopulated area of domestic economic thinking.

2 CONTEXT

2.1 General water policy context

Water policy issues cover a wide range of problems, both in scale and complexity. They may be divided into water management and water-damage-prevention issues. This classification is reflected in the structure of public institutions dealing with water issues. However, by its very nature, water plays a much more complex role in natural flows and social uses than can be effectively managed according to these rigid structures. Integrated Water Resource Management (IWRM) was one of the first international initiatives to address this complexity of water issues (UNDESA, 2015).[1] Within this approach, it became clear that the issue of water as a renewable resource cannot be separated from the technical and scientific issues of water supply, water resource management, water pollution control, water-damage-prevention infrastructure development, and the many related impacts on nature. Different approaches have provided an increasingly deeper understanding of natural-societal interconnectedness. The most prominent example is the ecosystem services approach (Costanza et al., 1997; Kumar, 2012). Unraveling this interdependence requires considerable technical-ecological knowledge, but despite having significantly advanced in terms of understanding this complexity, management challenges cannot be met without integrating the social dimension.

IWRM was a very important stage in addressing this high degree of complexity and interconnectedness. It helped in formulating the international conventions on water and water policy (Hassing et al., 2009). However, despite initial expectations, the results did not seem to translate into practice (Jønch-Clausen & Fugl, 2001). As Biswas (2004) expressed, IWRM has failed to identify a governance system that could deal with the complexity it represents. It is characteristic of this discourse that it points to the importance of social aspects, yet the focus remains on the details of physical/ecological solutions. At the same time, frustration is growing at the lack of implementation and the failure to find adequate, workable solutions to water-related issues (Woodhouse & Muller, 2017).

Despite the general public perception, "water failures" are not due to a lack of technological knowledge but are typically public policy failures (Pahl-Wostl & Kranz, 2010), (Woodhouse

[1] "IWRM is a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resulting economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."

& Muller, 2017) (Scholten et al., 2019). The most frequently reported crises in the media are related to the lack of drinking water and irrigation, and climate change is often cited as a root cause. However, these cases can largely be traced back to problems such as the development and operation of infrastructure that does not take into account the limits of users' financial ability to maintain it; the defining of development strategies that, for political reasons, ignore growth in demand; the prevalence of corruption in utility operations and of access to water, and a failure to apply incentive pricing (Zetland, 2011). In other words, these are problems that essentially do not require technological but rather governance interventions. This realization was made clear in the OECD's report Principles on Water Governance, published after a series of regional exploratory analyses (OECD, 2015). The rationale for the formulation of these principles in the area of water governance is the simultaneous presence of multiple drivers, each of which would be a major challenge to respond to individually. These drivers are diminishing water and environmental resources in relation to their demand and the need to renew aging or otherwise inadequate infrastructure. All these challenges are emerging in a sector that is fragmented geographically and in relation to management solutions, requiring capital-intensive, long-term investment and embedded in a very diverse web of societal interests that impede adaptation (OECD, 2011). The principles thus formulated reflect the fact that the interlocking natural-social complexity underlying the problems that have been identified requires a new quality of policy formulation and implementation compared to that applied so far.

In addition, despite the unresolved problems, drinking water supply and related water resource issues are the most extensively regulated water policy area. To respond to the water challenges posed by climate change, the qualitative leap identified by the OECD would need to be implemented across water policy fields that are even more complex than urban drinking water supply. The examples could be extended to other problems, such as water scarcity resulting from ecosystem degradation, water pollution leading to the depletion of water supplies, and land use changes leading to the degradation of an array of water-based ecosystem services (World Bank, 2016). Flood management fits into this picture as well. Here too, the drivers identified by the OECD that make it difficult to develop an appropriate institutional response can be identified, as described in detail in the next chapter.

A common feature of these situations is that the newly identified constraints and bottlenecks are often not subject to formal or effective regulation. Attempts to do this often stall. As one analysis of barriers to the implementation of water policies summarizes: "In *too many countries, there is a significant gap between what is written in law and policy and what is actually* *happening*." (Ménard et al., 2018) pp 14. The OECD report cited above attributes the cause of this phenomenon to the quality of the functioning of the so-called "meso-institutional layer." This is the institutional level where regulatory expectations from above, aimed at generating social benefits, clash with the interests of the groups that bear the cost of changes aimed at maintaining the status quo. The capability of this meso level of institutions is crucial in determining whether a frozen stalemate or workable rules emerge after the process of bargaining and enforcement. Effective implementation requires an effective meso-institutional layer. (Akhmouch et al., 2018)

In this space, the tools and methods used to translate overarching adaptation objectives into local rules are of particular importance. This is the point at which the planned use of the water resource in question, or access to the underlying ecological resource, clashes with the practice of customary law. The water policy challenge is characterized by the fact that, in the wake of new scientific discoveries, water links a wide range of stakeholders and interest groups in space and time, which should adopt standard sets of rules despite their cultural-, community-, and material differences of interest.

Policy development in flood risk management serves as an explanatory example in this thesis; what are the main features of the rules the crucial meso-institutional layer should incorporate? Territorial agreements, negotiations about the land use of individual plots, and landscape-level features need to be incorporated into these new sets of rules. The economic methods that are able to monetize the impacts of stakeholder groups on each other play a decisive role here. This is why the possibility of conducting cost-benefit analyses on flood risk mitigation is important and the focus of the thesis. The following sub-chapter describes this broader water policy challenge in the flood-risk-management policy field.

2.2 Policy context in the area of flood defense

The policy field of defense against flood hazards faces structural challenges that require a substantial upgrading of water governance skills, as described in the previous sub-chapter. Deteriorating external conditions due to both natural and social drivers highlight the issues associated with renewing capital-intensive infrastructure networks. Climate change is projected to make both water extremes (seasonal water shortages and surpluses – drought and flooding) both more severe and frequent (EC-JRC, 2020). Development-related changes in watersheds result in faster run-off that increases the risk in threatened downstream areas, where the previous development of defense systems has been shown to further incentivize an increase in the value at risk (Hartmann, 2016). Meanwhile, the state-backed quick-recovery and rebuild action triggered by disasters conserves conditions otherwise ripe for change (Slavíková et al., 2020).

Traditional defense strategies are no longer sufficient; adaptation is needed to avoid or minimize the disruption of socioeconomic processes (Kundzewicz et al., 2002). A growing expectation of the required adaptation is that it should rely on nature-based solutions. (This requirement is expressed, for example, in the EU Floods Directive, which requires its provisions to be implemented in a manner consistent with the EU Water Framework Directive).

Recognizing the complexity of water issues points towards an increase in the emphasis on spatial aspects. Flood protection solutions have necessarily had to go beyond previous practices based solely on the construction and raising of dikes. To reduce the threat, it will be necessary to include areas previously dewatered and protected. With this shift, the flood protection sector will thus become part of an expanding subset of socioeconomic networks, the success of which will be linked to the ability to implement changes in established land use and land management practices. As stated in the article "Land-use change and floods: what do we need most, research or management?" that presents the results of the Hydra research program that was initiated after severe flooding in Norway in the early 1990s:

> *There is a growing consensus that as we cannot avoid floods, and as flood protection works never can be fail-safe, softer alternatives implying getting out of harm's way and controlling flood source mechanisms better are becoming a new paradigm. Economic incentives are part of the new principles. (...) Land-use policy and flood risk mapping (risk = vulnerability * hazard) are of particular interest. Flood management should imply "negotiations" in the river catchment/basin context between water volumes/discharges on one side and land-use on the other. Land-use will impact on flood behaviour, and flood behaviour will limit the land-use options.* (Tollan, 2002. p.188, 189

The thesis raises questions about the potential of using economic approaches and economic instruments more extensively to handle the above-described water policy challenge and enhance the functioning of the meso-institutional layer for introducing transient water cover to dewatered landscapes. Recent work builds on linking technological changes in flood simulation with the potential of applying new-quality economic information in the local context to address the conditions of implementing land use adaptation.

The thesis is a synthesis of several research and analytical initiatives in which I have been involved in recent years. The overview below outlines my contribution to the work on which the thesis is based. In the first half of the 2000s, I was involved in a landscape rehabilitation project in the Bodrogköz area that explored the socioeconomic impacts of pursuing the long-term trajectory of water resource and land management policies that enable arable agriculture. In this period, the development of the first flood-peak polder, which was then underway, came under my purview. The EPI-Water FP7 research program between 2011-2013 provided the means for me – at the Water Economics Unit of the Regional Center for Energy Policy Research (REKK) – to deal with the topic of flood-peak polders along the Tisza River, the relationship between flood risk and land use, and the problem of their joint optimization in more depth and to pursue our own economics-driven approach (*EPI-WATER*, 2013). On behalf of REKK, I developed and led the conceptual design of a case study for the research program. Our case studies focused on optimizing flood-peak polder operation and the root causes of the inflexible agricultural practices that hinder solving the Great Plains' pluvial flood/waterlogging problems. I compiled the research design. The collection of field information and the analyses were carried out with my colleague András Kis, with the involvement of ecologist and water engineer colleagues (Ungvári et al., 2013). The research program laid the foundation for collaboration with the Middle Tisza Water Directorate aimed at exploring the economics of the operation of flood-peak polders under their auspices. This work provided an opportunity to apply and further develop the methodology for quantifying changes in flood risk based on data that had accumulated during previous flood-defense activities. This process culminated in R&D work (REKK, 2018) aimed at developing an operational management system for flood-peak polders on the Tisza and its tributaries. I was the project leader of this work on behalf of REKK. I was responsible for developing a coherent methodology in terms of both technical and economic information and participated as an internal opponent in the preparation of development modules, such as the design of the defense cost-estimation model and the programming of the calculation algorithms. The methodological development of the work and the theoretically relevant results are presented in the first article of the PhD, published in the Journal of Flood Risk Management (Ungvári & Kis, 2022b), the Hungarian translation of which has been republished in the journal *Vízügyi Közlemények* (Ungvári & Kis, 2022a).

Another field experiment within the EPI Water research program, the conceptual design and conduct of which I led, was published in the Journal of Environmental Geography (Ungvári et al., 2018). I consider the demonstration of the willingness of participating farmers to swap land use for compliance with the upcoming Ecological Focus Area requirement of the EU-CAP policy facilitated by an auction-based experiment a crucial result. We showed that it can be legitimately assumed that the enhancement of public interest investigated in this thesis and the initiation of land use adaptation can be achieved by economic means. This confirmed my belief that multifunctional land use solutions can be developed and need not only be created on state-owned territory or in areas excluded from economic value creation.

Between 2017-2021 I participated in the LAND4FLOOD Cost Action program (Land4Flood, 2020). The aim of the program was to identify and systematize solutions to the problem of flood risk reduction on private land. In addition to identifying problems, the program aimed to provide knowledge support for the successful implementation of projects and policies. The work was summarized in the compilation of the book *Spatial Flood Risk Management* (Hartmann et al., 2022). I contributed to a chapter of the book as lead author (Ungvári & Collentine, 2022). The associated academic and practitioner community inspired my work. This is the professional embeddedness behind the preparation of this text and the articles included in the PhD.

List of professional activities relevant to the subject and location:

Danube Floodplain Interreg Project - "Reducing the flood risk through floodplain restoration along the Danube River and tributaries" WP 4.4; Hungary: Tisza Pilot CBA, 2020-2021 as a subcontractor of the Kötivizig (Middle Tisza Water Management Directorate) on behalf of REKK. (Economic expert and project lead shared with András Kis)

Development of an economic decision-support module for the operation management system of the Tisza River flood-peak polder system. 2017-2018 (Gábor Ungvári, András Kis). National Water Directorate General in the "Contract for the complex implementation of the development of the operation management and monitoring network" in the framework of the KEHOP- 1.4.0-15-2016-00016 project (Economic expert tasks and research leader on behalf of Rekk)

Investigation of the risk-mitigation effects of the Zagyva flood-peak polders for the Szolnok Water Management Directorate. 2016 (Economic expert tasks and research leader on behalf of Rekk)

Impact of the opening of the Tiszaroff flood-peak polder on flood risk. Performing modeling tasks related to the Tisza Valley operation management system for the project KEOP-2.5.0/B/10/2010-0002. 2015 (Economic expert tasks and research leader on behalf of REKK)

Evaluating Economic Policy Instruments for Sustainable Water Management in Europe (EPI WATER project FP7), 2011-2013. I participated in the international research consortium on behalf of BCE-REKK. The task was the preparation of the Tisza case study. WP4 EX-ANTE Case Studies Floods and Water Logging in the Tisza River Basin (Hungary) Lead authors Gábor Ungvári and András Kis.

Economic analysis of the flood control of the Tisza; Prepared in the framework of the research program of the BME - Department of Water and Environmental Engineering NKFP - 3/A 0039/2002; Research supervisor: László Koncsos, Supervisors: Szabolcs Szekeres, Gábor Ungvári; Contributors: Edina Balogh, György Fonyó, Ferenc Tar; 2006 (I participated in the work as an economic expert).

Ed.: Flachner Zs., Molnár G., Kajner P.; Authors: Botos CS., Cselószki T., Farkas Sz., Fonyó Gy., Flachner Zs., Kajner P., Koncsos L., Molnár G., Pásztor L., Prix G., Szabó J., Ungvári G.: On the natural utilisation of the Cigánd and Tiszakarád flood polders and the implementation of the related flood protection, rural development, and landscape rehabilitation plans. Prepared within the framework of the Further Development of the Vásárhely Plan, Scientific Foundation Subprogramme. 2004 (I was involved in the work as an economic expert on behalf of the Hungarian Centre for Environmental Economics).

In addition to the listed projects, I was a member of the economics expert group involved in developing the National River Basin Management Plan (2010) and its first review cycle (2015), implementing the EU Water Framework Directive.

3 RESEARCH QUESTIONS AND TOPIC DELINEATION

3.1 Research questions

The overarching research question formulated at the beginning of the degree-acquisition process was reformulated into the following two questions:

1, Based on experiences with the Tisza River, can methodological advances in flood risk assessment increase social welfare in the context of multi-purpose land use?

2, What improvements can economic instruments support, aided by advanced flood risk assessment methodologies, for initiating multi-purpose land use adaptation?

3.2 Explanation of topic delineation

3.2.1 Why is flood defense the subject of the study?

Adaptation is a commonly articulated need in the context of climate change. Changes in flood threat and the societal responses this change triggers illustrate the relationship between the local and global drivers of the adaptation challenge.

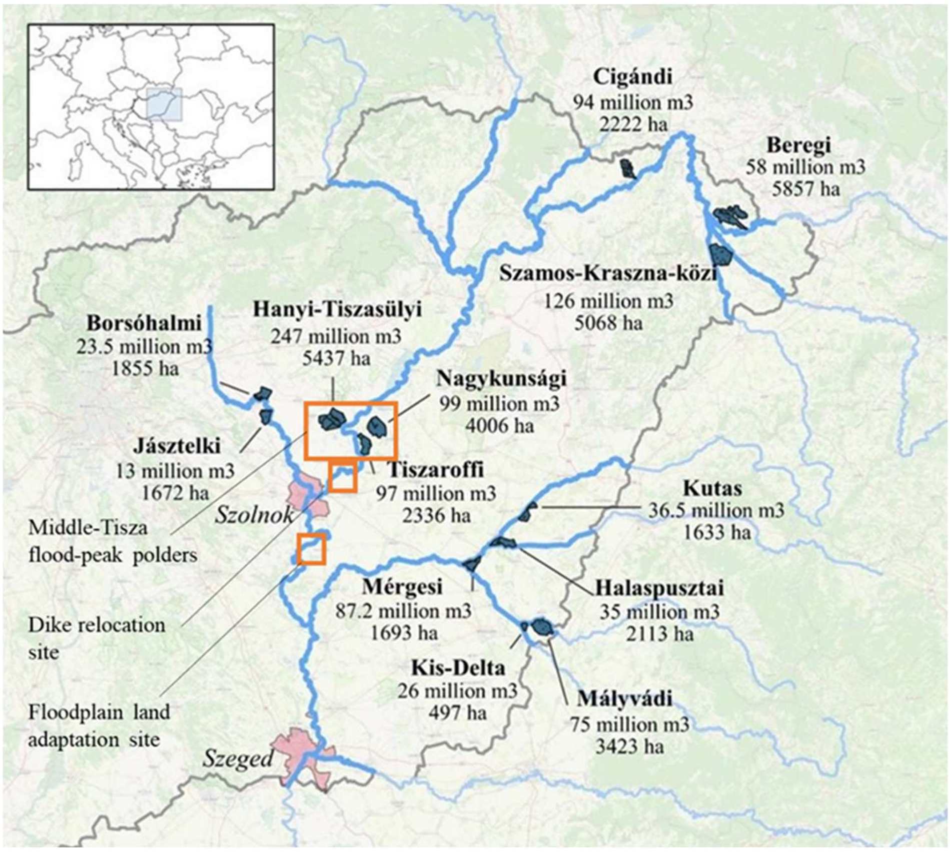
Technical advances in flood-risk mapping have now made it possible to apply a reliable cost-benefit- and, consequently, a provider-beneficiary approach to the organization of flood defense from a spatial perspective. Due to developments in technical capabilities, the impact of any location (territorial unit) on the accumulation of floods can be calculated. Consequently, its impact on flood risk in the river basin can be expressed in monetary terms. Moreover, the flood-risk modification potential of these spots (sites) can also be expressed, depending on assumptions about land use. Compared to previous options, this also makes it possible to identify the service providers of flood-risk reduction and groups of beneficiaries much more accurately. This new situation will allow more effective solutions to flood-risk reduction to be developed. This can be exploited by making a cross-sectoral comparison of public and private impacts and their relationship to land use alternatives in a monetizable form. These advances create a more suitable background for interpreting and negotiating adaptation challenges in economic terms.

3.2.2 Why is the Tisza River the territorial focus of the analysis?

The thesis focuses on the operation of flood-peak polders along the Tisza River and on issues associated with this empirical basis to explore the potential for adapting the land use of former floodplains.

The Further Development of the Vásárhely Plan (VTT), a complex flood protection and rural development program, was launched in the early 2000s. Since the first flood-peak polders were put into operation, new polders have been constructed. The evolution of flood simulation methodology between the design period of the VTT and the launch of the flood-peak polders' operational management system in 2019 provides an opportunity to illustrate the role that economics can play in decision support. This is a practical example of the policy improvements that can result from building decisions using cost-benefit methodology rather than a cost-minimization approach.

Figure Syn. 1 Network of flood-peak polders along the Tisza and its tributaries



Legend: Map shows the flood polder system of the area and highlights the location of the study areas.

Another reason for the chosen territorial focus is that the VTT program and its implementation have not been extensively assessed in the literature besides their hydrological aspects. This can be seen as a success or a failure depending on the viewpoint of the sector. The analysis provides an opportunity to identify lessons for public policy implementation. Besides the cost-benefit analyses the thesis incorporates, the policy implementation process is analyzed through the lens of the spatial flood risk management approach. The Tisza River case is put into a broader context by comparing it with a Polish flood-peak polder implementation on the Warta River.

The differences between the Hungarian and the Polish case highlight the nature of the undefined responsibilities and powers attached to land ownership and their consequences in forming spatial policies, among other lessons. This latter aspect is the focus of the Spatial Flood Risk Management approach.

4 THE SPATIAL FLOOD RISK MANAGEMENT APPROACH AND THE STATE OF THE ART

4.1 The development of the approach and its main components

This chapter provides an overview of the assessment methods used in this text that contextualize the underlying research results. It incorporates a description and formulation of the SFRM approach. This detailed exploration serves two goals; on the one hand, it makes identifiable my contribution to this approach (as shown in chapter 5.1); on the other hand, the SFRM approach as a tool in its own field focuses on the missing or unconnected elements of the policy implementation process that produce the water policy failures the OECD report reveals. The chapter also illustrates that putting the pieces together as the SFRM approach suggests is like filling with content the lacking meso-institutional layer for a river basin.

4.1.1 The need and the demand for new solutions

The floods of the 1990s and the turn of the millennium generated new questions. In many countries, research programs have identified the need to move forward because the solutions applied in the past will not be sufficient to deal with projected flood events. Proponents of a sustainability approach have started to promote the understanding that floods are natural events, cannot be avoided, and that protection systems will never provide full protection (Kundzewicz, 1999). To maintain the level of protection, it is necessary to intervene during the flood accumulation process and to adapt by reducing the value exposed to damage (Tollan, 2002). Among the strategies that use newer solutions, the Dutch program *Ruimte voor de River* ("Space for Rivers") has gained wider recognition (Busscher et al., 2019), and its name has become a slogan in its own right. Programs with a similar approach have been launched in several other countries and for various rivers, such as the Elba (de Kok & Grossmann, 2010; Förster et al., 2005) and Oder (Hudak et al., 2018). In addition to the natural-hydrological questions associated with flood attenuation, results have been published that focus on the social conditions necessary for successful implementation (Aerts et al., 2018; Klijn et al., 2021; Otto et al., 2018; T. Thaler et al., 2018).

Hartmann (2011) offers a conceptual overview of the process and defines the challenges. He concludes that if we want to create space for rivers, we need to reinterpret the approach to the management and maintenance of former floodplains. This challenge is also formulated by other authors (Rossano & Hobeica, 2014; Roth & Winnubst, 2009). Moreover, he points out that the use of floodplains is confronted with complex social constructions through which and within which this process of making progress must take place.

> *This rethinking needs to consider the different rationalities involved in contemporary floodplain management. These rationalities socially construct what happens in these areas. How does the social construction of the floodplains work? Which rationalities are the driving forces for the stakeholders' activities?* (Hartmann, 2011) p.166

This statement by Hartmann (2011) has not been invalidated, although considerable progress has been made since he wrote it. Despite efforts, there are still no large-scale areas available for the provisional storage of water in the former floodplains of rivers.

Land users and landowners have passively accepted flood-defense developments. This was a mutually convenient situation if it meant passively accepting the benefits of safety from floods. However, circumstances have changed. There is now a conflict of interest between agricultural landowners who have the potential to reduce flood risk and the broader group of beneficiaries downstream. Pursuing the public interest without addressing the impacts thereof would impose a cost on a smaller group, both directly in financial terms and indirectly in terms of the effort necessary to redefine their livelihood strategy. However, this situation is not identical to the NIMBY phenomenon. Here, it is not the acceptance of a deterioration in the quality of life that is at stake. The conflict of interest culminates in the question of what the ability or willingness to change the customary activities of agricultural land users' livelihoods is based on. In the latter case, a successful negotiation can be assumed on a financial basis if the benefits created by changes cover the costs of those affected by the latter. However, experience has shown that, in many respects, there is a lack of governance and cooperation capacity for supporting the management of this new situation of conflicting interests among stakeholders. In addition, there is a lack of research and research findings for assessing the effectiveness of the methods that are used, or identifying the reasons for the limitations of these approaches. The complexity of the decision space concerning the management and use of floodplains is increasingly well understood, partly due to the many difficulties and constraints associated with developing coherent solutions (Raška et al., 2022). This is one of the water policy areas described by the OECD report cited above as lacking a meso-institutional layer.

A river basin is an aggregation of the land cultivation and land cover characteristics of all its individual areas. A standard, landscape-level feature is the transformation of runoff into a flood wave after a rainfall event. The sum of individual locations' land-use characteristics influences the height of the flood wave that is generated. The flood risk originating from a given landscape can be considered a "common pool resource" (Kerr, 2007).

Overuse of the resource (which increases flood risk) occurs when the cost of individual land-use decisions (e.g., paving a new surface or cutting down a forest area) are not recovered because no rules mandate compensation in proportion to the costs incurred by other parties. This is the case when the conditions of ownership are undefined in terms of modifying flood risk.

In contrast to the issues arising from degradation associated with common pool resource management challenges, flood risk management aims to increase safety (reduce the level of risk). It is possible to plan, from a hydrological point of view, the coordinated use of different territories along the hydrological connectivity pathways defined by the geography of the catchment to achieve the optimal level of this common pool resource (safety level), but the practical implementation difficulties of this are obvious. However, as (Kerr, 2007) points out:

> *Macrowatershed management could also benefit from improved technology to understand and track upstream-downstream relationships. Technologies that could track hydrological relationships and trace impacts of (...) one location on another would open new possibilities for developing indicators and monitoring systems to facilitate management*. (p. 106)

Quantitative flood risk assessment methodology is one such process that can trace impacts and express them in monetized form, reducing the cost of establishing agreements among relationships to facilitate their management.

Measures resulting in the slowing down of flood-wave accumulation and cutting the peak of flood waves both presuppose some form of land use change that can be valued through its impact on risk. There is an opportunity to develop a relationship between groups of providers and beneficiaries that can be shaped by the use of individual and community resources in different ways (T. A. Thaler et al., 2016). These (physically possible) service-provider-beneficiary relationships can be established between distant points in the catchment by enabling financial transfer solutions if property rights to the transient impacts of land use are clarified (Hartmann et al., 2019) and appropriate solutions are applied to bridge transaction costs (Shahab et al., 2018).

4.1.2 The evolution of calculation methods - quantitative flood risk assessment

Although how to calculate flood risk has long been theoretically clear (the flood damage event multiplied by the probability of occurrence), in practical terms, it has always reflected the information-processing capabilities of the time and has evolved with these capabilities. This technological capability constrains the questions that the methodology can be used to answer. Thus, as technology evolves, so do the questions that can be answered in the context of decision support. An early example (van Dantzig, 1956) compared investment costs and the estimated cost of avoided disaster to determine optimal dike height. Flood-risk calculations, when applied within the flood defense sector itself, compare the balance between a given investment cost and the achievable impact and prioritize investment alternatives. Beyond these decision-support aspects, how risk is quantified is secondary if the results are consistent across these two aspects. The purpose of demonstrating this consistency was the goal of Scorzini & Leopardi (2017), for example who carried out a very detailed study of hydrological processes and damage modeling over a large number of catchments was carried out, comparing the results calculated by qualitative and quantitative risk assessment methodologies. This illustrated the strengths of applying a quantitative method over a qualitative one. Meanwhile van der Pol et al.(2017) examined the limits of applicability of the probabilistic approach using a CBA analysis.

The evolution of simulation technologies in the field of water damage prevention over recent decades can be identified in the move from qualitative flood risk assessment methodology to quantitative flood risk assessment. This process is reviewed in the introductory chapter of the first article of the Ph.D. thesis (Ungvári & Kis, 2022b). This technological change not only allows for more accurate information-based decision support in the field of flood risk management but also opens the door to new possibilities for application in the sense of the previously cited (Kerr, 2007) expected technological advances in watershed-scale "common pool resource" management.

The advancement in and importance of quantitative flood risk calculations to the applicability of economic methodologies can be seen in the fact that it is now possible to make cost-benefit comparisons instead of applying cost-effectiveness or cost-minimizing approaches. Using the previous qualitative evaluation method, the basic units of calculation were land use types that aggregated broad territories with similar characteristics, where exposure was determined based on the average values available for these types. The new methodology simulates the impact of the interventions on flood wave accumulation at high resolution and catchment scale; this involves considering many components (micro-relief, soil type, roughness, and infiltration factors). The same change is true of the components affecting damage (depth of inundation, duration, velocity of water flow, etc.) in the area exposed to flooding (European Commission, Joint Research Centre, 2016; Huizinga et al., 2017). Thus, not only has the lowest-cost solution for averting a flood threat of a given return frequency become calculable (the benefit is the difference between the two investment costs), but the hazard reduction – the change in the value of flood risk as a benefit – can also be calculated. This new information can be used to clarify the impacts and link the benefits, not just the costs, affecting different sectors due to a development project. At the same time, knowing the range of benefits can help determine the investment required for establishing and maintaining territorial cooperation for successful implementation. The range is certainly wider if the benefits include not only the savings in terms of investment but also the value of the flood-risk reduction.

Despite the above-mentioned merits, there are limits to how extensively quantitative flood risk assessment can be used. When applying decision support using the flood-risk calculation approach, the issue of climate change cannot be ignored. The formerly dominant paradigm was to view floods in consecutive years as independent events, reflecting a statistically stationary state (Milly et al., 2008). This assumption has been revised in the light of new knowledge, which will have implications not only for how this methodology should be applied but also for what solutions for development should be considered applicable in the light of continuous change. van der Pol et al. (2017) reviewed the incorporation of climate-change impacts into CBA studies using flood-risk calculations. The authors conclude that the impact of climate change cannot be considered using a risk-based approach, as there is no reliable information on how the frequency of events is changing. However, it is not reasonable to ignore this effect, as different probabilities can be assumed for different types of events. According to the article's authors, this situation can be characterized as decision-making within a framework of uncertainty describable only by imprecise probabilities. Their conclusion about development-related decisions is that the design of scalable (flexible) solutions is probably more economically reasonable than inflexible solutions. In this respect, the design of flood-peak polders as a modularly expandable solution is preferable to further raising dikes. At the same time, robust solutions regarding the overall social impact of land use management can be expected from a combination of different benefit options (e.g., flood-risk change, agricultural production, and ecosystem services). This is a policy challenge whose success will be determined by the quality of the institutional system. The institutional framework for land use management and its quality is also relevant to another claim (van der Pol et al., 2017). In addition to the uncertainty associated with the probability of rainfall events, the latter authors mention another feature that calls into question the ability to model future climate-change impacts from a risk perspective. This is feedback from learning in the future – the incorporation of future experience and innovation into today's models. The integration of future knowledge into adaptation processes will have a crucial impact on the future state of water basins due to its effect on the ability to implement policy (that embodies the quality of the institutional layers).

4.2 Coherent support for policy implementation

The previous chapter discussed the theoretical challenges and methodological advancements that support the formulation of innovation in flood defense policy. Spatial Flood Risk Management is an innovative approach that intends to address these challenges by using new developments. SFRM is the result of the scientific collaboration associated with the Land4Flood EU-Cost Action program (CA16209), which ran between 2017-2021 that was set up to rethink and systematize knowledge. The "Nature-Based Flood Risk Management on Private Land" (Hartmann et al., 2019)[2] sets out the conceptual framework. It places flood prevention within a broader conceptual framework of nature-based solutions. "*Nature-based solutions are actions which are: (1) inspired by, (2) supported by or (3) copied from nature"* (European Commission, 2015). Using this approach, nature-based solutions (NbS) is an umbrella term for other frequently used concepts such as "Natural Water Retention Measures," "space for rivers," and "green-blue infrastructure." The potential impacts of putting these solutions into practice are wide-ranging. Beyond the direct impacts on water quantity and quality, they enable the utilization of many additional ecosystem services.

Flood defenses are linked to the feasibility of these concepts in two important respects, but both are key issues for other sectors. The first is the need for additional land for flooding in the former floodplains of rivers that have been protected by the construction of flood defenses at the expense of periodic inundation. The second is that these additional areas are typically privately owned.

How can these lands be made available for water? Developing new and legitimate rules is by no means a minor detail that may be briefly settled at the end of an engineering-focused planning process. Nevertheless, past flood protection developments have typically followed

[2] I am a co-author of a commentary in this book, that puts a case study's findings into an economic context.

this logic. This is the challenge that the Land4Flood process has set out to address, with disciplines ranging from hydrology to ecology, agriculture, spatial planning, economics, sociology, and law, the latter mainly dealing with property rights, but the list could go on. An interdisciplinary framework for implementation needs to be established to address this multidisciplinary challenge. It is not enough to make land physically accessible to water; solutions must also be found to frame the occasional flooding within social rules (meaning legitimate landscape management regulations). This latter task is as challenging, if not more so, than the scientific clarification of the question 'How?'

The program's synthesis (Hartmann et al., 2022) already reflects a streamlined approach and context (illustrated by Figure Syn. 2 and Table Syn.1). It provides a coherent structure for the respective issues and tools in line with the logic of policymaking, focusing on the additional land needed for flood-risk reduction. The primary objective of setting up this synthesis structure is to support the successful establishment of multi-purpose land management systems. Three basic aspects are awarded an equal role in the approach: the natural, biophysical characteristics of the landscape; the ownership of land (with an emphasis on the issue of responsibilities and authorizations, which are not yet clearly defined); and the current form of the landscape as the institutionalization of interests (Hartmann, 2022b).

In practical terms, this means distinguishing between three preparation phases with different thematic focuses depending on the location in the river basin where flood-risk reduction can take place: the hinterland, the middle-confluence section of the river, and the flood-prone city itself.

Figure Syn. 2 Focal points of intervention in the river basin

Source: Adapted from Hartmann (2022b, Figure 1.2)

The preparatory phases of the process are (1) biophysical-hydrological planning, (2) the exploration of land ownership and the socio-institutional context, and (3) inducing a change in land use behavior using legal and economic instruments.

Table Syn.1 (below) shows the 3x3 correlation matrix. Each column represents the preparation phases for the distinct location types. The cells in the table indicate the key issues during each phase of the process.

Table Syn.1 The Land4Flood matrix associated with the Spatial Flood Risk Management process

LAND4FLOOD	HINTERLAND RETENTION *(slowing the accumulation, NWRM)*	FLOOD RETENTION & STORAGE *(room for polders, dike relocations)*	RESILIENT CITIES *(adapted urban areas)*
FLOWS *(hydrology engineering& ecology)*	Spatially spread, small scale retention measures' accumulative effects Capped impact of increased roughness and infiltration	Frequency of the transient water storage: room for the rivers or controlled polder Potential for bundling with ecosystem services	Reduction of damage, reduction of exposure, retention areas, sponge cities
LAND *(socio-institutional context of property rights & land use)*	Legal challenges of restricting land use A service for downstream regions or an imposed liability, obligation on land?	Transfer damage to a less valuable site. Hard conflicts on involving fertile and valuable land (up -stream) Setting the scene for the easement right of water	The levee effect on urban floodplain development – urban sprawl on low lying areas. Is the development option a right?
INSTRUMENTS to induce change *(law & economics)*	Transaction costs of dispersed measures. Get the willing landowners from the most effective locations into the schemes	How to obtain the easement right of water for a reasonable price? The challange of obtaining a contiguous site, new bundle of ecosystem services	Instruments of value capture

Source: Modified from Hartmann (2022b, Table 1.1)

The biophysical-hydrological planning phase (1) identifies the scale and the intervention alternatives; it also specifies where and how much land is needed for a given intervention alternative. This is the field of natural science exploration and planning from an engineering perspective. Phase (2) explores the land's status and socio-economic context, focusing on exploring customary uses beyond formalized rules. This approach can be used to map the web of interests affected by the provisional water cover on the land and drive stakeholder responses. It is necessary to raise the question of liability/entitlement related to property rights when the impact of land on flood risk is not previously known (e.g., can a forest area be cleared in accordance with a forest management plan if it substantially increases the flood risk of a downstream area in a quantifiable way?) The advancement in simulation technology makes it possible to explore these links (connectivity) much more precisely than before, but the responsibilities for the impacts, whether positive or negative, are not (or cannot yet be) resolved. They need to be integrated into existing regulatory frameworks. This is what allocating previously undefined aspects of property rights means. Deciding on such allocation issues goes beyond the authorization of decision support that's role is to facilitate the implementation process (means clarifying the respective parties of the allocation decision). From our point of view, this decision determines which party bears the cost of shifting between the targeted (social optimum) and the current land use. The analogy with Coase's classic case of air pollution is clear (Coase, 1960), wherein the optimal level of pollution does not depend on the allocation of the right to pollute. Nonetheless, decisions supported with the appropriate legitimacy are necessary (and indispensable) regarding the allocation of access rights to unpolluted air. This is the starting point on which economic regulation can be built, and it determines whether subsidies ("carrots") or penalties ("sticks") can be used in the spirit of a Pigouvian tax to trigger adaptation. This is the task of the preparatory phase (3), which can be used to develop instruments for supporting a shift towards coordinated land use (i.e., incentives or penalties) and financial transfer mechanisms. The information from the earlier phases of the preparatory process can be used to select and develop the most appropriate economic instruments for the challenge.

The usefulness of the SFRM approach is that it organizes the analysis and planning tools into a coherent structure. If Table Syn.1 is understood as defining the implementation paths for increasing social utility, then these phases are all necessary but individually insufficient components. Optimization criteria formulated at the level of the physical-hydrological simulation of run-off scenarios do not consider that the current use of these areas is a response to rules embodied in the institutions that have hitherto determined the use of the landscape. This cannot be fed back into the hydrological simulation versions without clarifying the socioeconomic and legal context of landscape use and taking into account the possibility of the adaptation of stakeholders to new landscape utilization rules.

Without the mapping of ecosystem services and the financial quantification of the services they provide, it is also not possible to develop an optimal pattern of land management. Moreover, natural assets are also exploited or made available through local institutions and regulatory systems. Financial incentive instruments such as PES (Payment for Ecosystem Services) may be appropriate in phase 3 of the implementation, but without the results of the earlier phases of planning (robust territorial impacts and identification of the service-provider and beneficiary groups), a financial transfer mechanism in itself will not be sufficient to operate a local payment vehicle successfully (Hartmann, 2022b).

An additional source of significant added value of the synthesized 3x3 Land4Flood structure is that it can target scientific research in the under-explored or problematic areas of the implementation processes. This thesis advances and contextualizes what is set out in the forward-looking summary of the SFRM approach:

> "Kis et al. (2022), but also Ungvári and Collentine, support the need to be able to prove the effects of measures for beneficiary parties from an economic angle. Ungvári & Collentine (2022) identify the issue of the monetary evaluation of retention-related benefits." (Hartmann, 2022a, p.166)

The chapter has provided an overview of the state-of-the-art approaches to flood defense associated with the water policy challenge described by the OECD report, Principles on Water Governance (Akhmouch et al., 2018). To successfully cope with future flood events, additional, mostly privately owned land must be incorporated into flood-risk-reduction measures. This is an advanced-level water policy challenge, the successful accomplishment of which requires building on the improvements in recent decades of quantitative flood-risk assessment methodology and the conceptual development of the implementation of multi-purpose, cross-sectoral policies. The Spatial Flood Risk Management approach is a framework under development that is designed for this need. This framework provides a roadmap whereby the essential building blocks of a flood policy implementation process may be built on each other. This structure addresses the sectoral and disciplinary diversity of the necessary knowledge and experience according to the specificity of the locations from the river-basin perspective. The advanced risk assessment and conceptual approach reinforce and presuppose each other's existence, as cross-sectoral coordination requires comparing the costs and benefits the quantitative method identifies.

Another important conceptual development from the literature is associated with the framing of the challenge: managing flood risk as a river-basin-level phenomenon in relation to individual land use decisions. In this context, it is reasonable to interpret a landscape's current flood-wave-formation characteristics as common-pool resources. Current land use patterns can be interpreted as the sub-optimal supply of a service to the public. The focus of the Spatial Flood Risk Management approach on exploring the socioeconomic context of land and the undefined conditions that are related to the definition of property rights helps define service providers and beneficiary groups whose agreement is a key element of the flood policy implementation process that aims to increase overall social benefit at the river-basin level.

5 APPLICATION OF ECONOMIC METHODS THAT ENABLE THE DEVELOPMENT OF MULTI-PURPOSE LAND-USE SCHEMES SUITABLE FOR RECEIVING FLOODS

This chapter brings together the different components of the thesis and highlights my contribution. In sub-chapter 5.1, the hydrological impact of flood-peak polders and other flood-risk mitigation measures are interpreted from an economic perspective to specify properly their services in a river-basin context. Sub-chapter 5.2 describes the application and results of the quantified risk assessment method in the case of the Tisza River flood-peak polders. These results create the basis in sub-chapter 5.3 to interpret the Tisza River case using the Spatial Flood Risk Management approach. Sub-chapter 5.4 reveals the potential of the cross-sector analysis of multi-purpose land management schemes using a cost-benefit approach.

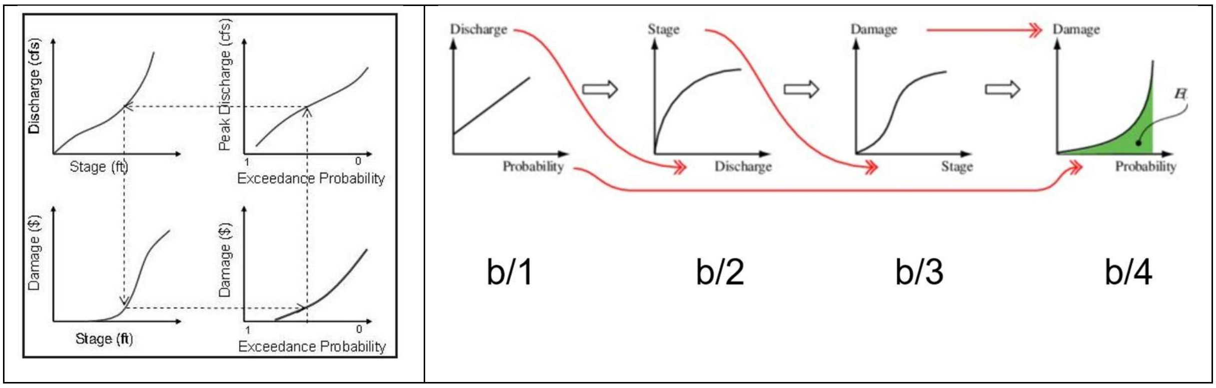
5.1 Connectivity through the impact on flood risk

5.1.1 The drivers of flood risk change

The predictability of flood-wave modification makes it possible and interesting to investigate the economics associated with the engineering descriptions of flood formation. In my opinion, this can provide the greatest impetus for the implementation of practice-oriented Spatial Flood Risk Management processes because it then becomes possible to link flood modification effects, which are spatially distant from each other, through their impacts on flood risk at different locations. The impacts on the level of risk can then be used to investigate and quantify the potential gains associated with improvements. The approach also can highlight when inappropriate regulatory solutions lead to increased costs or missed opportunities, which can occur if the information on public costs that is identified is not fed back into the decisions of the individuals who have contributed to causing them.

Figure Syn. 3 below describes the relationship between the magnitude of the damage and the probability of occurrence of the rainfall event that triggers a flood disaster and the underlying drivers. On the left-hand side, the system of relationships is shown from a very compact engineering approach. The right-hand panel, b), breaks this down more explicitly, indicating how each component shapes the flood risk (the green area under the curve in b/4) at a given point in the river basin.

Figure Syn. 3 Drivers shaping the components of flood risk

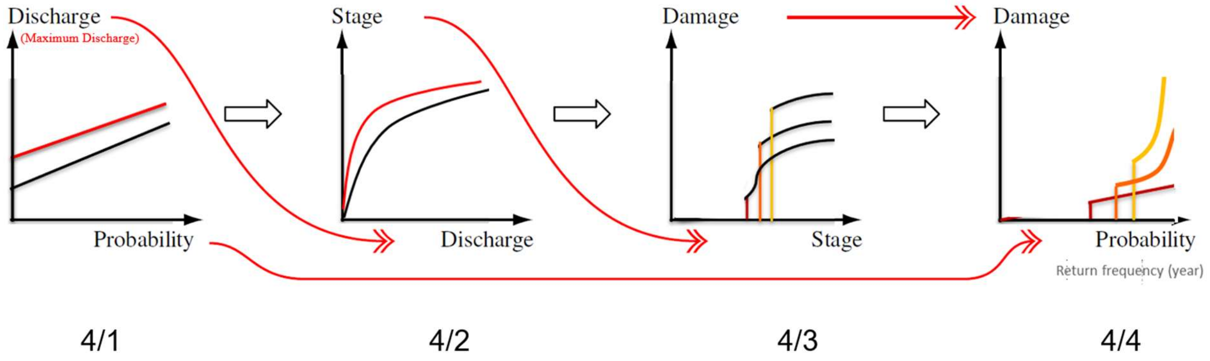


Source: a) Davis et al., (2008, Figure 3; b) Qi et al., (2005), Figure 1.

The sub-charts on the right (b/1 to b/4) show that the relationship between the probability of occurrence of a damage event (b/4) and the rainfall event causing the damage (b/1) is shaped by several factors. One factor is the speed at which the total amount of rainfall accumulates to form a flood wave (the shorter the accumulation time, the higher the maximum discharge value for the flood wave and the faster the flood wave passes). Another factor is the cross-section available for the flood wave to pass through at a given point in the river corridor. These determine the water level (stage) at which the flow peaks (b/2). The peak water level (stage) of the flood wave is a significant determinant of the extent of damage (b/3).

When we talk about the unprecedented magnitude of damage from a previously unprecedented flood wave (or the increased frequency of a rare flood wave) being the consequence of climate change, we are claiming that not only has a less frequent rainfall event occurred (rightward steps on the curves in b/1 and b/4), but also that the probability of a given rainfall event occurring has increased (change in curve shape in b/1), all other aspects being unchanged. It should be noted, however, that three other slow-moving drivers must be considered before assuming the impact of climate change, which change the shape of the curves that transform relationships and lead to an increase in risk. These driving forces are an increase in the value under threat, a decrease in the runoff capacity of the river corridor, and an acceleration in the accumulation of flood surges. Figure Syn. 4 illustrates the impact of these drivers on the relationship.

Figure Syn. 4 Impacts of long-term drivers on flood risk



Source: adapted from Qi et al. (2005, Figure 1). Legend: Figure 4/1 and 4/2: The red curve represents the effect of the driving forces that modify the accumulation of runoff. Figure 4/3 depicts the effect of building and increasing the dikes in two further steps to eliminate a proportion of the damage. Figure 4/4 illustrates that with the raising of the dikes, damage only occurs during increasingly rare flood events (the probability of occurrence is expressed as the given frequency of return periods in years).

5.1.2 The impacts of drivers

5.1.2.1 Increase in exposed value

In the short term, building a dike and thus protecting an area means eliminating part of the hazard. In the longer term, however, there are several other aspects to consider. Protection makes the formerly exposed area desirable for further development and therefore increases its value. This should not be seen as a problem in itself, as this is the purpose of the investment. The viability of this approach is confirmed if the financial conditions for expanding the capacity of the protection infrastructure can be met when development becomes necessary again due to the experience of higher floods. This cumulative process is illustrated by the three curves in Figure 4/3. Moving from left to right, the step-by-step dike elevations eliminate a proportion of the damage curves that shift higher and higher (Davis et al., 2008). The depiction of the evolution of risk is consistent with Figure 2 of Aerts et al. (2018), which describes a multi-step increase in the magnitude of risk under assumptions of limited rational behavior.

In addition to natural events, in Figure 4/3, the relationship between the flood level and the magnitude of damage includes another probability – the probability of failure of the protection infrastructure itself. As the water level of the flood wave approaches the height of the dike, the probability of failure increases. In the Figure 4/4 sub-chart, the probability includes the likelihood of the rainfall event and of the failure of the protection infrastructure together. For this reason, the probability of the occurrence of a given damage value is greater than the probability of a flood level topping the dike. At the same time, the defense infrastructure appears has finite capacity in the relationship. Its expansion and maintenance as cost components can be compared with the impact on the risk reduction capacity of interventions elsewhere in the river basin.

It is rational to defend any increase in value exposed to damage against increasingly rare and destructive events. However, there are physical and financial limitations to raising dikes as a defensive solution. Other considerations emerge and make examining alternative solutions to further raising dikes necessary. Higher dikes require an increased ground surface area (Schweitzer, 2001). Another question to resolve is the conflict of interest between being protected against very rare hazards (i.e., 100-year return frequency or even less frequent floods) and improving the quality of everyday life (e.g., community access to the river, increasing demand for recreational riverine environmental areas, etc.).

5.1.2.2 Decrease in runoff capacity in the river corridor

The limits of a dike-increase-based defense strategy become apparent if, in addition to the gradual accumulation of the increase in the protected value, two additional long-term processes are included, which are represented by additional graphs of the relationships (Figure 4/1 and 4/2) and which force further adaptation (and expenditure). The relationship between the peak flood level and the required runoff cross-section is indicated in Figure Syn. 4/2. The basic message from this relationship is that a greater discharge of water flowing through per unit of time results in a higher peak flow. However, studies inspired by the floods on the Tisza around the turn of the millennium (1998-2001) of unprecedented repetition and peak flow revealed that floods with similar discharge rates tend to result in higher flood peak levels over time (Szlávik, 2003). These results highlight the presence of hitherto ignored systemic effects. The study of Schweitzer (2001) identified the already significant impact of annual sedimentation on the floodplain in the river corridor over a century and a half and the consequences of changes in floodplain land use. Figure Syn. 4/2 illustrates the effect of these driving forces and the decrease in the cross-section of the river corridor that causes the same discharge to have a higher peak flood level.

5.1.2.3 Precipitation occurrence and discharge

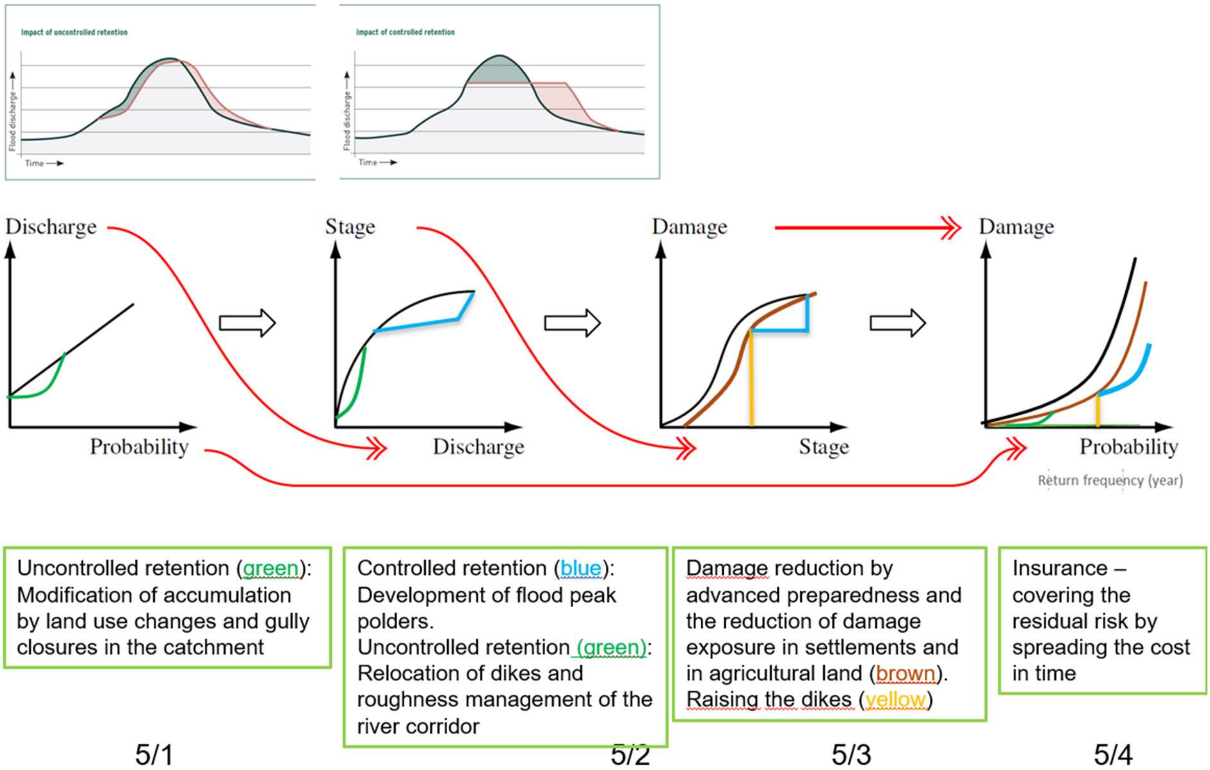
Figure Syn. 4/1. relates to the fact that less frequent extreme precipitation events are associated with higher water discharge. However, the shape of the flood wave that accumulates in response to a given probability rainfall event also depends on how quickly the falling water reaches the watercourse. The greater the velocity, the shorter the length of the wave, but the more significant the maximum discharge of water that passes through a river section within a unit of time, hence the peak height of the wave (Pohl & Bezak, 2022a). In areas of accumulation (typically mountainous areas), the replacement of forests for pasture, drainage channels for roads and road protection, the expansion of settlements, and the paving (and reduction in roughness) of surfaces, in general, all accelerate the rate of flood wave accumulation. These processes are reinforced when formerly open flood plains at the foot of mountains are protected by the construction of new dikes, as has happened, for example, in the case of the Tisza River in the transboundary river sections. Thus overall, the probability of a given maximum flow, or the maximum flow of a flood wave resulting from a given probability of occurrence, increases even without a change in the probability of occurrence of the precipitation event. If the vertical axis in Figure Syn. 4/1 does not represent the total amount of precipitation during a rainfall event, but the maximum discharge, which is relevant for the peak flood level, the curve describing the relationship shifts upwards due to the changes. These processes, individually but cumulatively, increase the perceived flood threat and flood risk in the lower reaches of the river basin.

To these three drivers, which reinforce each other, is added the actual impact attributable to climate change. Current climate modeling results and projections suggest that changes in our region will have less effect on the total amount of precipitation falling in a year than on its more concentrated occurrence in the form of fewer but more intense rainfall events (Skarbit et al., 2022). That is, the maximum runoff value and the amount of precipitation falling in a single rainfall event may be expected to increase, i.e., an upward shift of the curve in Figure Syn. 4/1. Flood risk increases due to long-term societal drivers, even without assuming climate change, but these drivers can be influenced and managed to adapt successfully to changing conditions due to climate change. We need to move in the same direction, applying a wider set of modular, expandable solutions; this is what adopting a spatial management approach can provide.

5.1.3 Flood-risk mitigation measures

The novelty of the challenges arising from the above-described contextual framework is that simulation techniques are capable of dealing with spatial characteristics and hydrological processes at a much greater spatial resolution than before, allowing us not only to think about protection on the exposure side (raising dikes, reducing damage exposure, improving evacuation capacity, etc.) but also to intervene predictably in the process of flood wave accumulation and runoff. The top row of figures in Figure Syn. 5 indicates that by using additional space, such solutions modify the shape and course of the flood wave.

Figure Syn. 5 Measures and instruments for modifying flood waves and flood risk



Source: top row, Munich RE (2014); middle row adapted from Qi et al. (2005, Figure 1). Legend: Explanation of interventions: measures are distinguished by colors, express their distinctive effect, and modify the underlying relationships.

The interventions described in the figure on the upper left are aimed at slowing down the accumulation of the flood wave (Pohl & Bezak, 2022b). This impact can be induced by, e.g., afforestation of the catchment's accumulation areas, the creation of gully closures, and the collection of drainage from roads. In the confluence area – along the middle section of rivers – similar slowing effects can be achieved by, e.g., widening the floodplain via dike relocation. The effects of these interventions are illustrated by the green-curve modifications of the original (black) curves in Figure Syn. 5, which modify the basic relationships (black curves). However, the impact of these interventions on flood risk is at some point overridden by the increase in the intensity of the rainfall event or the magnitude of the flood wave. Their hydrologically significant impact on runoff can be attributed to lower intensity, smaller flood waves (hence the green curves at the more frequent end of the probability scale). These interventions account for a small fraction of the total impact on the magnitude of risk. However, locally, in sub-catchments, these interventions alone can significantly impact flood risk and be associated with other important ecosystem service co-benefits.

Interventions described by the top row, right-hand chart in Figure Syn. 5, can be implemented where sufficient land is available. These areas can be located along the middle section of rivers where flood-peak polders can be implemented to cut off the peak of the flood wave. From a flood-risk reduction point of view, this measure is more effective (on a per capita land area basis) than measures that slow down flood wave formation. Their effectiveness lies in the fact that they only have a targeted effect on the peak volume of the flood wave that is the most dangerous.

Risk management solutions involve dividing the intervention portfolio (elements in the green boxes) into domains financed by private or community resources. The former include solutions for the insurance market and reducing individual exposure. In contrast, the latter includes measures for defense infrastructure development and maintenance, land use, and landscape conservation practices funded by the community or a subset of the community. Figure Syn. 5 highlights that quantitative risk assessment analysis is suitable for comparing a wide range of measures and providing information on which measure is the most appropriate solution. This is the point from which it is difficult to move forward based on natural-physical characteristics alone without an inter-disciplinary, policy-implementation-centered approach like Spatial Flood Risk Management.

The fact that there is still insufficient space along rivers for transient water cover and that individual interests prevent the enhancement of community benefits may be because it is not worthwhile for society to compensate for flood damage to a delimited area in exchange, or it may be worthwhile compensating, but stakeholders cannot successfully structure the conflict-resolution challenge. One explanation for the latter is that the institutional capacity and/or the supporting economic information are lacking.

5.2 The relationship between flood-risk reduction and land use

This sub-chapter presents the elaboration and use of quantitative flood-risk calculations, including how management options are broadened if this economic information is available. The case of the Tisza River flood-peak polder development provides the basis for this elaboration. Moreover, it provides an evidence base that helps identify organizational (management) challenges associated with the shift towards nature-based solutions.

5.2.1 Spatial and Nature-based solutions

A key aspect of managing the risk of flooding is the level of protection our solutions provide against floods with a specific return frequency. In the case of defense systems based solely on the height of dikes, this relationship can be seen, with some simplification, as a binary relationship: up to a given flood level (typically a 100-year return frequency), this protection is close to complete, but above this level (for more extreme floods) it can no longer provide protection. In the case of a flood protection strategy that includes an additional polder, this relationship becomes more complex. A flood peak that can be discharged from the river corridor in a controlled manner can reduce the flood risk depending on the capacity (size) of the polder. From a hydrological point of view, the controlled inundation of the polder is necessary if the peak flood wave height exceeds the level of the dike, i.e., for floods that are even less frequent (more severe) than of 100-year return frequency. In the case of such rare flooding, there is no reason to make significant changes in the land use of the polder and thus reduce its economic productivity. For this reason, controlled-discharge reservoirs are not usually considered a nature-based solution. At the same time, any solution that provides (even temporarily) additional area for the river can be viewed as a spatial flood-risk management solution. A spatial solution is really considered to be a nature-based solution if the use of this additional area is associated with the floodplain habitat. The confusion between the two concepts exists because the most easily accessible additional surfaces for flood-risk reduction are located "under" the habitats that are disconnected from rivers but still of high natural quality.[3] In the case of nature-based solutions, flooding can be assumed to occur with high frequency (even every year), which requires the development of more water-tolerant or water-conditional land-use solutions. Usually, this results in lower productivity and income from direct-use activities. There is a very serious management challenge between creating surplus land for flooding and developing nature-based land-use solutions.

The economic challenge of implementing spatial flood-risk management with nature-based solutions is optimizing the interrelated flood frequency and land use characteristics within a common framework. The joint maximization of individual and community benefits provides the optimal solution from a societal perspective. This requires, however, that areas are not optimized in terms of a single function but in terms of a bundle of services.

The logic of the cross-sectoral and cross-utilization approach is seeing how flood-risk reduction as a service interacts with different land use scenarios, moving from infrequent to more frequent flooding, and how the overall utility of the service packages changes accordingly. Do any of

[3] Or the restoration of natural vegetation cover in the catchment area is expected to increase roughness, which will slow down the accumulation.

them generate a positive balance? Does the surplus cover the compensation required for those who bear the cost and the transaction costs of initiating the adaptation process? Do they provide a solution to the challenges of changing agricultural livelihood practices associated with land use? Is the spatial flood-risk management process trying to support a sustainable goal?

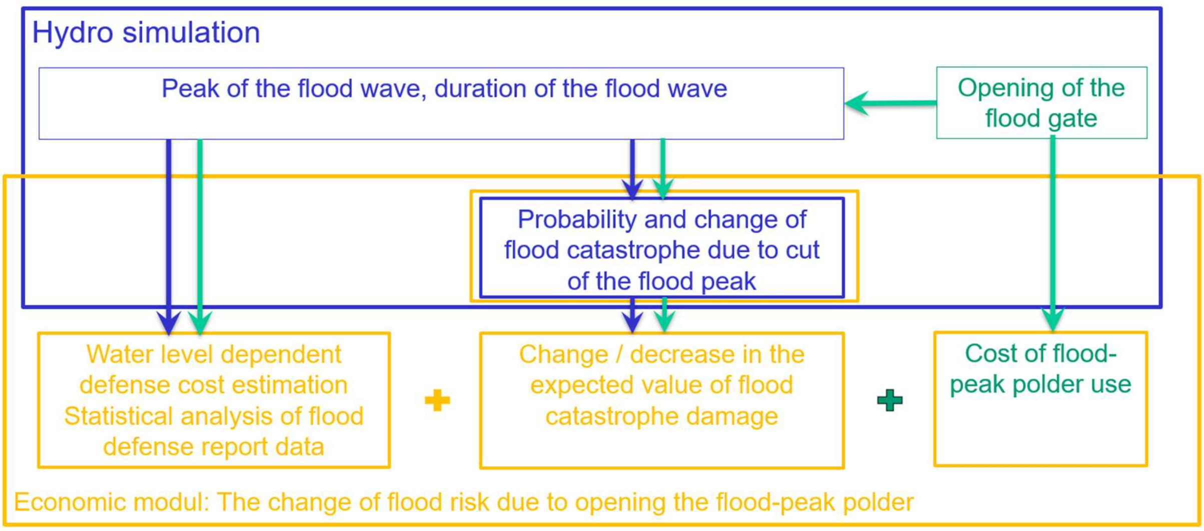
The underlying economic dynamics of this approach are demonstrated using the example of the development of the flood-peak polders along the Tisza River.

5.2.2 Questions concerning the economics of flood attenuation interventions

The most effective solution for reducing the flood peak in the middle section of a river is using floodgate-controlled flood-peak polders, which can cut off the top of an approaching flood wave. This is because, unlike the other solutions associated with the "Room for the River" approach (the relocation of dikes or passive flooding of the polder through a spillway), the available area can be exclusively flooded with water from the top of the wave that generates the most significant problems. The capacity of the other solutions is partly filled up and used by water from the less dangerous sections of the flood (illustrated by the top-right chart in Figure Syn. 5)

Unlike passive solutions, opening a flood-peak polder implies a decision. This decision can be based, in line with the classical practice, on hydrological characteristics, i.e., aimed at preventing the flood level from exceeding the level of the dikes (or of the sandbags installed upon the dike during the period of defensive work). However, it can also be based on economic considerations. The figure below illustrates this relationship.

Table Syn.2 Drivers behind the decision to open a flood-peak polder

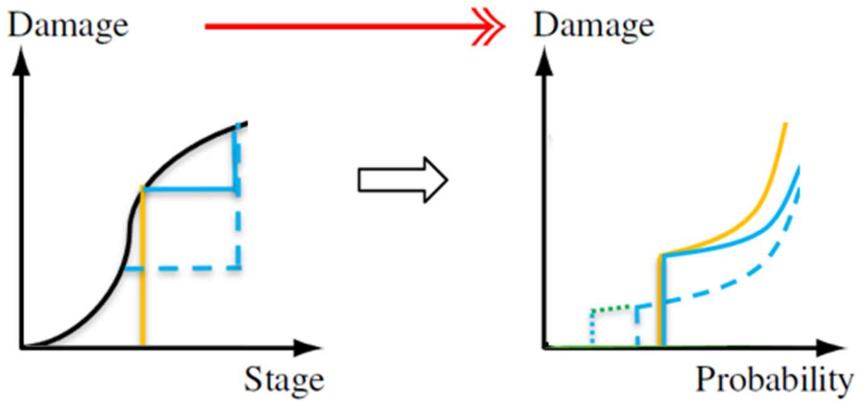


Source: REKK (2018)

It makes economic sense to open a flood-peak polder if the value of the damage caused inside it is exceeded by the avoided expected cost (including the avoided disaster). From here on, this is referred to as the "expected value of cost reduction" (i.e., the benefit of opening a flood-peak polder). A detailed discussion of the calculation methodology can be found in the first article of the thesis (Ungvári & Kis, 2022b). Another distinctive conceptual term refers to the flood level at which the benefit of opening a flood-peak polder equals the damage caused by flooding the polder, which is the economic break-even point. This flood level can also be described by the return frequency of the flood event with the same flood peak level.

Flood defense dikes are typically designed to safeguard against a 100-year return frequency flood. This flood level is also the planned opening frequency of the polders built according to the "Further Improvement of the Vásárhelyi Plan" program (as the respective law defines the objective). This reflects the hydrological approach of opening a polder (Ungvári & Kis, 2022b). However, based on the economic approach, the economic break-even point calculation for the polders shows that it is rational to open them even at lower peak levels (which means more frequent floods). The calculations fall within the 20-40 year return frequencies for the Tisza River polders (Ungvári & Kis, 2022b). This relation is depicted in Figure Syn. 6; the opening of the flood-peak polder does not occur at the height of the top of the dike (yellow line) and have an effect (blue line) on the damage curve but is opened at a lower peak flood level (dashed blue line). In the figure on the right, the area under the curves equals the risk. The dashed blue curve indicates the impact of opening according to the economic approach instead of the blue curve, which describes opening near the dike height. (The yellow curve indicates the dike-only original situation).

Figure Syn. 6 Opening of flood-peak polder at the dike crest and the economic break-even point



Based on the economic break-even point approach, a change in damage exposure in the polder influences the break-even flood level at which the decision to open is considered profitable.

Our previous studies have shown that a reduction in exposure alone 'pushes down' the economic break-even point. However, the permanent reduction in agricultural productivity associated with a reduction in exposure, assessed over all years, amounts to a more significant loss than the value of compensation that can be avoided in years of flooding (Weikard et al., 2017). It is not worth making the land use area of a flood-peak polder available for all floods, taking into account the goal of flood-risk reduction alone, and therefore changing current land use based on arable farming (illustrated with a blue dotted curve in Figure Syn. 6).

The economic-break-even point approach, however, defines the additional benefits needed to ensure that the total benefits from land use associated with flooding exceed the income from arable farming. This is the precondition for making space available to the river every year and specifying the increase in total social benefit of the adapted land use. This issue is the subject of the second article in the thesis (Ungvári, 2022)

At the time of the development of the Tisza River flood-peak polders, CBA-type calculations were not yet possible (Halcrow Water, 1999). Investment decisions were based on a cost-minimization approach. The legal arrangements for the eventual use of private land in polders also fit this logic. They consisted of lump sum upfront compensation equivalent to approximately 30% of the land value and an obligation to pay compensation on a case-by-case basis if the polder is inundated. With this solution, landowners received a substantial lump sum compensation, while the actual disruption of cultivation was postponed to an uncertain future date. Developers thus reduced their investment costs compared to expropriating the entire polder area.

A decade after the construction of the flood-peak polders, the decision point concerning opening the polders was reassessed in a development program aimed at integrating the individual polders into a complex system (REKK, 2018). This assessment was carried out on a cost-benefit basis, capitalizing on the technical improvements that made quantified flood-risk assessment available (Ungvári & Kis, 2022b).[4] The results provide insight into the relation between the structure of the flood-risk benefit that is realized and the nature of land use in the polders. According to the ex-post calculations, the reduced risk that the flood-peak polder development achieved and the area of land that made this feasible would have made the investment beneficial even if the land for the polder had been expropriated at the time of the

[4] This is the first article in the thesis. It explores the applied methodology and the results in detail. Here, only the elements that fit with the line of thought of the synthesis are highlighted.

investment. However, it can be deduced from the above reasoning (5.1.3) that this economic benefit is derived from the risk reduction impact of very rare floods (Ungvári, 2022). If the goal is constrained to providing additional land for rivers, this may be seen as a missed opportunity, but if land use adaptation is seen as a means of increasing overall social well-being, then land use change is justified if the quantifiable and robust benefits outweigh the value that would be lost by the change. If the land were in public ownership, the state, as the trustee, would be justified in changing the land use if benefits to the public and individuals could provide this surplus. This management challenge was not met at the start of the VTT process (see sub-chapter 5.3). However, the opportunity cost of multi-purpose land use can now be mapped more accurately (sub-chapter 5.4).

In the remainder of this chapter, I argue why, despite the difficulties, it is justified to consider using flood-peak polders in the context of nature-based solutions and, when appropriate, to incur additional costs to achieve complex land management solutions.

An alternative to constructing flood-peak polders could be widening the floodplain by relocating dikes. Ex-post analysis of a floodplain-widening intervention in the Fokorú-puszta area of the Tisza River upstream of Szolnok shows that the balance of the intervention is positive (REKK, 2020), taking into account the reduction of flood risk and the ecosystem services that can be realized through land use change. However, when the impact on flood risk is compared with the specific (per unit area) impact of flood-peak polders with a similar spatial reach, the flood-risk reduction effect of widening the floodplain is only 20%-38% of that of the polders (Ungvári, 2022). The result of the comparison is not overturned when ecosystem services are considered. Widening a floodplain, when there is an opportunity for this due to other development considerations, is a beneficial intervention. The economic balance of such a development can be significantly improved by creating opportunities for ecosystem services. However, if the aim is to achieve the maximum flood-risk reduction effect for a given area, it is appropriate to consider complex solutions that provide opportunities for both controlled flood discharge and other types of benefits.

Partly similar conclusions can be drawn from the preparatory calculations for a complex development program in the Elbe River at Lenzen (de Kok & Grossmann, 2010; Teichmann & Berghöfer, 2010). In the analysis, scenarios of floodplain widening, flood-peak polder construction, and a flood-peak polder operated with regular flooding were investigated. Regarding the impact on flood risk, the performance of the dike relocation was significantly less than that of the flood-peak polders. The difference that reverses the order of the findings occurs when two types of ecosystem services are considered (the first of these is the value of floodplain ecosystem restoration, based on a willingness-to-pay study; the second relates to improvements in nutrient retention capacity that can replace the development of wastewater treatment plants). Including ecosystem services in the comparison indicated that dike relocation could be the preferred option. This led to a successful process of planning, negotiation, and investment. However, only 10% of the costs were borne by the stakeholders. The provincial and federal governments provided the rest of the necessary funds. Neither the willingness-to-pay study nor added nutrient retention capacity created the basis for a local financial transfer mechanism between beneficiaries and service providers. The 600 hectares of land re-introduced to the floodplain were transferred into public ownership. As a result of the land consolidation and land-swap programs for which the provincial government purchased the land, those wishing to continue farming were able to do so on the protected side of the new dike on land with a more advantageous parcel structure (Drees & Sünderhauf, 2006). The inclusion of additional land to the floodplain as a result of the program was successful. It is worth noting, however, that behind the significant results and the long and detailed stakeholder negotiations required for success, public resources were relied upon to put all stakeholders in a better position, and only a small part of the flood-risk reduction potential has been exploited. The high transaction costs, the fact that the management of conflict resolution has been almost entirely externally financed and that the space opened up to water became public property make it unlikely that this implementation method will spur the creation of space for watercourses on a larger scale in more locations. A more viable option, Teichmann & Berghöfer (2010) conclude, is that the most attractive outputs are expected from solutions that combine flood-peak polder infrastructure with realizing ecological benefits. However, the case highlights the importance of having functioning local institutions that can engage in conflict resolution, negotiate an acceptable development scenario, and identify the financial solutions to fund it.

5.3 The challenges of implementing multi-purpose land use

Along the Tisza, developing a system of flood-peak polders can be interpreted as a paradigm shift that went beyond the previous strategy (the critical element was the repeated raising of the dike heights). Solutions on a similar scale and complexity have been implemented in only a few places in Europe (Netherlands [Busscher et al., 2019] and Germany [Thieken et al., 2016]). The use of controlled opening is unique at this scale, as is the size of the polder areas. However, the perception of the Further Improvement of the Vásárhelyi Plan program is far from unanimous (Borsos & Sendzimir, 2018; Werners et al., 2010). Indeed, the successful policy, in terms of flood protection, was part of a complex flood protection and rural development plan. The land-use change objectives defined in the program were not achieved, and the program can therefore be considered a policy failure in this respect. The explanations are manifold (Albright, 2011; Sendzimir et al., 2008); they touch on several layers of institutional and cultural preconditions (or the lack thereof) that are necessary for a successful policy-making process (Werners et al., 2009). For drawing further conclusions, however, it is useful to describe the process in the context of the Spatial Flood Risk Management approach and to differentiate between providing the necessary space and creating the more complex institutional system needed to develop nature-based solutions. The development of flood-peak polders as an effective infrastructure solution and the institutional framework established to provide the necessary additional land for their operation can be seen as an initial step in an adaptation process that has already significantly increased social well-being (in the form of reduced flood risk and avoided higher investment costs, as elaborated in Ungvári & Kis [2022b]). However, the arrangements established to include additional land have not been able to exploit all the potential benefits that could be achieved through the operation of the infrastructure. This is a successful Spatial Flood Risk Management development that has not exploited the potential of nature-based solutions. Lessons learned from the process of similar flood defense investments suggest that achieving rural development objectives requires institutional and management capabilities (the meso-institutional layer, as defined by the OECD report) and further social and organizational prerequisites (Pahl-Wostl et al., 2013). I believe their enhancement can only be expected after clarifying that flood-risk reduction is a service a territory provides and defining the responsibilities and entitlements associated with the ownership of the respective land. (The economic potential for such a development in the region is analyzed in a paper by Ungvári [2022]).

The third article that makes up my PhD (Warachowska et al., 2023) compares the development of flood-peak polders on the Tisza and a Polish river, the Warta. Both river basins have experienced severe floods in recent decades. In 2010, the first flood-peak polder at Tiszaroff was successfully opened to attenuate the flood wave. On the Warta, despite the creation of the physical conditions, the polder has not yet been put into use. Due to the debated terms of use, farmers in the area prevented the release of water using temporary barriers.

The institutional frameworks for claiming the inundation of areas are significantly different in terms of clarifying the conditions attached to land ownership in the polders. In the Tisza River case, the legislation reflects the initial assumption that the inundation of a polder area is an event in the public interest to the detriment of private property and that since it is intentional, as it is caused by the opening of floodgates, landowners are entitled to compensation. In the case of the Warta River polder, the land-access conditions have not been clarified. The public institutions have tried to avoid compensation altogether or to limit their liability to payments covering only a fraction of the damage caused based on a disputed piece of legislation concerning land classification. Land users have acted to avoid direct financial losses and have prevented flood attenuation, burdening the downstream populace. A crucial difference between the two cases is that ex-ante studies on the Tisza River revealed the cost difference between investment alternatives with similar hydrological effects (cost-minimization approach). This revealed that the higher overall costs of the alternative development scenario dwarf future compensation payments linked to the polder area. No similar comparison was made for the Warta River, where the unclear land classification and the favorable geographical conditions of the area triggered the intended use of polder capacity.

The Tisza solution is a typical example of top-down regulation, which was successful because it ensured fair conditions, but stakeholders could not participate in the planning process. This top-down planning approach, irrespective of its details, has the potential to fail. The Dutch "Room for the River" program provides an instructive example of how development plans have had to be withdrawn after being announced due to social protest. The opposition to developing an emergency polder from the Ooij polder was not a classic NIMBY action. Participants built up a solid flood-policy-based critique of the plan, which could clearly have been avoided through a more openly managed development process (Roth & Warner, 2007; Warner, 2008). In the case of the Overdiepse polder, the development of the flood protection function was implemented with significant changes and delays compared to the announced plans. Ultimately, successful implementation involved a farm-by-farm consultation process forced by the farmers concerned to manage the conversion of the affected economic activities (Roth & Winnubst, 2014, 2015). The latter case is presented as an example of a successful solution associated with the Dutch program (Busscher et al., 2019); this retrospective analysis reviews the design process of the broader Dutch program with a focus on the different disciplines involved and their respective professional organizations and the range of methods developed.

Within the framework of the conditions set out in the VTT Act, the choice of landowners was limited to whether they accepted the above-quoted terms or faced expropriation of their land. In the latter case, they would have lost the EU-CAP subsidies linked to agricultural land, which were the financial basis for their livelihood. As can be seen, this legal solution created the right conditions for the provision of additional land for flood protection services. Meanwhile, despite the attempts, the rural development sub-program failed. The planning process of the sub-program incorporated consultations with local stakeholders, but nature-based solutions have not been implemented in the polders. This policy failure can be traced back to the quality (or lack) of the respective meso-institutional layer because financial resources were available to support the land adaptation process.

The elements of the VTT complex rural development program were initially aimed at changing the land use of the polders and switching to floodplain farming activities. To achieve this complex objective, special SNA (Sensitive Natural Areas) program packages were developed for the polder areas under the EU Common Agricultural Policy support scheme 2007-2014. Despite the financial resources thus made available, there has been no change in land management practices in the polders. If we look at the decision from the agricultural land users' point of view, who are concerned with maximizing income, the following elements should be taken into account:

(1) Floodplain-specific activities typically generate less income than arable farming. The logic of the EU-CAP SNA subsidies was to compensate for the loss of income due to lower productivity and to finance a complementary incentive element. The SNA payment scheme did not provide higher specific (per hectare) support than arable payments, contrary to the initial plans, due to the vested interests that determine the CAP sources' distribution in respect of national jurisdiction.
(2) The activities that generate the environmental benefits of the SNA programs are considered as costs or lost revenue in usual agricultural practice. Changing the type of farming on parts of farmland would require significant changes in established farming practices, primarily experienced as a constraint by those involved.
(3) Additional value generation would only have been possible using new, untested, or undeveloped product pathways with very uncertain prospects. The pasture incentive programs lacked the livestock in place that had previously created the economic demand for this type of land use.
(4) These new land management solutions also require effective cooperation between farmers situated next to each other because of the need for shared water management, but a culture of effective cooperation is lacking.

Overall, there has been no interest in the polders as the financial incentives do not provide a higher income in the short term but, in the longer term, would have involved high transaction costs and economic activities with very uncertain returns.

The VTT case highlights an important land management characteristic that strongly relates to the area's institutional capacities. Unlike spatial solutions, nature-based solutions require the active role of the land user. In the case of a simple spatial solution, the land use activity does not build on the natural vegetation or natural landscape features of a floodplain. A damage-compensation type passive relation between the land user and the beneficiaries of the flood-risk reduction is sufficient. But the realization of public flood benefits always remains a constraint on business activity. Creating and maintaining such an arrangement from an institutional point of view is easier (albeit not easy) than reorganizing the business model that the current land use supports. Most of the benefits a nature-based solution provides cannot be translated into direct or short-term income revenue streams for the landowner insofar as additional arrangements and financial payment vehicles that share such benefits with the provider are lacking. At the same time, such benefit-sharing schemes can support business models for the landowner that may improve their economic position. These solutions require more advanced agreements and a facilitating institutional environment where the costs and benefits for the parties involved must be monetizable and robust. The next chapter focuses on the underlying cost and benefit issues a nature-based solution must deal with.

5.4 Linking sectors and locations

The focus of the analysis in my second article (Ungvári, 2022) is the complex case of land management in a former floodplain area in the Middle-Tisza region between Cibakháza and Tiszaföldvár (REKK, 2021). The case description reflects on the aspects discussed in the thesis and, in applying the Spatial Flood Risk Management approach, explores the preconditions for developing a nature-based complex landscape management system and its economic viability.

The cost-benefit analysis looked at scenarios for the multi-purpose use of the site from a theoretical point of view; no actual development in the area was considered. Three flood modification scenarios were examined for three land use scenarios (one being no change to current land use). The three flood modification scenarios reflect the cases used as examples earlier in the text. The first one assumes the opening of the area to all floods. The second is a spillway and partial lowering of the dike height (this solution was applied to the Overdipese polder and the Warta polder), with the result that floods with a return frequency of 30 years or more overtop the dike and inundate the thus-created polder. The third scenario assumed the operation of a flood-peak polder, as already constructed in other locations along the Tisza. The scenario assumes cutting off the peak of floods with a 50-year return frequency or greater. The land use scenarios assume the current land use, a partial adaptation with the continued dominance of arable land, and full afforestation of the area. The partial adaptation scenario can be considered the maximum acceptable level of change based on the principle of common sense. As the respective article presents the details of the analyses, only the most relevant parts will be highlighted here that support the present line of thought.

In addition to the impact on flood risk, the analysis quantifies the agricultural and forestry benefits and the ecosystem services (carbon sequestration) that would be provided. The results of the other site analyses presented in the same article (Fokorú puszta dike relocation) justified narrowing the ecosystem service scope to carbon sequestration, which was found to have the most significant impact. On the other hand, I aimed to investigate more robust and widely accepted impacts, which would allow clear conclusions to be drawn.

- The partial land use adaptation scenario was worse in all respects than the other two land use scenarios. This is because flooding scenarios inflicted less but still significant damage, while the reduced productivity worsened the relative performance of this scenario compared to the current land use. Further, both scenarios were outperformed by the afforestation scenario.
- In all scenarios, the impact of flood-risk reduction (including the cost of investment to delineate the area to be flooded) without considering the value of carbon sequestration resulted in a negative present value. (To ensure the proper context, it must be borne in mind that the simulation was theoretical; the area delineation was not subject to hydrological planning that assessed how to maximize the area's per capita flood-risk reduction potential. This is thus an 'ordinary' site from a flood mitigation perspective.)
- The profitability of the medium-quality arable land, calculated with and without current EU CAP subsidies, is less than the profitability of afforestation scenarios if the value of carbon sequestration is included (The results are robust within a 50-year, 2%-5% discount rate range).
- Incorporating the value of carbon sequestration due to afforestation fundamentally changes the overall financial balance. Assuming the upper end of the future carbon price range (€37-€74/ton CO_2) used by the EBRD and the World Bank for project valuations, the flood scenarios with lower investment costs (frequent flooding and flooding through a spillway) show a positive economic balance. However, these results are sensitive to changes in discount rates.
- A change in the current land use by afforesting the area would result in a positive balance of value for both land users and the public, while from the land users' point of view, the breakdown of costs and benefits throughout the lifecycle is unfavorable and requires further consideration.

The table below shows why, despite the win-win situation identified by the cost-benefit analysis, it cannot be assumed that land use change will occur per se.

Table Syn.3 Summary of results

	Land use (LU) and flood scenarios								
	Current LU, no flood (BAU)	**Forest LU, no flood**	**Forest LU, all floods**	**Forest LU, spillway**	**Forest LU, flood gate**	**Forest LU, no flood**	**Forest LU, all floods**	**Forest LU, spillway**	**Forest LU, flood gate**
Results, Net present value	million EUR					ratio: NPV scenario / NPV BAU			
Investment cost (flood defense)	0	0	-20,1	-20,1	-31,8	-	-	-	-
Farmers' balance with Transfers	23,4	32,7	32,7	32,7	32,7	1,4	1,4	1,4	1,4
Farmer's balance without Transfers	8,7	22,5	22,5	22,5	22,5	2,6	2,6	2,6	2,6
Public benefits*	-4,5	11,2	12,3	13,1	20,3	-2,5	-2,7	-2,9	-4,5
Sum of all CBA items	18,8	44,0	24,9	25,8	21,3	**2,3**	**1,3**	**1,4**	**1,1**
Sum without CO2 benefits	23,4	32,7	13,7	14,5	10,0	1,4	0,6	0,6	0,4

Legend:NPV calculated for a 50-year life cylce with 2% discount rate. * Explanation for interpreting the indicated rows: the "flood-risk change" in public benefit is the difference between the reduction of flood risk as a benefit (with a positive sign) and the damage caused by flooding of the area. For the Current LU, the cell is negative because the value of the "flood risk change" is zero, while arable cultivation results in CO2 emissions. In the columns showing the ratios on the right-hand side of the table, the resulting negative sign means that the balance of public benefits from afforestation has turned positive and increased by 2.5 to 4.5 in absolute terms.

For farmers, subsidies make the low productivity of current agricultural activity profitable. The ratio of the income generated by afforestation to the current income increased by subsidies is only 1.4, compared to 2.6 times higher when the subsidies are removed. From the farmers' point of view, this (x 1.4) increase is not a particularly attractive proposition (despite the higher income). This is because the necessary change in farming practices is a process involving considerable adjustment costs for the farmers, both in terms of machinery and applicable farming knowledge and, on the other hand, because the income from forestry activities is not recouped evenly but generated decades after afforesting an area.

Looking at the results according to the 2%-5% discount rates, the position of flood-risk reduction investment and forestry activity is even more divergent. Table Syn.4 provides the background with the key elements of this sensitivity analysis.

Table Syn.4 The results of the flood scenario alternatives of afforestation compared to the BAU scenario at different discount rates.

	Land use (LU) and flood scenarios			
	Forest LU, no flood	**Forest LU, all floods**	**Forest LU, spillway**	**Forest LU, flood gate**
disc.rate	ratio x BAU	ratio x BAU	BAU	BAU
2%	2,3	1,2	1,4	1,1
3%	2,2	0,8	1,0	0,6
4%	2,1	0,5	0,7	0,1
5%	2,0	0,1	0,3	-0,3

Legend: The BAU scenario is the same as in Table Syn.3, the Current LU, no flood scenario. The 2% row is the same as the "Sum" row in Table Syn.3. The negativ value in the last row only reflects that the scenario with the given discount rate already has a negative NPV.

Due to the significant initial investment costs, the flood-risk mitigation effects of the scenarios ("all floods", spillway and "flood gate") are associated with a greater deteriorating negative balance at higher discount rates, compensated to a diminishing extent or not at all by the surplus of the afforestation element of the scenarios over the arable scenario (BAU).

The most relevant fact is that even with higher discount rates, the result of forestry activity ("Forest LU, no flood" scenario, the first column of Table Syn.4) is robustly higher than the outcome of the arable dominated, Current land use (BAU) scenario. There is only a shift from x2.3 to 2 ratio. This is due to the structure of income. Annual arable income is stable over the years, but there are income-replacement subsidies for afforestation at the beginning of the period, and the annual value of carbon sequestration grows over time. These elements occur in parallel with the annual incomes derived from the arable scenario over the period; therefore, their relation is not sensitive to changes in the discount rate. The revenues that are sensitive to discount rate changes are those associated with the periodic selective cutting interventions and the value of the perpetual timber stock at the end of the period. These later revenue elements in the later phase of the life cycle tend to be higher in nominal terms than the arable revenues. The stability of the difference between the results of the arable and afforestation scenarios is created by the value of accumulated CO2.

However, from the perspective of the realization of community benefits from afforestation, there is no need for a perpetual subsidy for the lower productivity farming activity of farmers after conversion. What is necessary from the public perspective is "only" the management of the conversion process. The necessary condition is establishing a financially balanced income pathway during the conversion period. Moreover, there remain questions about the willingness to change, incentives to change, and the willingness of landowners to cooperate.

Using the Spatial Flood Risk Management approach, on the one hand, the analysis presented in this chapter identifies the cost-benefit outcomes for the stakeholder groups and the economic scope for a bargain to be struck between them. On the other hand, the analysis highlights the unsolved issues associated with benefit sharing between individuals and the public domain. These gaps in the meso-institutional layer hinder the formalization of a fruitful provider-beneficiary relationship.

6 CONCLUSIONS AND DISCUSSION

6.1 Addressing the questions raised in the thesis

1, Based on the experience with the Tisza River, can methodological advances in flood-risk assessment contribute to increasing social welfare in the context of multi-purpose land use?

Flood-peak polders on the Tisza River were created to attenuate the very rare, extreme flood waves that can cause catastrophic flooding if dikes are overtopped. However, when flood-peak polders are examined using a quantified risk assessment methodology and a cost-benefit approach, it can be argued that the use (opening) of flood-peak polders for a much more comprehensive range of flood events can be justified. This contribution is the central message of the first article of this thesis (Ungvári & Kis, 2022b).

The inundation of polders can be considered justified when the expected cost reduction, including risk reduction, is greater than the compensation required to pay for the flooding of the polder. Cutting the peak of flood waves between the economic break-even point flood level and the designated level of opening due to flooding based on physical parameters can increase social well-being, i.e., through the advanced use of the flood-peak polders. For polders along the Tisza, the economic break-even point is within the range of 20-40 year return frequency floods compared to the planned 100-year return frequency (Ungvári & Kis, 2022b).

The construction of flood-peak polders along the Tisza was justified by the difference in investment costs between this option and the alternative of further raising the dikes. However, using a quantified flood-risk assessment methodology, the value of the service provided by the additional area that is inundated can be clearly identified and compared with the cost of using that area. This framing helps establish acceptable terms for using private land to pursue public benefits. The cost-benefit approach has clear advantages over the cost-effectiveness approach (Ungvári, 2022). As the third article in the thesis (Warachowska et al., 2023) points out, in the case of the VTT program, the cost-effectiveness approach was sufficient to develop acceptable rules for the inundation of the flood-peak polders, in contrast to a situation where the rules for compensating the damage caused by using the polder remained unclear, which consequently prevented its operation. This latter setup led to a level of social well-being below its potential. The success or failure of the strategy is strongly connected to the possibility of monetizing the positions of the stakeholders.

The method of quantified flood-risk assessment indicates that the intervention alternatives that can be developed in the middle section of a river (such as flood-peak polders and floodplain widening) are associated with very different per capita risk reduction performance in terms of the size of land required for flood-peak polders (Ungvári, 2022). The most significant added value of flood-peak polders is created in the case of very rare floods when the performance of floodplain widening is much lower. Non-flood-risk type benefits are associated with floodplain widening, as opposed to flood-peak polders, if they preserve arable land use. The results suggest that without special attention and regulatory support, only a fraction of ecosystem services can be realized for the benefit of the public (Ungvári, 2022).

The optimal solution can be created by integrating into one system the effective flood-risk reduction benefits that can be achieved through controlled inundation and the non-flood-risk-reduction type benefits that can be realized in the case of frequent flooding. A prerequisite for integrated management is that the value per unit area of the benefits that can be realized and monetized robustly exceeds the income that the current arable-dominant use can generate. The first article indicates that this condition cannot be met based on flood-risk reduction benefits alone. The calculations presented in the second article (Ungvári, 2022) show that this condition can be met but requires a higher level of spatial planning and stakeholder coordination capabilities than the current practice provides. What is lacking can be described as the effective functioning of the meso-institutional layer identified in the OECD assessment (Akhmouch et al., 2018); this is what the Spatial Flood Risk Management approach (sub-chapter 4.2) aims to achieve in the field of policy.

2, What improvements can economic instruments, aided by advanced flood-risk assessment methodologies, support in terms of initiating multi-purpose land use adaptation?

The construction and commissioning of the Tisza flood-peak polders were the first components of spatial flood protection in Hungary. As a result of the VTT development program, flood risk along the Tisza has been significantly reduced. However, the level of well-being thus improved falls short of the potential associated with this initiative (chapter 5.3).

Even though the land use of the polders along the Tisza River is currently arable-dominated, it is worth exploring the possibility of its multi-purpose use. In the struggle to develop economically sustainable solutions, public subsidies (EU-CAPs) as permanent transfers should not be the yardstick for comparing different land management packages, although they can play an important role in their implementation (sub-chapter 5.4).

The Spatial Flood Risk Management approach and the international experience with flood-peak polders suggest that it is more appropriate to look at the current situation of the VTT development program as a stage in a process in which further welfare gains depend on the ability to link the service provider (cost bearer) and the beneficiary groups. A higher level of well-being can be expected from combining multilateral agreements on using additional land for flood management and providing a bundle of ecosystem services. The challenge is whether a system of agreements and rules can be established to enable decisions and the reconciliation of interests in land use adaptation and whether financial transfer mechanisms can be set up for this purpose. The Spatial Flood Risk Management framework as a policy implementation roadmap can be used to support such regulation-making activities (chapter 4.2).

The Spatial Flood Risk Management approach emphasizes the need to consider privately owned land in institutionalized relationships between service providers and beneficiary groups if community benefits are to be realized. In this approach, the method of quantified flood-risk assessment plays a key role, as it can help define the link between actors in different locations and sectors in the river basin using economic terms (chapter 5.1). The experience that has accumulated with handling the challenges of common pool resource management from a theoretical point of view will play an important role in managing landscape-level features like the attenuation of flood accumulation (sub-chapter 4.1).

Transaction cost theory also provides information on the level of investment that community actors should make to build the complex agreements a nature-based solution requires. Transaction costs are a natural accompaniment of spatial planning processes, but they are frequently concentrated on the side of landowners. Even win-win settlements cannot be achieved without community investment to cover them. Economic instruments can also play an important facilitating role in the planning phase of a multi-purpose land management initiative (Ungvári & Collentine, 2022).

The Spatial Flood Risk Management approach should be broadened to focus on implementing benefit bundles beyond flood defense. This is the topic of the following forward-looking discussion chapter.

6.2 Discussion and recommendations

The OECD Principles of Water Governance (OECD, 2015) describe the lack of a properly functioning meso-institutional layer as a critical element of perceived water policy failures (Akhmouch et al., 2018) that thwart broader adaptation-related struggles designed to manage the numerous hazards that are unfolding in relation to a changing climate. From an institutional planning perspective, the goal of integrating public benefits into management rules that govern/regulate individual activities is perpetual because scientific discoveries inevitably lead to new aspects to integrate. Water-related environmental flows that connect many natural resources (green infrastructure) and built-infrastructure-related management problems are a rich source of such integration challenges (chapter 2). Water policy failures emphasize the difficulty of submitting more and more complex relations to rule-based activities. The lack or limited functioning of the meso-institutional layer means that adequate rules have not yet been issued, or existing rules have no legitimacy to enforce and resolve these newly defined water policy goals in local circumstances. The Spatial Flood Risk Management approach that was applied and further elaborated in this thesis (sub-chapter 5.1) can be seen as a method for identifying and filling holes in the meso-institutional layer of river-basin-wide water policy implementation practices (sub-chapter 4.2). According to the proposition of SFRM, flood-risk management is the reasonable starting point for rolling out policy implementation aimed at solving a more comprehensive set of landscape-level, nature-related management issues associated with multi-purpose land use. Economic instruments and tools can contribute more effectively to this process than has recently been generally experienced. The SFRM provides the basis for the instrumentalization of managing common pool-resources in a river-basin context. For example, cost-benefit analysis aided by quantified flood-risk assessment methodology should not just be seen as a new methodological extension for mapping cross-sectoral impacts in higher resolution (sub-chapter 5.4); it can provide valuable support in setting the scene for multi-stakeholder conflict-resolution negotiations connected to the policy implementation process. This is a less common use of the methodology that facilitates stakeholder involvement by clarifing the economic position of each party.

However, filling the gaps in the effective operation of the meso-institutional layer in question stretches the boundaries of water governance systems. In aiming at the implementation of nature-based solutions, an improvement in the perspective of participants' roles is necessary. There must be a shift from state/municipal organizations viewing themselves as executors and stakeholders as users or passive adopters of measures to state entities acting more like managers and regulators of cooperation platforms and stakeholder groups being considered providers and beneficiaries of many of the services governed and negotiated according to the rules of the platform. This shift in attitude may make the difference in successfully implementing spatial or nature-based flood risk management solutions. The evaluation of VTT development in the thesis (sub-chapter 5.3) sheds light on this differentiation, as it was assessed according to the underlying organizational conditions. In parallel with this need, planners and policy implementers may be tempted by the advancements in simulation and data management methodologies to expand the scope of top-down planning regimes and develop solutions to nudge land users effectively into participating in compensation schemes. As the cited examples showed (sub-chapter 5.4), this is a realistic phase in the practice of implementation from the perspective of both the approach and the applied policy implementation toolbox. However, at the same time, a 'glass ceiling' of benefit maximization may be expected. With landscape-wide natural/water resource management challenges, poorer-than-expected results are forecastable if the organizations associated with the landscape management institutions cannot be equipped with improved capabilities for managing common-pool resources.

Further benefits can only be realized if governance structures can deal with the new dynamics required by water policy implementation, whereby state/community agencies are facilitators of the implementation and maintenance of landscape management rules among parties with diverging interests. The SFRM approach heavily builds on identifying service providers and beneficiary groups across the river basin and institutionalizing their relationships. Experience shows (T. A. Thaler et al., 2016) that the necessity of formalization and sound economic conditions grow with the distance between the stakeholder groups connected by the services in question. Watershed service providers' willingness to participate in such schemes is strongly connected to their expectations about future land utilization.

Providers of nature-based solutions must be active managers of their resources and must be able to develop their economic positions. To change farmers' attitudes, it would be worthwhile acknowledging that financial schemes associated with transient water cover are basically designed to compensate for assumed disturbances, yet to tolerate them, not to capitalize on them. Looking ahead to the options explored in the second article (Ungvári, 2022), the long-term goal could be to more clearly define interests with the potential for expanding value generation. As a first step, however, the current legislation that is already in force must be enforced more vigorously to steer farmers towards land use that takes better account of natural endowments. The interest in positive incentives is reduced by the weak enforcement of regulatory instruments that target the negative externalities of arable farming (Rákosi et al., 2017). The most relevant of these regulations are the Water Framework Directive, the national rules for financing the territorial water management infrastructure, and the EU-CAP's Ecological Focus Area legislation. In the latter case, the focus should be on prioritizing solutions with the potential for encouraging transient water cover in set-aside areas. In addition to enforcement, public involvement can help reduce and bridge transaction costs (Ungvári et al., 2018). Deals associated with the benefits of transient water flows also require spatial selforganization on the providers' side. This involves a high transaction cost challenge that it would be worth the public supporting to unlock the greater benefits of multi-purpose, water-conditional land use.

There are new terms in the EU-CAP (2023-2027) cycle's payment conditions. Subsidy schemes help adapt agricultural land use practices to encourage water-friendlier behavior. The development process of changing the land use associated with VTT polders can exemplify that subsidies alone cannot achieve this objective (sub-chapter 5.3). A different, more effective, and cheaper way of providing incentives should be found, and the focus should also be on managing the transaction costs of the process.

The public has a significant interest in the benefits that can be made available through afforestation in former floodplain areas. This interest is attached to both flood-risk reduction and carbon sequestration. The same cannot be said of landowners; for them, there is no afforestation trajectory whereby a desire to increase productivity coincides with an increase in long-term carbon sequestration and forest management revenue. This situation poses an obstacle to upscaling in relation to additional private areas that can be permanently and robustly managed for flood attenuation benefits.

If the size of the benefit can be quantified, the question is how it should be allocated between landowners and the public to encourage implementation. Rather than subsidies, marketisation of the carbon sequestration capacity of the floodplain forests to be created during land use adaptation could be one way to attract the interest of landowners. Calculations have shown that, at present, the settlement of this benefit element would have the most significant impact on the financial balance of landowners (sub-chapter 5.4). However, this is not yet an option for a domestic landowner planting a forest on their own land. There are national and EU-level obstacles to this. What must be highlighted here is that the accountability for carbon sequestration as a benefit currently falls entirely on the state. Does this mean that the expropriation of the carbon content of forests by the state is currently the greatest obstacle to opening up space for water in the floodplain? Is this practice consistent with the property rights attached to the land or the forest created on it? Are we not dealing with an undefined dimension of property that needs to be resolved before economic instruments can be applied to trigger land-use adaptation that increases the overall benefit of the respective areas? Clarifying the ownership of the eligible carbon sequestration entitlement in floodplain forests or at least reaching agreement on revenue sharing is a necessary step forward. On the other hand, the possibility of raising revenue from forests' carbon-sink capacity is significantly limited by the problems associated with the eligibility for carbon sequestration projects in Europe (Verschuuren, 2018). Forestry and agricultural activities are not part of the EU ETS market, and only one or two European countries are currently planning to develop national offsetting schemes (van der Gaast et al., 2018), but there are EU-level initiatives that are intended to tackle the issue (Meyer-Ohlendorf, 2023).

The linking of property-rights issues related to afforestation on privately owned floodplain areas with flood-risk management is a logical extension of the Spatial Flood Risk Management approach. However, the much broader ecosystem service potential of floodplain forests suggests that this spatial management approach, based on the logic applied to flooding, can play a pivotal role in managing the other water extreme, drought, as well as nature-based solutions to drought begins with flooding (private) land suitable for infiltrating water.

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ARTICLES OF THE PHD:

ARTICLE 1: REDUCING FLOOD RISK BY EFFECTIVE USE OF FLOOD-PEAK POLDERS: A CASE STUDY OF THE TISZA RIVER

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Journal: *Journal of Flood Risk Management.* 2022;15:e12823. https://doi.org/10.1111/jfr3.12823

Keywords: flood risk management, cost-benefit analysis, quantitative risk assessment, controlled inundation, nature-based solutions, flood peak polder, Monte-Carlo simulation

ABSTRACT

Between 1998 and 2006 a series of extreme flood events took place on the Tisza River and its tributaries. In Hungary this triggered the development of flood-peak polders as a more cost-efficient solution of defense compared to raising the dikes. The recent analysis applies Monte-Carlo simulation based quantified risk calculations with a cost-benefit type comparison. Results indicate that compared to the originally planned, 100-year return frequency flood that threats to topple the levees, lower flood levels already provide economic justification for polder use.

Apart from the optimal timing of opening the floodgates, the controlled inundation of polders requires the consideration of its cost-benefit effects as well. The development of the economic decision-support system for the controlled use of the flood-peak polders along the Tisza River provides an insight to the efficiency gains that a more informed, quantitative economic analysis can offer in risk reduction.

The analysis reveals the potential for a more efficient management of flood polders. The decision support of controlled polder inundation includes all the necessary information elements for the cross-sectoral comparability of impacts that is the foundation for any multi-purpose land management scheme that enables nature-based solutions.

1 INTRODUCTION

The catchment of the Tisza experienced an unprecedented frequency of record-breaking floods between 1998 and 2006, with four floods exceeding previous maximum flood heights along the

Tisza and most of its tributaries. In 1998 the rainfall event of the Upper-Tisza catchment was above the 100-year return period. During the 2001 flood, a dike breach catastrophe took place (Szlávik, 2003). These events triggered a scientific re-evaluation of past floods that resulted in a new strategic approach in order to provide defense against previously unobserved flood waves that eventually triggered the development of flood peak polders. The core feature of these new facilities is the controlled way of their inundation.

On downstream, flat sections of a river "give more room for the river" type measures (Busscher et al., 2019) can be categorized as uncontrolled and controlled mitigation. Compared to uncontrolled inundation, a controlled opening provides a higher value risk mitigation service per the same land area, assuming the technical feasibility of opening high flow-through-capacity floodgates at the optimal hydrological moment to cut off and store the top of the flood wave that poses the greatest threat. As such, there is a distinct economic decision point warranting the opening of the flood gate only under a controlled inundation case.

After the construction of the flood peak polders and during their integration into the operational defense tasks, it became clear that sound decisions on the use of the polders to modify a flood wave require information not only on their hydrological but also their economic effectiveness. This paper presents the results of the research program initiated by the General Directorate of Water Management of Hungary focusing on the system level operation development of the Tisza polders (REKK, 2018). The research defined the appropriate economic content to support decisions on polder use and developed the corresponding methodology. It also produced the first results using this methodology, generating outcomes in addition to the core data need for operational defense.

The decision-support module helps to decide whether it is economically worthwhile to use polder(s) and reduce the peak of an approaching flood wave instead of scaling up the defense operations along the levees. An economically sound decision requires information on how cost and benefit elements change between the scenarios: controlled inundation needs a risk evaluation of the approaching flood event to measure it against damages inside the polder.

The economic decision support methodology follows a cost-benefit analysis (CBA) approach. It is based on combining and integrating physical, economic and hydrological information from a number of different sources in a Monte Carlo analysis (hydrology-simulation forecasts of approaching flood waves; a cost analysis of past defense operations and the national flood risk management information project (ÁKK) that was initiated by the EU Floods Directive procedures). This information background allowed the calculation of changes in flood risk using a quantitative flood risk assessment methodology, comparing scenarios of polder use with their forecasted original and modified flood waves. The feasibility of a CBA-type analysis was enabled by the advancement in the risk assessment methodology.

Quantitative risk assessment has become available due to technological advances (Tollan, 2002); (Davis et al., 2008; Lorente, 2019). Cutting-edge flood risk calculation is based on pairing the elaborate damage functions and the high spatial resolution physical impact information which is an outcome of flood simulation events across a wide range of probabilities (Huizinga et al., 2017).This helps to overcome the inevitable distortions that categorization induced generalization brings. In qualitative risk assessment the creation of sub-categories for the occurrence of inundation and damage exposure is a key element of the methodology. Assigning values to variables is based on generalization and expert judgement. There is inherently an embedded "*element of subjectivity (…) determining which factors will influence the risk scores and by how much (in the form of weighted scores)*" (Ganjidoost et al., 2019). This method provides a reasonable compromise in delineating the areas for further, more sophisticated and resource intensive flood risk analysis, but it lacks the integrity of a transferable, assigned economic value.

This difference was presented in (Scorzini and Leopardi, 2017) in the form of very detailed parallel methodology calculations of the same river basin areas. Their qualitative risk assessment method narrowed down to the same set of high priority basins but failed to reflect properly on the differences that the more sophisticated quantitative assessment method provided. Similar results were found by (Albano et al., 2017) in the Serio valley case. However, the growth in processing power and increasingly detailed resolution alone are not sufficient to circumvent the stringent methodological requirements (Molinari et al., 2019). The advancement in risk assessment methodology also supports a shift from the viewpoint of the economic methodology applied. Decisions in the context of the safety oriented approach (Lendering et al., 2019) that focus on the quantification of hazard for a specific design level (in relation to the capacity of a defense infrastructure) are effectively supported by cost minimization analyses. The quantified risk assessment provides the ability to compare the magnitude of the flood risk reduction as a benefit that, in economic terms, represents the entry for the cost-benefit approach. The Tisza polders' case reflects this shift.

From a strategic point of view the results presented in this paper delineate the economic sphere for combining the flood risk reduction impacts of the Tisza polders with other Nature Based Solutions-type benefits that the polder development did not deliver so far (REKK, 2018). This challenge fits into a wider trend. Changing societal views on the environment and the recognized limitations of our traditional flood defense capacities result in a shifting concept of flood defense towards protection based on resilience (Otto et al., 2018; Samuels, 2019). Managing flood hazard by transient water cover on currently protected land is a crucial point of difference compared to developing stronger and higher defense structures on land parcels already dedicated to flood defense. Nature-Based Solutions include a wide range of flood mitigation measures, although they all use more land for enhanced flood safety and require agreements based on the legal foundations of access to this land. In this context flood risk reduction gains have to counterweigh the costs that temporary water cover generates in the polders. Quantified flood risk methodology plays a key role in the struggle to monetize information (Huizinga et al., 2017) to manage cross-sectoral stakeholder-conflict-resolution. The opening of the floodgates of a controlled inundation flood peak polder is such a decision point when public gains must surpass the individual damage cost the polder use invokes.

2 THE COST-BENEFIT BASED DECISION SUPPORT OF POLDER OPENING– THE CASE OF THE TISZA FLOOD PEAK POLDER-SYSTEM OPERATION

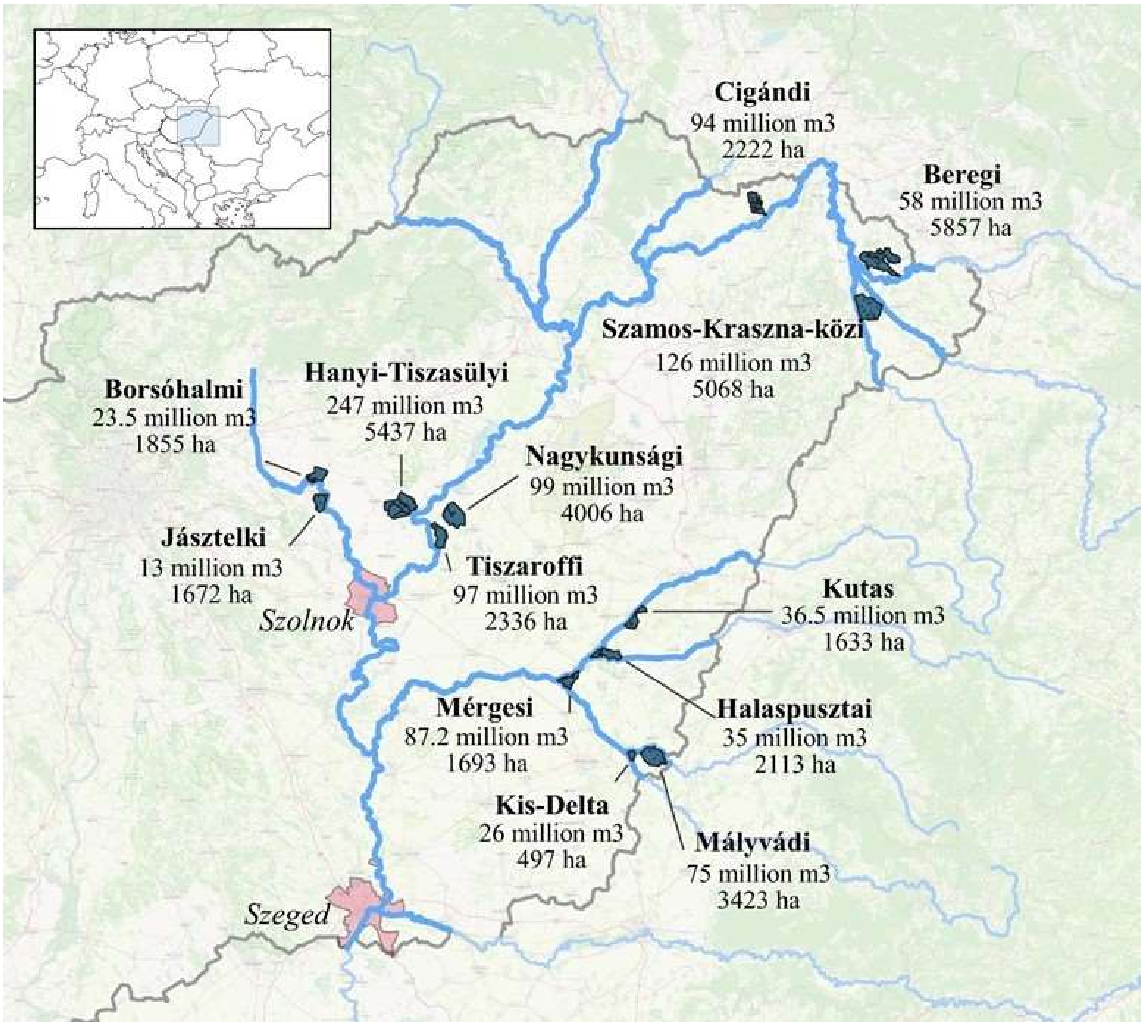
2.1 The context

The flood defense infrastructure had needed an upgrade even before the 1998-2001 period. From a hydrological perspective, the rise in peak flood levels was driven not only by exceptional weather events but also by long term changes in the catchment's land use and sediment accumulation on the active flood plain (between the dikes) all along the middle section of the river (Schweitzer, 2001). In 2003, only 60% of dike sections along the Tisza were in compliance with height requirements set by regulations (Szlávik, 2001). The Tisza and its main tributaries are diked along their path through the Great Plain, hosting 2850 kms of dikes (Somlyódy and Aradi, 2002). The supplementary investment need for the dike system was estimated at 175 billion HUF (EUR 690 million) in 1999 prices (Halcrow Water, 1999). Government decree 2005/2000 ((1.18) ordered a 6 billion HUF/year (EUR 24 million/year) dike development program for a ten-year period. Spending more to increase the dike level along the whole dike system would have required investments on a scale that was unrealistic for Hungary's central budget.

From an economic decision perspective, adopting flood-peak polders was based on the cost-minimization methodology. The infrastructure alternatives were expected to cope with an additional 1500 million cubic meter of flood discharge volume. This capacity requirement was developed using both former flood expectations and updated statistical probabilities on future floods on the Tisza as well as its tributary rivers (Szlávik, 2003). Two alternatives were investigated: 1) the uniform expansion of the dike to heights required by the increased flood discharges for a total cost of 315 billion HUF, (EUR 1.23 billion in 2001 prices) or 2) the construction of 10 flood-peak storage polders for a total estimated cost of 100 billion HUF (EUR 390 million in 2001 prices) (Szlávik, 2001). Building polders to cut the peak of the critical flood waves proved to be almost 70% cheaper than upgrading long swathes of dikes along the whole section of the river across the country.

A quantified cost benefit method to estimate the impact of risk reduction did not have a role in the development decision. A supervisory report on flood defense concluded that the geographic representation of past flood events and localized, inundation specific damage values were not available for the preparation of a quantified risk assessment methodology (Halcrow Water, 1999). The 6 biggest flood-peak polders on the Tisza were completed after 2007, with the total capacity of 721 million m^3 (Dobó, 2019). The polders along some of the tributaries date back to the second half of the last century, ranging in size from 40 to 60 km^2 and storing between 13 and 87 million m^3 (see Table Art.1.2 .) The peak flood reducing impact of the polders depends not only on their storage capacity, but also which river they belong to, their exact location and the size of the mitigated flood. As Table Art.1.2 will display, the maximum mitigating impact of polders on the Tisza ranges between 20-60 cm, on the tributaries it is in the 43-152 cm range.

Figure Art.1.1 Overview map of the region with polder areas along the Tisza and its tributaries.



Legend: Flood-peak polder name, capacity, and area coverage

The utilization frequency of flood-peak polders was linked to the most extreme floods whose levels would otherwise exceed the dike height. Formally, the task of the polder system was to supplement the dikes to cope with floods with a return period of 100 years or higher (1022/2003 (III.27) Gov. decree).

Compensation for the use of agricultural land in the polders for provisional flood water storage consists of two items: an upfront one-sum compensation for all the inconvenience and value loss associated with the scheme and an event-based damage compensation (Law, 2004/67). The upfront payments were based on the quality of the land and amounted to 20-30% of crop land prices at the time in the region (Kurucz, 2010). The event-based compensation element requires full compensation for damage to the agricultural activity including lost net income and the cost of restoring the productive use of the land. Landowners faced the decision of accepting the scheme or triggering an expropriation process by the same law.

From a policy-making perspective, the application of the event-based compensation scheme helped to delay an issue with high conflict potential into the unknown future. High up-front expropriation payments were mostly avoided, and the essential flood defense infrastructure development was greenlit, aiding the preparation for future floods that were expected to intensify.

As described, the question of quantifying flood risk change played no decisive role in the infrastructure development during the 2000's, but the issue emerged during the late 2010's from the perspective of operative defense and financial resource management. Flood defense operators were interested to know the flood level at which it is worth opening the floodgates and buying additional safety at the expense of the full damage compensation payment to the agricultural producers in the flood-peak polders (Weikard et al., 2017).

2.2 Cost benefit methodology of controlled polder use

The cost benefit methodology described below was developed to support the coordinated use of the polders in the Tisza basin. It is part of the polder-system operation-management software and provides economic information on the impact of potential inundation scenarios of different polders and polder combinations together with the information of hydrologic simulation modules (REKK, 2018).

The three types of costs – catastrophe damage, flood defense operations and the cost of polder use - are computed in the economic model. For any given flood wave as an input, a large number of potential disaster-related, location specific impacts exist, each with a different probability of occurrence. This is the reason for using Monte Carlo simulation within the economic model. Ideally, polder use modifies the flood wave, cutting the peak of the flood, lowering flood risk and easing defense operations (Koncsos and Balogh, 2010).

Opening a polder makes economic sense if total expected costs decline, i.e. TC' < TC as exemplified below by comparing the total cost of the original flood wave and the modified flood wave.

Eq. (1) $TC = C_c + C_d$

Eq. (2) $TC' = C_c' + C_d' + C_p$

Where,

TC is total cost *without* polder use, related to the original flood wave

C_c is the expected value of the catastrophe damage along the original flood wave

C_d is the estimated defense cost along the original flood wave

TC' is total cost *with* polder use, related to the modified flood wave

C_c‘ is the expected value of the catastrophe damage along the modified flood wave

C_d‘ is the estimated defense cost along the modified flood wave

C_p is the cost of polder use

A well-founded decision on polder use requires a sound estimate of each of these cost items, but it also provides decision-makers with valuable input to make methodologically sound choices.

2.2.1 Catastrophe damage

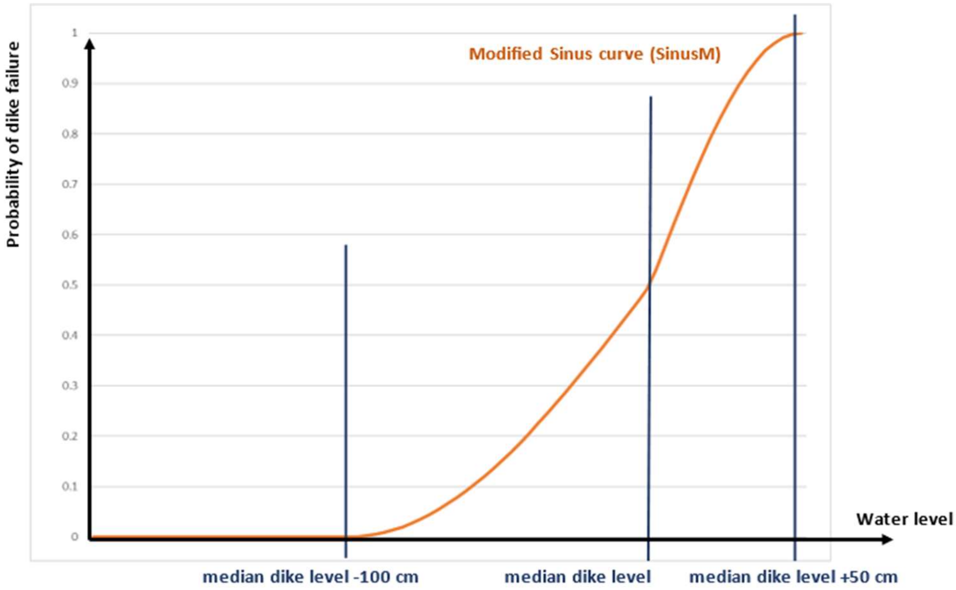
The calculation of catastrophe damage is based on the results of Hungary's flood risk mapping program[5] (ÁKK Konzorcium, 2015) in harmony with EU Flood Directive standards. Two sets of ÁKK results are utilized in the cost benefit methodology: 1) Data on potential dike failure locations and 2) Inundation damage data when a dike section fails. All flood protection dikes were assessed within the ÁKK program. Sections in similar conditions were delimited, and "failure segments" were defined. This information provided the basis for deriving failure probability curves of each failure segment in the subsequent polder-system operation-management program of the Tisza (REKK, 2018).

The applied methodology follows the probabilistic approach set out theoretically by several authors Bogárdi (1972); USACE (1996); Qi et al. (2005); Davis et al. (2008) and in an applied manner, for example by (Simm et al., 2009) who propose the use of a sinus shaped probability curve set. Figure Art.1.2 illustrates the logic behind the applied failure probability curve. The level of flood is depicted by the horizontal axis, the probability of failure is depicted by the vertical axis. The probability of dike failure combines the flood height at a given failure segment with its duration derived from the typical length of high water levels associated with large Tisza floods. Negligible probability was assumed at the base of the safety range (the median dike level minus 100 cm) for properly built and maintained dike sections, 50% failure probability at the median dike level, while at the median dike level +50 cm it tends to reach guaranteed dike failure[6].

[5] From here on "ÁKK", based on its Hungarian language abbreviation

[6] The boundaries of the probability range in relation to the median dike height reflect the agreement of the engeneering expert panel that contributed to the development of the presented methodology.

Figure Art.1.2 Dike failure probability as a function of water level.

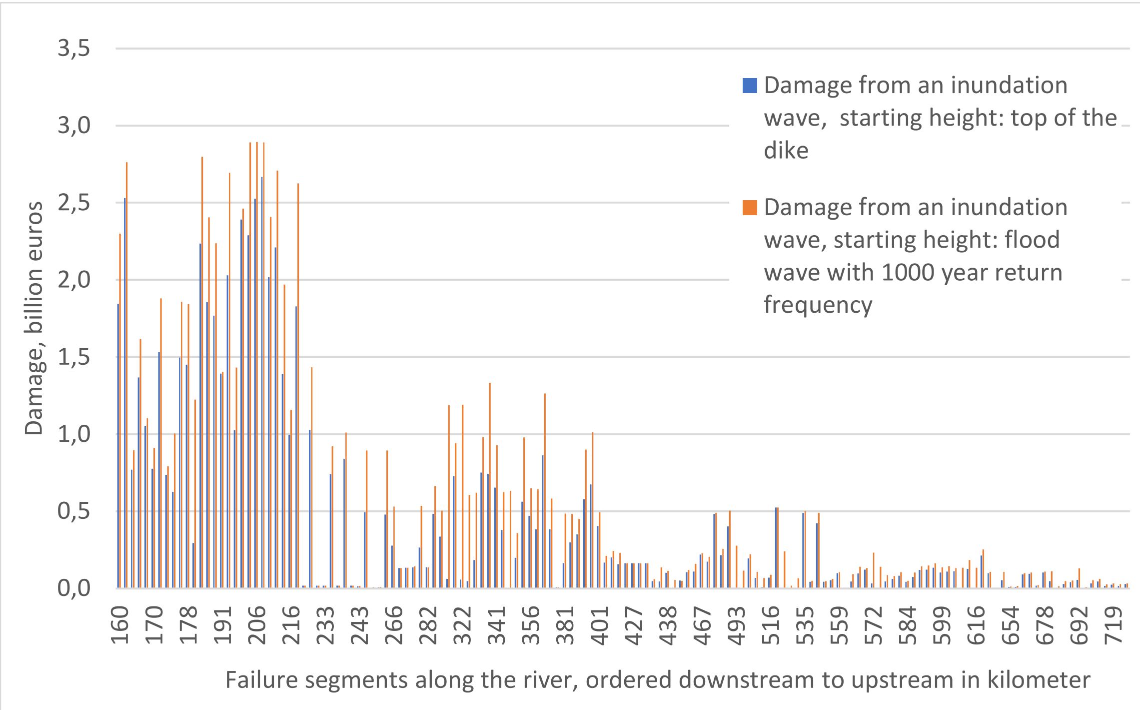


Legend: Vertical axis – probability of failure; Horizontal axis – water level in relation to the dike level

The shape of the curve does not embed dike quality information like in (Hui et al., 2016) or (Simm et al., 2009), but the water level at which it starts to rise does. In case of more fragile dike sections a lower water level already poses risk. These approaches, usually applied in advanced assessment environments overviewed by (Tourment et al., 2016), require a spatially comprehensive and detail-extensive information base of the dike infrastructure that is not available in Hungary. Location specific dike quality information of the failure segments was incorporated in the ÁKK risk mapping methodology to modify the overflow heights of the dike sections at each of the failure segments. Known issues at these locations were converted into stepwise dike height reductions. This way the methodology provides a spatially coherent representation of the varying dike levels at which the probability of dike failure starts to accumulate in each segment. This approach synthetized the experience-based expert knowledge of the 560 dike-keeper sections in 12 water directorates across Hungary. Such conversions bear some degree of bias, albeit as the results of (Vorogushyn et al., 2009) on fragility curves and breach mechanisms (piping, seepage, rupture) show, the increasing probability of all failure mechanisms also correlate with the load pressures that increase with the peak level of the flood wave.

Catastrophe damage is typically higher on the Tisza than its tributaries due to more water flooding larger areas and bigger towns located along its banks. Figure Art.1.3 reviews the spatial distribution of potential inundation damages at each failure segment along the Tisza from the southern border of Hungary (on the left of the diagram, downstream) to the north-eastern one (on the right, upstream). Damage data is available for 383 failure segments with median damage of around EUR 80 million. The largest catastrophe damages are concentrated around the agglomeration of the two major cities, Szeged and Szolnok, at the 170-200 km and the 330-345 km river sections. The highest damage value exceeds EUR 2.5 billion, corresponding to flooding the biggest city along the Tisza in Hungary, Szeged (REKK, 2018). This data was used by the Monte Carlo simulation to estimate C_c and C_c‘ in Eq. (1) and Eq. (2)

Figure Art.1.3 Damage values of flood catastrophes at failure segments for two flood wave heights along the Tisza



Source: (REKK, 2018) Vertical axis – Inundation damage in billion euros, Horizontal axis – failure segments (catastrophe points) along the river ordered downstream to upstream in river-kilometer

2.2.2 The cost of flood defense operations

Defense infrastructure can incur significant damage in extreme flood events when long lasting operations are necessary on multiple locations across an extensive length of dike infrastructure along the Tisza and its tributaries (Koncsos, 2011). Larger floods require more resources and higher costs as the probability of seepage, berms and other structural problems emerge.

A regression analysis was conducted to estimate the defense cost of an approaching flood (C_d in Eq. (1)) and the one modified by polder use (C_d’ in Eq. (2)) by finding connections in past defense operations along the Tisza and its tributaries in the expected role of the variables that drive the cost of flood defense operations, including the peak height of the flood wave, the duration of the flood, and the condition of the most affected dike sections (REKK, 2018). Detailed Tisza flood defense cost data was processed for the period of 1999-2017 to screen defense operations of major flood events. 55 river segments during 5 major floods (years 1999, 2000, 2001, 2006, 2010) were selected for the analysis. Officially the severity of floods is categorized for each river segment in an increasing order as category I, II, III and extraordinary. Category III and extraordinary events, representing the costliest defense operations, were used in the analysis. Altogether 108 observations were analyzed from 55 river segments, with one observation for 16 segments, and multiple observations for 39 river segments.

The choice of a semi-logarithmic specification of the regression equation was motivated by the consideration that the logarithmic transformation of the defense cost variable, which is highly skewed to the left in its original form, yields a dependent variable with a normal distribution. The regression model explains 61% of the variability of the defense cost. Table Art.1.1 below describes the characteristics of the dependent and the explanatory variables. The significance levels of the explanatory variable are listed in the last column. The analysis confirmed that two variables explain most of the flood defense costs on any given river segment: 1) the duration of the flood wave, measured by the number of days spent within category III or the extraordinary category and 2) the peak height of the flood. The latter variable is expressed in "return period". Two control variables were applied to better characterize the river segments; length in kilometers and a dummy variable for unobserved heterogeneity between the river segments. The regression model makes it possible to calculate the expected values of C_d and C_d', based on the results of hydraulic modelling of the flood event with and without the use of a polder.

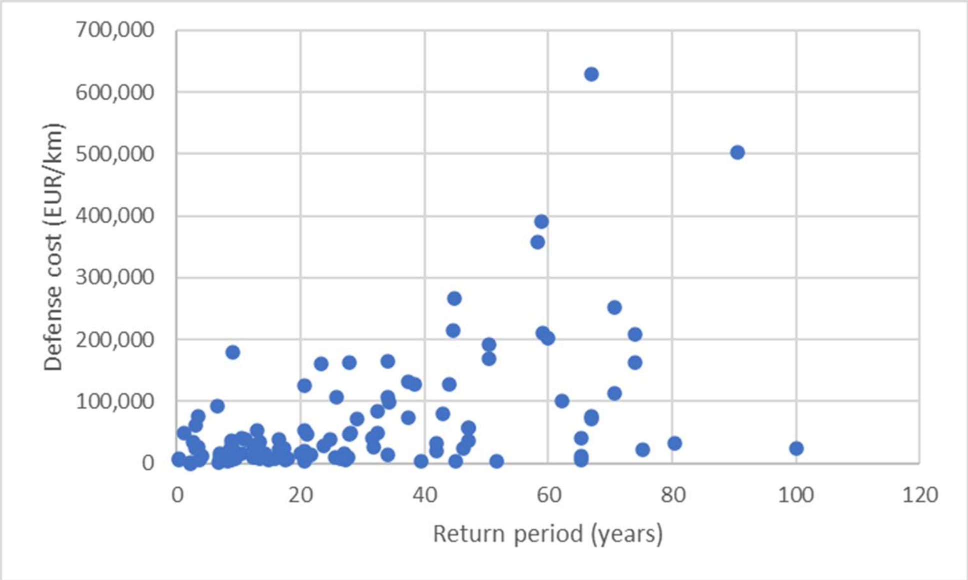
Table Art.1.1 Basic characteristics of regression model variables

Variables	**Average**	**Median**	**Max.**	**Min.**	**Variance**	**Significance level**
Defense cost (million euros)	3.21	1.45	20.10	0.01	4.32	
Explanatory variables:						
Return period (year)	30.37	25.66	99.96	0.44	23.13	1%
Days in defense operation	24.56	28	36	2	9.84	5%
Length of the section (km)	51.81	43.51	143.05	18.22	25.1	1%

Source: (REKK, 2018)

The defense costs of an individual dike section follow a stochastic pattern in connection to the severity of the flood. Problems such as berms and slips happen in a small fraction of events even under similar pressure from the flood, while the resultant cost differences can be substantial as illustrated by Figure Art.1.4. Comprehensive restrospective information on dike quality and dike quality developments was not available, which supports the representation of the defense cost as a stochastic element in modeling based on the information that the distribution of the regression model's variance provides.

Figure Art.1.4 The relationship between defense costs and flood return period within the analyzed sample.



Source: (REKK, 2018)

2.2.3 The cost of polder use

The cost of polder use (C_p) depends on land use, season and damage to infrastructure. When a polder is flooded, the depth of the water is between 1 and 5 meters, and the duration of inundation ranges from weeks to months. Forests and meadows may escape major damages, but any field crops or horticultural products are entirely compromised. Damage to crop production accounts for already incurred costs and lost profit. As the growing season progresses, incurred costs rise. Depending on the crop, the accumulation of costs starts between October and March and lasts until harvest time, usually between June and October. In addition to crop loss other maintenance type cost elements occur (e.g. deep ploughing is needed as well as the reconstruction of damaged infrastructure, mainly canals). The cost of polder use was estimated based on 2016 and 2017 land use data, crop yields and crop prices (REKK, 2018). These costs are summarized in Table Art.1.2 for each of the available polders together with some of the other key attributes of the polders.

Table Art.1.2 Storage volume, inundation damage and flood peak mitigating impact of existing polders along the Tisza and its tributaries in Hungary

Name of the polder	River	Year of commis–sioning	Maximum flood peak reduction due to polder use (cm)	Volume of stored water (million m^3)	Polder area (hectare)	Inundation damage (million EUR)	
						Minimum (October to March)	Maximum (August)
Tiszaroffi	Tisza	2009	20	97.0	2,336	1.27	2.02
Cigándi	Tisza	2008	43	94.0	2,222	0.64	1.14
Hanyi-Tiszasülyi	Tisza	2012	44	247.0	5,437	2.81	4.92
Nagykunsági	Tisza	2013	25	99.0	4,006	2.16	3.81
Szamos-Kraszna-közi	Tisza	2014	39	126.0	5,068	3.23	5.39
Beregi	Tisza	2015	60	58.0	5,857	3.74	4.33
Borsóhalmi	Zagyva	1999	152	23.5	1,855	0.92	1.52
Jásztelki	Zagyva	1984	97	13.0	1,672	1.29	2.04
Kutas	Berettyó	1966	72	36.5	1,633	0.60	1.03
Halaspusztai	Berettyó, Sebes-Körös	1973	43	35.0	2,113	0.90	1.32
Mályvádi	Fekete-Körös	1995	127	75.0	3,423	0.55	1.16
Kis-Delta	Fehér-Körös	1999	59	26.0	497	0.31	0.54
Mérgesi	Kettős-Körös	1980	83	87.2	1,693	1.14	3.20
				1017.2	37,812	19.56	32.42

Source: (REKK, 2018)

The large seasonal variation of inundation damage is related to land use. Damage to crop and horticulture dominated agriculture is more sensitive to the time of the year than damage to natural vegetation covered areas. Likewise, there is great variation among the polders with respect to the unit damage, measured in EUR/hectare. For some polders, such as Szamos-Kraszna-közi, Jásztelki, Kis-Delta and Mérgesi it is well above 1000 EUR/hectare during the harvesting season, while off-season damage may fall even below 300 EUR/hectare (Cigándi and Mályvádi). Given the highly variable damage exposure, the choice of optimal polder use for mitigating a specific flood depends not only on hydrological considerations, but also land use in the polder and season.

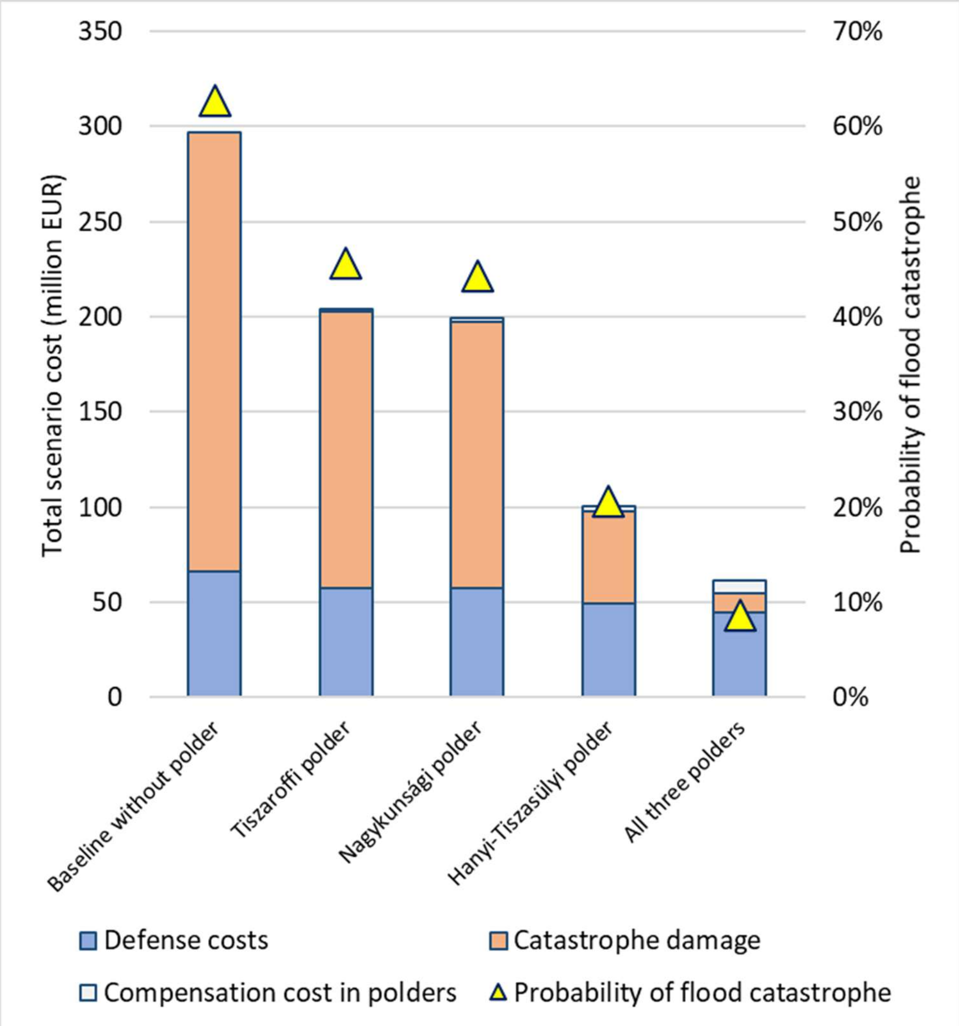
3 RESULTS:

3.1 Decision support for individual flood events: the example of the year 2000 flood

With the above-described methodology, the record-breaking flood in the year 2000 was simulated and inspected ex-post. This was more extreme than a 100 year return period flood. In spring 2000, following a quick snow melt in the Carpathian mountains and prolonged precipitation, water levels reached new record highs at several water gauges along the Tisza as well as the Bodrog and Sajó, its tributary rivers. Defense operations along the dikes surpassed previous highs, in terms of man-count, sandbags and vehicles (Kapros, 2002). The town of Szolnok was at a serious risk of flooding and a major catastrophe was nigh.

Between 2009 and 2013, three polders were completed directly upstream of Szolnok: the Tiszaroffi (year 2009), the Hanyi-Tiszasülyi (year 2012) and the Nagykunsági (year 2013). Hydrological modelling scenarios were run and fed the Monte-Carlo simulation to see how these polders would perform economically individually and together if a flood similar to the year 2000 flood wave came along. The corresponding results are displayed in 0, comparing modelling results to the baseline scenario without polder use. The expected value of catastrophe damage is the largest component of total costs, though defense costs are also substantial, and the compensation cost of polder use is relatively small. As the figure shows, the most economically attractive solution is to use all three polders. In this case the EUR 6.2 million cost for agricultural damage payments would be compensated several times by the lower expected costs of catastrophe damage and defense operations.

Figure Art.1.5 Total cost of scenarios and probability of flood catastrophe, year 2000 flood on the Tisza, modelling results



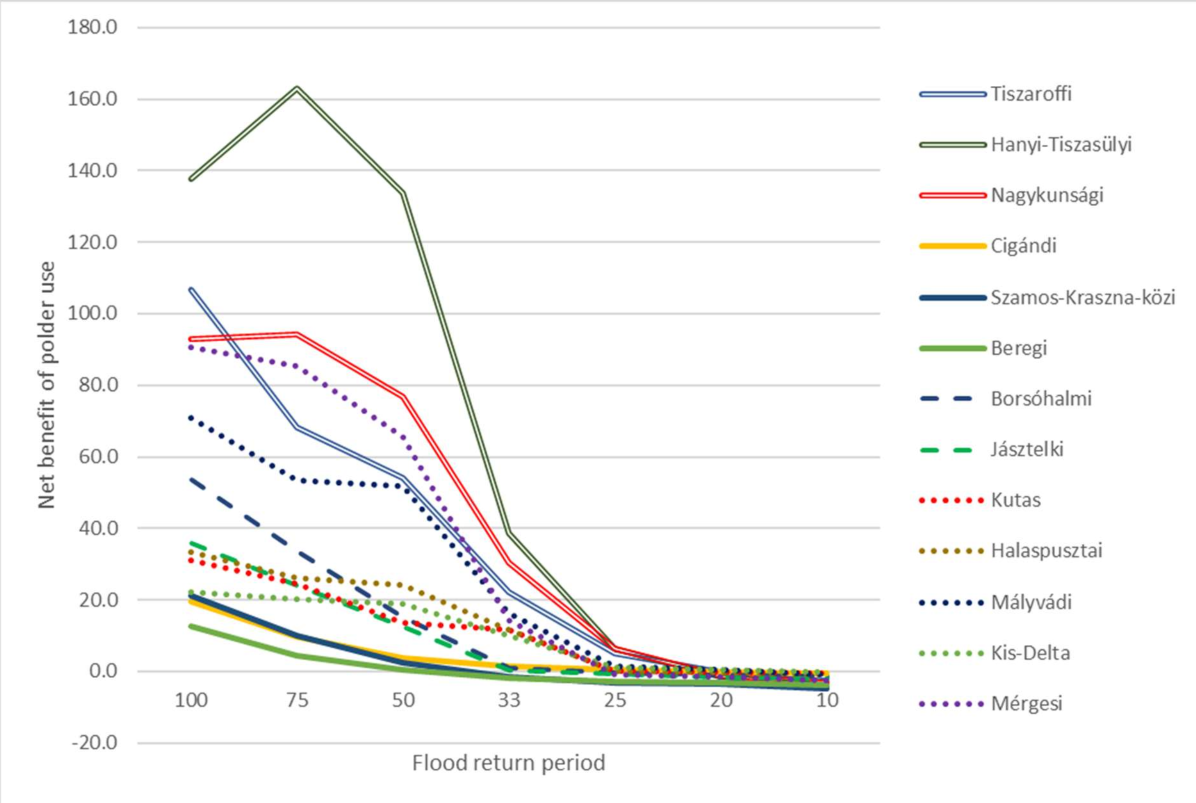
Legend: Vertical axis (left) total expected cost of the scenarios in million euros, (right – yellow triangles) Probability of flood catastrophe of the scenarios; Horizontal axis – flood wave scenarios

3.2 Expected frequency of polder use

As described before, the declared goal of the polder system is to ensure supplemental protection in case of historic floods – those with a return period of 100 years or more (2004/67 Law on the further development of the Vásárhelyi Plan). Modelling results, however, suggested that opening the polders may also be economic for less severe events. The economic break-even point of each polder was calculated in terms of the flood return period above which polder use is economically worthwile.

A "uniform" 100-year flood wave was constructed and based on that a range of average flood waves with return periods of 75, 50, 33, 25, 20 and 10 years were created using the method by lowering the water level through the whole duration of the flood. Then scenarios were created for all floods' return periods and all polders to model the net benefit of opening the polder. Figure Art.1.6 shows the results of this analysis. The economic break-even point is where the net benefit curve crosses the horizontal axis. In case of the Tiszaroff polder - the only polder that was already put to use during the 2010 flood - use of the polder is economically justified for floods with a return period of 20 years or higher. In other words, this polder is expected to be used about 5 times in a century.

Figure Art.1.6 Net benefit of polder use for various flood return periods (million EUR)



Legend: Vertical axis – Net benefit of polder use in million euros; Horizontal axis – flood return periods in years

The results of the exercise for all polders are summarized in 0. Using most polders is economically justified for floods with a return period of 20-30 years, while the Szamos-Kraszna-közi and Beregi polders on the upper stretches of the Tisza should be used for floods that are projected to take place twice a century. All polders are rational to be used significantly more often than the originally targeted 100-year frequency.

Table Art.1.3 The economic break-even point of single polder use scenarios

Name of the polder	River	Economic break-even point (flood return period, years)
Cigándi	Tisza (Upper Tisza)	21
Szamos-Kraszna-közi	Tisza (Upper Tisza)	43
Beregi	Tisza (Upper Tisza)	49
Tiszaroffi	Tisza (Middle Tisza)	20
Hanyi-Tiszasülyi	Tisza (Middle Tisza)	21
Nagykunsági	Tisza (Middle Tisza)	21
Borsóhalmi	Zagyva	26
Jásztelki	Zagyva	28
Kutas	Berettyó	24
Halaspusztai	Berettyó, Sebes-Körös	24
Mályvádi	Fekete-Körös	17
Kis-Delta	Fehér-Körös	13
Mérgesi	Kettős-Körös	25

Source: (REKK, 2018)

3.3 The coordinated use of multiple polders

Polders used on their own already generate substantial economic benefits, as illustrated in Figure Art.1.6. However, they do not fully eliminate the occurrence of flood catastrophes. Hydrological modelling results show that using more than one polder for a major flood further mitigates catastrophe risk (Table Art.1.5). Using the cost benefit methodology described in Chapter 2, it was possible to examine the economic aspects of using multiple polders for any given flood. The Middle Tisza river section offers the best location for such exploration, since three polders are available in close proximity to each other: the Tiszaroffi, Hanyi-Tiszasülyi and Nagykunsági polders.

Table Art.1.4 describes the net benefit for single polder use as well as for the application of polder combinations. As flood return periods increase, the combined use of polders becomes more viable. In case of a flood return period of 30-40 years using two polders is already attractive, although the opening of the Hanyi-Tiszasülyi polder, the largest of the three Middle Tisza polders, is equally effective. For larger floods the utilization of two or three polders generates more flood risk reduction benefit than single polder use.

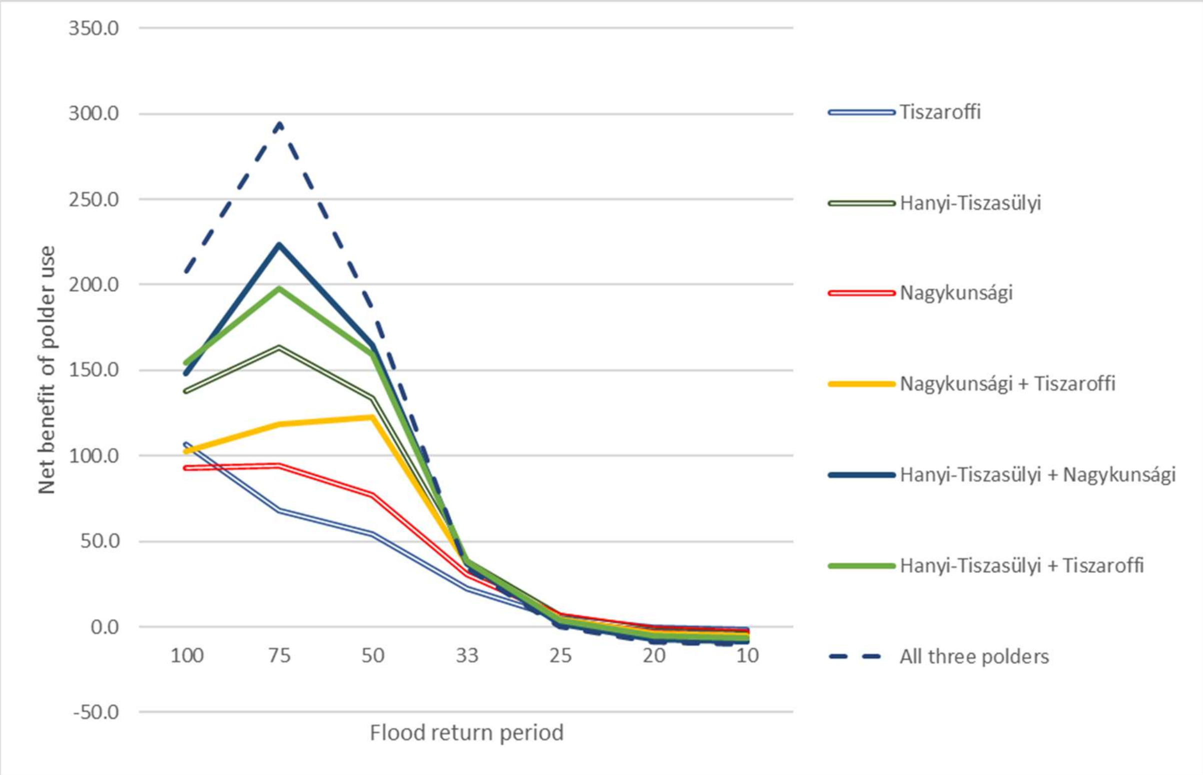
Table Art.1.4 The net benefit of polder use for various flood return periods in the Middle Tisza (million EUR / flood event)

Polders in use	Flood return period						
	100	**75**	**50**	**33**	**25**	**20**	**10**
Nagykunsági	92.8	94.2	76.6	30.5	6.3	-1.4	-3.1
Hanyi-Tiszasülyi	137.7	163.1	133.5	38.4	6.6	-1.7	-3.9
Tiszaroffi	106.8	68.3	54.0	22.2	5.2	-0.3	-1.5
Nagykunsági + Tiszaroffi	102.2	118.5	122.3	36.9	4.6	-4.1	-5.5
Hanyi-Tiszasülyi + Nagykunsági	148.3	223.5	164.9	37.0	1.5	-7.1	-8.4
Hanyi-Tiszasülyi + Tiszaroffi	154.3	198.1	159.1	38.4	4.0	-5.4	-6.6
All three polders	207.9	294.4	185.3	34.8	0.0	-9.1	-10.4

Source: (REKK, 2018)

The graphical illustration of the net benefit values in 0 shows a somewhat unexpected phenomenon: with the exception of the single use of the Tiszaroffi polder the net benefit (i.e. the difference between two scenarios, with and without polder use) for a 100-year flood is lower than that of a 75 year flood. While for a 100-year event potentially enormous flood damages can be prevented by polder operation, the relative effectiveness of polder use, i.e. how much it reduces the likelihood of a catastrophe, also declines. As shown in Table Art.1.5 polders substantially reduce the probability of a flood catastrophe for flood return periods of 33-75 years, but only moderately for a 100-year flood event. The net result of higher catastrophe damage and lower effectiveness of catastrophe prevention is the decline of the net benefits for all polders. The high probablity of catastrophe events in case of 100 year return period floods originates from two sources. Levees by decree are built to cope with such floods (with stronger defense at specific sections), but as described in chapter 2, the coverage of the design flood level is incomplete. On the other hand, an uncertainty arises from the simulation inherently. The levee quality in the ÁKK risk mapping evaluation for the whole length of the infrastructure was managed by transforming known structural issues to reduce the levee top height. This is a satisfactory solution for most analytical purposes but it may cause an inherent bias if probability differences are calculated close to top of the levee range.

Figure Art.1.7 Net benefit of the single and combined use of the Middle Tisza polders for various flood return periods, (million EUR)



Legend: Net benefit of the single and combined use of the Middle Tisza polders for various flood return periods, (million EUR)

As illustrated by Table Art.1.5 , even the combined capacity of polders to mitigate floods is finite and declines for increasingly large floods. These results, however, also outline an acceptable investment cost range for additional future polders, since adding a polder would help further reduce catastrophe risk and corresponding damages for floods with return periods approaching 100-year frequency. The hydrological and subsequent economic modelling of the impact of an additional polder would assist in determining the maximum investment cost at which the supplemental polder development would still provide economic benefits.

Table Art.1.5 Probability of flood catastrophe under various assumptions with and without the use of polders and their combinations in the Middle Tisza

Flood return period (years)	**100**	**75**	**50**	**33**	**25**	**20**	**10**
Without polder use:	97.5%	79.8%	46.5%	12.8%	3.4%	0.5%	0.0%
With the use of one or more polders:							
Nagykunsági	96.2%	73.2%	34.2%	4.6%	0.3%	0.0%	0.0%
Hanyi-Tiszasülyi	94.2%	66.1%	22.7%	1.6%	0.0%	0.0%	0.0%
Tiszaroffi	95.3%	75.1%	39.2%	7.6%	1.3%	0.1%	0.0%
Nagykunsági+Tiszaroffi	94.8%	67.5%	23.5%	1.6%	0.0%	0.0%	0.0%
Hanyi-Tiszasülyi + Nagykunsági	91.3%	51.4%	9.9%	0.1%	0.0%	0.0%	0.0%
Hanyi-Tiszasülyi + Tiszaroffi	92.3%	57.2%	13.1%	0.4%	0.0%	0.0%	0.0%
All three Middle Tisza polders	86.0%	35.9%	2.9%	0.0%	0.0%	0.0%	0.0%

4 DISCUSSION

Up until recently decision support for the inundation of flood peak polders along the river Tisza was only available in the form of hydrological information. The combined hydrologic and economic analysis built on the merits of the quantitative flood risk assessment methodology sheds light on both ends of the flood probability spectrum, depicting how the benefits provided by polders can be further improved. Originally, polders were designed to cope with rare, extreme events. Economic calculations have validated the expectation that the highest benefits originate from the combined use of multiple polders at extremely large floods and delineate the conditions under which the development of additional flood mitigation sites provide net benefit gains against rare events beyond the 100-year return period ones.

Results also show that the use of both single and multiple polders can already be justified based on the economic impact of their flood risk reduction performance for floods with a return period below the originally planned hydrological trigger of 100-year. Using the polders for these medium sized floods implies the partial replacement of labor-intensive, top of the dike defense operations and reducing the risk for the incidence of costly dike-structure problems during defense operations. This element further improves the benefits which are set against the compensated agricultural damage costs of polder inundation.

International experience with the actual utilization of the physically available flood risk reduction sites along medium sized rivers is mixed. Even in well documented European cases the literature offers only sporadic information on the economic calculation methods that lay behind the decision to use the designated polders (Thaler et al., 2016). There are locations where polder opening is connected to the overtopping capacity (Förster et al., 2005; Adriaenssens et al., 2017), schemes were settled on previous methods of risk calculation in (Roth and Winnubst, 2014) or the polder use is blocked due to unsolved conflicts of interest between stakeholders and authorities (Przybyła et al., 2011)(Hudak et al., 2018). Their reassessment with advanced solutions like the methods described in this paper helps to clarify if the overall societal performance of polders can be enhanced.

The economic argument in support of more frequent polder-inundation helps to overcome an inherent contradiction of controlled polder use. Currently polder inundation is viewed as a rare disruption, leaving agricultural practices in the area unchanged, this drives the subject of land use agreements that enable the transient water cover towards event based compensations (Weikard et al., 2017). These schemes leave no room for the realization of Nature-Based Solutions that would provide wider social benefits but require frequent inundations (Hartmann et al., 2019). Therefore, the two land-use strategies are mutually exclusive. Our analysis suggests that the distance between these two land use regimes can be reduced, providing a better basis to assemble a bundle of ecosystem-based benefits that credibly outperforms a cropland dominated land management regime. As both drought and flood risk show an increasing tendency under a changing climate there is an escalating need for solutions that offer mitigating impact against both water extremities. Polder systems with their scalable use are in good position to provide resilience against a wide range of uncertain hydrological events the probability of which is more difficult to predict due to climate change.

In order to be able to integrate agreements into a multi-purpose land use architecture, flood risk calculation results must be more precisely comparable across economic sectors (Jongman et al., 2012) when conflict resolution about future land use options is targeted (Hartmann et al., 2018). For the purpose of reconciliation, the quantified expression of risk reduction gains is the method that makes it possible to compare the benefits and costs with other types of land uses that are enabled or replaced by the land-based flood mitigation measure of a particular piece of land. Valuation effectively supports establishing contractual arrangements as described in (Zandersen et al., 2021) and (McCarthy et al., 2018). Improving the economic terms of agreements, in line with the Austrian experience, shows considerable variation in instruments, but unresolved compensation issues act as a significant obstacle to successful implementation (Nordbeck et al., 2018).

Pairing flood risk reduction of controlled inundation with other ecosystem-based land management practices can unlock multiple benefits (Hartmann et al., 2019). Flood risk mitigation is a high value benefit estimated with less uncertainty than other nature-based benefits because the provision of most ecosystem services depends on the successful management of specific ecosystem functions over a long period of time, something that cannot be taken for granted. From the perspective of the efficient use of public financial resources and practical planning, the financial viability of a flood risk mitigation scheme involving additional land can be the facilitating factor that makes the organization of other ecosystem-based benefits possible. Bundling flood risk mitigation with ecosystem services is a solution that helps to bridge the distance between recent investments in ecosystem services and their future service benefits. As the emergence of ecosystem service auction platforms demonstrates (Dericks, 2014) the comparable monetized valuation of benefits is becoming an important necessity as well.

5 CONCLUSIONS

The case of the Tisza polders demonstrates how the development of analytical tools during the paradigm shift in flood protection can open the way to new, more socially efficient utilization of polders that were originally developed for flood disaster prevention of last resort. Calculations for the Hungarian section of the Tisza show that from an economic perspective, 20-50 year return period floods already justify the inundation of a single flood-peak polder or a combination of multiple polders. This range contrasts with the original assumption that the polders would be utilized only for 100-year or larger floods. A quantitative assessment of the flood risk reduction impact of controlled inundation is the key tool for unlocking these public gains.

The results show that higher capacity flood-peak polders are more effective in reducing expected costs not only for the largest floods, but also for most of the flood spectrum. In case of moderate floods, where the value of risk reduction is lower, two other elements also bear significance: defense costs along the levees and, especially in case of large polders, the magnitude of the potential damage from partial inundation. This suggests that further studies should focus on a more detailed exploration of the drivers modifying the economic break-even point when a polder's inundation becomes justifiable from a cost-benefit perspective.

Flood mitigation gains from the use of polders on their own for moderate floods do not necessarily surpass the agricultural benefits provided by these sites. This puts an emphasis on the need to calculate costs and benefits based on bundles of potential ecosystem services provided by polder areas. Without this, agricultural cultivation will prevail over the polders despite its high social opportunity cost.

Further, site-specific research is needed to assess the conditions under which more frequent polder use effectively supports the transition from intensive agriculture to extensive land use, harnessing an enhanced level of ecosystem services related to groundwater recharge, carbon sequestration, heat mitigation, biodiversity and various recreational activities. This is a task that can contribute to the enhanced use of polders in other river basins that were developed for last resort purposes as well.

Acknowledgements: The authors are grateful for the opportunity to use the results of the project: Economic decision support to the development of the system management of the flood-peak polders of the Tisza valley from the "KEHOP project" 1.4.0-15-2016-00016 of the National Water Directorate of Hungary. The project report is referenced in the text as (Ungvári & Kis, 2018).

The authors would also like to thank the continuous encouragement and support of Attila Lovas and Sándor Kovács of the Middle-Tisza Water Directorate (KÖTIVIZIG). Last, but not least, they are grateful for the long discussions with József Váradi, András Horkai and Péter Farkas, during which much of the quantitative risk-calculation based economic decision-support methodology was developed.

Data availability statement: The data that support the findings of this study is available from the corresponding author upon reasonable request.

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ARTICLE 2: COMBINING FLOOD RISK MITIGATION AND CARBON SEQUESTRATION TO OPTIMIZE SUSTAINABLE LAND MANAGEMENT SCHEMES - EXPERIENCES FROM THE MIDDLE-SECTION OF HUNGARY'S TISZA RIVER.

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Journal: Land 2022, 11, 985. https://doi.org/10.3390/land11070985

Keywords: flood risk management; CO2 sequestration; cost-benefit analysis; agriculture; forestry

ABSTRACT

The record floods experienced along the Tisza River between 1998 and 2001 brought a paradigm shift in infrastructural solutions for flood protection. A flood peak polder system was built for transient water storage without any substantial change in land use in the polders, despite the potential to do so under the new scheme. The recent improvement of quantified flood risk assessment methodologies and stronger foundations for the valuation of carbon sequestration benefits now provide more information on the magnitude of missed opportunities and the potential for comprehensive land use and flood risk management solutions.

This paper evaluates and combines the results of three cost-benefit type analyses on the conflicting relations of pursuing flood risk mitigation and land management goals. Although the studies were conducted at different locations of the same river stretch, they are all inspected using the same flood waves.

Results assert that as EU-CAP agricultural subsidies stabilize individual benefits from arable land use in the short run, public benefits and long-term individual benefits fail to reach their potential value. The combined analysis of flood risk change and CO2 sequestration provides the economic rationale for the ecological revitalization along rivers with flood peak polders, helping to solve the conflict between hydrological and ecological objectives in floodplains.

Capitalizing the value of the community benefits of forests in terms of CO2 sequestration is limited by the unresolved property rights allocation of this natural capacity between landowners and the state, the latter being responsible for fulfilling international CO2 reduction agreements. This uncertain legal background is an obstacle to the creation of sustainable economic

conditions for the development and expansion of beneficial land management processes along rivers.

1 INTRODUCTION

The steady increase in flood risk is a widespread phenomenon (Hirabayashi et al., 2013). Flood risk has two components, both of which strengthen this trend. On the social side, the economic value exposed to floods is increasing (Barredo, 2009). Regarding the probability that a flood occurs, the effect of climate change and deteriorating catchment conditions are reflected. As in many other regions, a shift in the pattern of rainfall events is observed in Central Europe (Rojas et al., 2013). Even without a change in annual precipitation, we can expect more concentrated precipitation events with occasionally higher discharge volumes (Forzieri et al., 2017). These drivers force the implementation of new flood protection solutions. The "spatial flood risk management" approach partly responds to these challenges (Hartmann et al., 2022). It focuses on the reconciliation of the natural and socio-economic conditions of areas that have capacity to mitigate floods. The need to integrate additional land into floodplains arises because, typically, the land along rivers that is still available for floods, even supplemented with the defense capacities (levies), can no longer provide adequate peak-discharge capacity. At the same time, the approach aims at creating higher quality environmental conditions along rivers, valued more and more by society (Hartmann et al., 2019). This is reflected in the legislative expectation for the joint implementation of the EU Floods Directive and the Water Framework Directive. However, integrated implementation typically lacks robustly applicable public policy solutions. This analysis examines the potential and limitations of such integration, using the example of the middle section of the Tisza River, from the perspective of how specific elements of economic assessment methodology can be applied to establish land use change processes that are considered justified from a policy perspective, while rarely implemented.

At the turn of the millennium, the countries of Central Europe faced an unprecedented series of high magnitude floods (Szlávik, 2005), which led to the reconsideration of defense strategies. This process unfolded along the Hungarian stretch of the Tisza River as well, setting a new course to flood risk management. The preferred method of raising dikes has been replaced by a multi-pronged strategy led by flood-peak polders that manage floods with a return frequency of 100 years or more, with dikes to be developed to the previous design standards, and the restoration and maintenance of run-off capacities in the floodplain (2004/LXVII Act on the Further Development of the Vásárhelyi Plan, hereinafter referred to as VTT). This change, on the one hand can be seen as a paradigm shift due to the advances in flood management, but on the other hand, there has been no substantial shift in the use of the floodplain or the areas within the polders (Sendzimir et al., 2010), which was an explicit objective of the VTT development plans and a driving force behind similar European processes, for example, nature based solutions (Hartmann et al., 2019).

Opinions differ widely on the use of areas protected by flood defense infrastructure from rivers, including where water management and flood damage infrastructure is most effective in developing and preserving public and private interests (Borsos and Sendzimir, 2018; Láng, 2017). This issue is of particular importance in the lowland section of the Tisza, where de-flooding has confined the river to a particularly narrow area compared to other European rivers (Koncsos, 2011). It is now clear that the large-scale socio-economic development initiated in the first half of the 19th century transforming the floodplain generated long-term costs being felt today (Nováky, 1993).

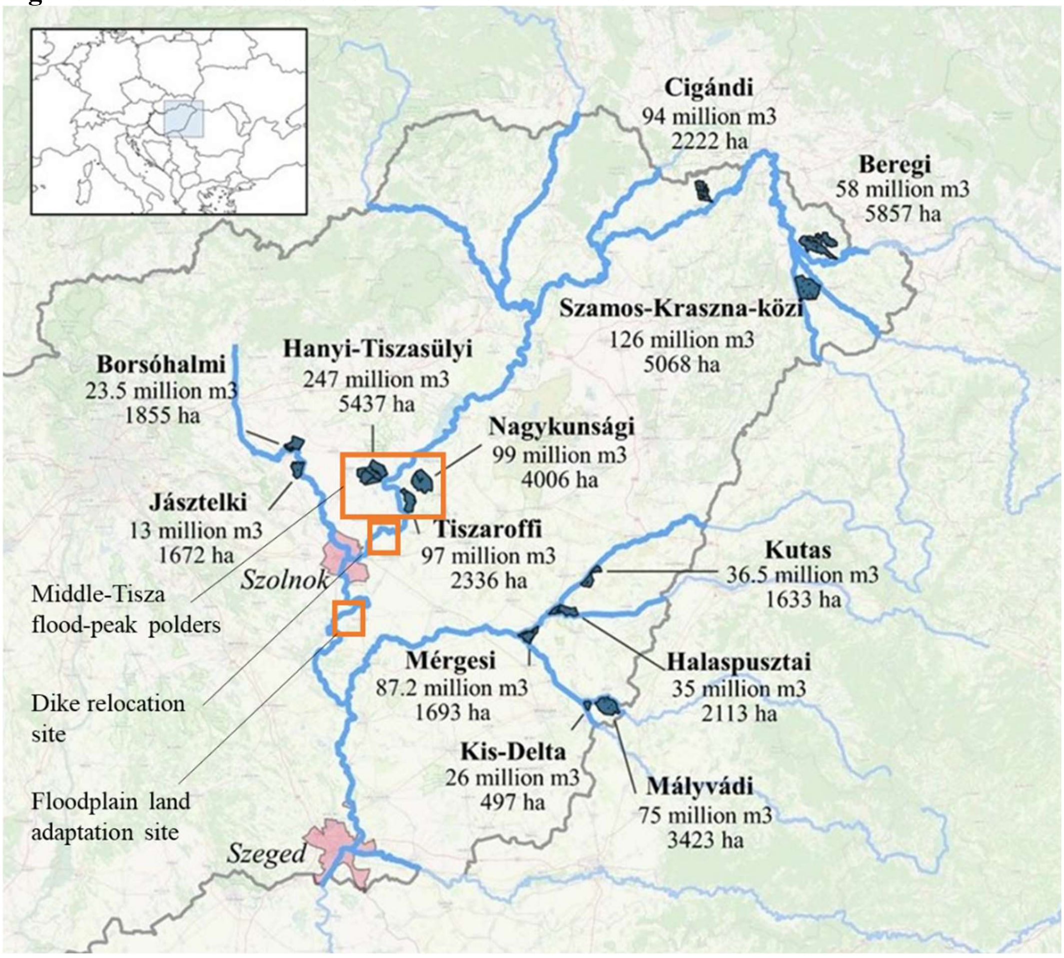
The expansion of supply-type agricultural production has degraded regulation-type ecosystem services that could handle, for example, the increased frequency of water extremes (Somlyódy and Aradi, 2002). The question is how the economic monetization of these regulating services (Marjainé Szerényi, 2021) can support the reorganization of lands to improve social welfare. The areas connected to the current floodplain either by dike relocations or flood-peak polders already contribute to reducing flood risk, irrespective of their current land-use, which can be considered a service to the people living in the former floodplain of the river (Dobó, 2019; Koncsos and Balogh, 2010). However, the potential for introducing additional regulating-type ecosystem services is already land-use dependent. Increasing the total individual and community benefits with knowledge of the underlying natural science is fundamentally a public policy challenge (Hartmann et al., 2022).

This paper aims to reveal the economic specifics of this policy challenge and proceedings that have the potential to overcome this challenge.

2 DATA AND METHODS

Over the past decade and a half, a polder system was developed with new large flood-peak polders along the Tisza river and the smaller shallow flood-emergency sites along the tributaries were upgraded with floodgates. (see Figure Syn. 1). Research programs have quantified the flood risk reduction impact of these interventions on the Middle and Upper Tisza.

Figure Art.2.1 The middle section of the Tisza River



Legend: Map shows the flood polder system of the area and highlights the location of the study areas. Adapted from (Ungvári & Kis, 2022)

The economic analyses presented in this article are made possible by the improved methods of quantified flood risk assessment (Davis et al., 2008; Huizinga et al., 2017) and the quantification of the benefits of ecosystem services, in particular the mitigation of climate change through CO2 sequestration (EBRD, 2019). Besides infrastructure development, these are the aspects that have the highest potential to shape the decisions on the ground. The interrelations are analyzed with the cost-benefit approach whether transformed land uses in river corridors and former floodplain areas have the economic backing to cover the costs of change towards sustainable multipurpose land management forms.

This article draws on and develops the results of three analyses (REKK, 2021, 2020, 2018). All three are an integral part of previous works led by the author. The added value of this article is that it presents, based on the results of these three sub-analyses carried out for different purposes, a coherent methodological approach that allows a quantifiable expression of the public interest and a financial comparison with the land use value, optimized for pursuing private interests. The approach builds on the most accepted economic value elements of land use and flood risk management. The application of the approach demonstrates that, even without the elements of ecological services that are difficult to quantify, there is sufficient information to support a positive economic equilibrium for land use solutions that provide higher public benefits and are financially sustainable, as a prerequisite for the transformation of private uses, while integrating profit seeking activities.

The first report (REKK, 2018) explores the economic value of the flood peak reduction effect of the controlled opening of polders and an article based on it (Ungvári and Kis, 2022) presents the methodology of the calculation. It introduces a breakeven point flood frequency approach, above which (for less frequent, more severe flood events) the opening of a polder can be considered economically justified under current rules. In contrast to this, the present article examines the relationship between more frequent (that means lower peaking) floods and the use of the polders below the breakeven point. This is the probability segment of floods where the conflicts between the public and private use of floodplains (due to the presence or absence of frequent flooding) are concentrated. The second report used (REKK, 2020) calculates the economic balance of a dike relocation intervention and gives detailed account of the steps of the calculation process. It provides basis for comparing the magnitude of the benefits, the different ecosystem services that can be realized in case of the polders' controlled and the dike relocation's uncontrolled inundation. It reveals the different ecosystem services' contribution to the economic balance.

The third analysis (REKK, 2021) aimed to explore the economic outcomes of different land use and flood regimes on a former floodplain area. It uses the same methodology as REKK, 2020. The land use scenarios identified in the analysis did not produce results sufficiently characteristic to further consider their economic aspects. Therefore, this paper builds on the results of an analysis of an additionally prepared scenario assuming full afforestation, in order to interpret the scale of the benefits from CO_2 sequestration.

3 RESULTS

3.1 Description of the status quo

This chapter describes the transformation of flood defense strategy along the Tisza River that created the infrastructure and the potential that points towards a sustainable land use on the floodplains. The status quo description explains the nature of the policy barriers. The results subsequently presented will outline the economic context identified for realizing this potential.

In the early 2000s when the review of the flood defense strategy began, experts did not have the technology and information background to quantify the impact of development alternatives for flood risk (Halcrow Water, 1999). By the mid-2010s, when the flood peak polder system was already in place, these technical conditions had been satisfied under the EU Floods Directive. It is this guidance and progress that allows for our cost-benefit economic analysis.

Flood-peak polders became necessary when it was discovered that the cross-sectional runoff capacity of the river corridor (the area between the two dikes) cannot be adapted to the long-run trend of rising flood peaks using the current dikes (Szlávik, 2003). The development of increasingly higher peaks from even similar discharge volumes is influenced by the deteriorating runoff conditions in the catchments and by the floodplain filling with sediment load from the watershed. This latter process has caused a significant rise in the ground level of the floodplain (1.5-2 meters) since the construction of the dikes in the mid-19th century (Schweitzer, 2001). Consequently, the long-term loss of flood defense capacity is an inherent feature. In the short-term (a few decades or even years), the runoff cross-section can be further degraded by increasingly thick vegetation, which slows down the flow and the resulting backwater that causes flood levels to rise (Delai et al., 2018; Nagy et al., 2018). The resulting increase in flood risk will exacerbate conflicts of interest about land management decisions in the floodplain between flood protection, nature conservation, agriculture and forestry. All these stakeholders have only partially compatible demands for land management and maintenance. The interventions to curb natural processes increase the risk of the spread of invasive species (Ortmann-Ajkai et al., 2018), which in turn has a feed-back effect worsening flood risk. Within the floodplain (between the dikes), increasingly costly and marginally less efficient measures can contain drivers that make forward-looking multi-purpose land use difficult to achieve. This encourages efforts to extend the floodplain and find different ways of increasing the space available for the river.

The shift towards flood-peak polder design was also motivated by the cost of the alternative scenario of raising the dikes, which was three times more expensive than a polder system with similar protective capacity (Szlávik, 2001). This is considered as a “cost minimization” economic decision algorithm on investment alternatives with no monetization or comparison of benefits from alternatives.

Figure Syn. 1 shows polders constructed or upgraded between 2004 and 2017, including Tiszaroff, Nagykunság and Hanyi-Tiszasüly reservoirs, the dike relocation at Fokorú-puszta, and the complex land management simulation at the Cibakháza-Tiszafüred former floodplain area.

Flood-peak polders are equipped to deal with the rarest of extreme flood events up over a 100-year return period when the cross-sectional discharge capacity is no longer sufficient to hold the flood waters between the dikes, even after temporarily raising them with sandbags to compensate for level deficits. Opening the flood gates provides controlled inundation that allows the peak of the flood wave to be cut off (Rátky and Szlávik, 2001). This is more effective compared to passive solutions such as dike level reduction toward the polder or dike relocation, where the excess water storage capacity is partly filled by water from the less threatening segment of the flood wave. The passive solutions have a lower flood risk reduction effect, either in terms of the additional area or the water quantity (de Kok and Grossmann, 2010; Pohl and Bezak, 2022; Teichmann and Berghöfer, 2010). However, in terms of the potential for providing ecological services, controlled-operation flood-peak polders do not always fit with nature-based solutions. The extreme floods that would trigger the inundation of these polders, as originally designed, are too rare to provide the necessary water supply to the ecosystem. From an infrastructure management point of view, it is preferable to keep the arable farming that is located in the area and compensate for damage on a case-by-case basis (Weikard et al., 2017). This logic was implemented in the legislation that provides a framework for the use of the flood-peak polders of the Tisza River (2004/67).

The context, however, changes when the flood-peak polder opening is based on the economic balance of flood risk reduction gains over farmers' compensation for the damages in the polder inundated rather than the exhaustion of the cross-sectional capacity of the river corridor as a hydrological or defensibility trigger. The technical conditions for examining this question were not yet available when the polder system was designed, but now a more sophisticated cost-benefit approach (CBA) using quantified flood risk change methodology could be applied. The combined analysis of the individual outcomes can be used to compare the magnitude of public benefits to individual benefits in case of the different land use and flood mitigation solutions applicable in the floodplains and the polders.

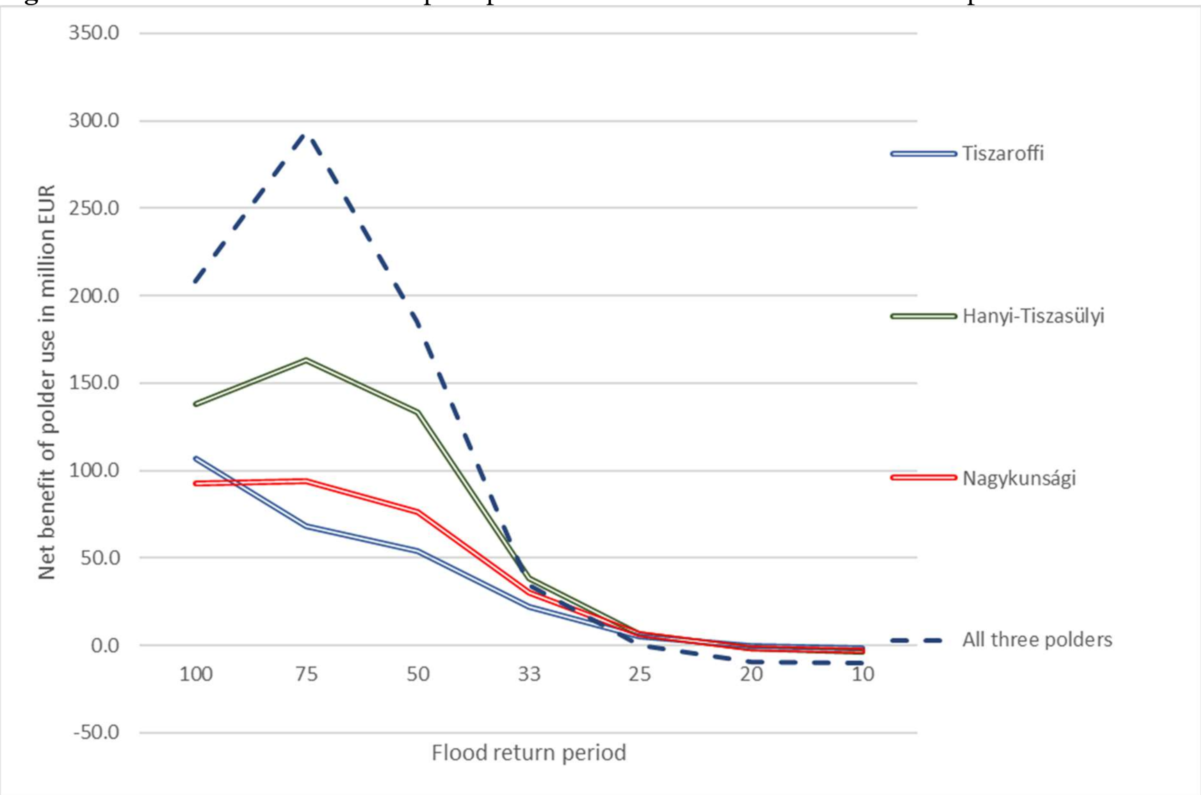
3.2 Single purpose flood risk reduction performance of the Middle-Tisza flood-peak polders

The first block of results summarizes the economic decision sphere of flood-peak polders' use and reveals the limitations of applying only one public benefit as optimization criterion for land use optimization.

(Ungvári & Kis, 2022) presented a detailed methodology for quantifying the flood risk mitigation effect of flood-peak polders with controlled inundation. The results prove that, from an overall societal perspective, it makes sense to allow more frequent use of flood peak polders, despite the significant event-based costs associated with inundation.

Using the polder to cut the peak of a flood provides the benefits of reducing flood risk and costs of flood defense activity downstream at the cost of compensation paid for agricultural damage caused by polder inundation. The relationship between the return frequency of the flood waves and the economic balance of the three polders in the Middle-Tisza section is illustrated in Figure Syn. 2 from (REKK, 2018). The results are based on a 50-year period using a discount rate of 2%. The economic break-even point for opening polders is located where the curves intersect the horizontal axis, representing the return period of a flood in which costs and benefits balance each other. These fall within the 20-25 year flood range return period compared to 100 years assumed on hydrological grounds. The concept of the economic break-even point creates a connection between the peak level flood in the river and the productivity of land use inside the flood-peak polder.

Figure Art.2.2 Middle Tisza flood peak polders' net benefit over different return period flood events



Source: Raw data of the figure (REKK, 2018)

In the longer-term, the economic breakeven point is affected both by the change in the value of the threatened properties downstream (typically an increase) and by the change in compensation for the inundation damage inside the polder. The latter can result from increased agricultural production intensity, which pushes up the economic breakeven point and leads to less frequent openings, or from changes that reduce exposure, like more extensive land use, which has a downward effect on the economic breakeven point, leading to more frequent inundation. The productivity of land-use inside the polders therefore has an impact on the potential for risk reduction through opening the flood-peak polder.

Benefits from flood risk reduction in relation to land productivity can be quantified by aggregating the risk reduction effect that can be achieved with floods above the return period of the breakeven point (the area between a curve and the horizontal axis in Figure 2). Table 1 shows the value of flood risk reduction as a 'service' per hectare of polder area. The first three columns describe the service values of the operation, ranging from EUR 18,000-34,000 per hectare.

Table Art.2.1 Flood peak polder area economic performance

	a)	b)	c)	d)	e)	f)	g)
	Value of flood risk reduction service in a 50 year time period	Size of the polder	Value of flood risk reduction service in a 50 year time period / hectare	Value of flood risk reduction service below the break-even point	Value of flood risk reduction service below the break-even point / hectare	Price of land in the region	Per hectar value of flood reduction service below the break-even point / price of land
Polder	million EUR	hectare	EUR/ha	million EUR	EUR/ha	EUR/ha	ratio
Nagykunsági	72.6	4,006	18,128	13.6	3,400	4,277	0.80
Hanyi-Tiszasülyi	99.4	5,437	18,279	19.3	3,545	4,277	0.83
Tiszaroffi	81.3	2,336	34,818	8.3	3,548	4,277	0.83

Legend: EUR values calculated by the year 2020 average HUF/EUR exchange rate. Source of data (REKK, 2018)

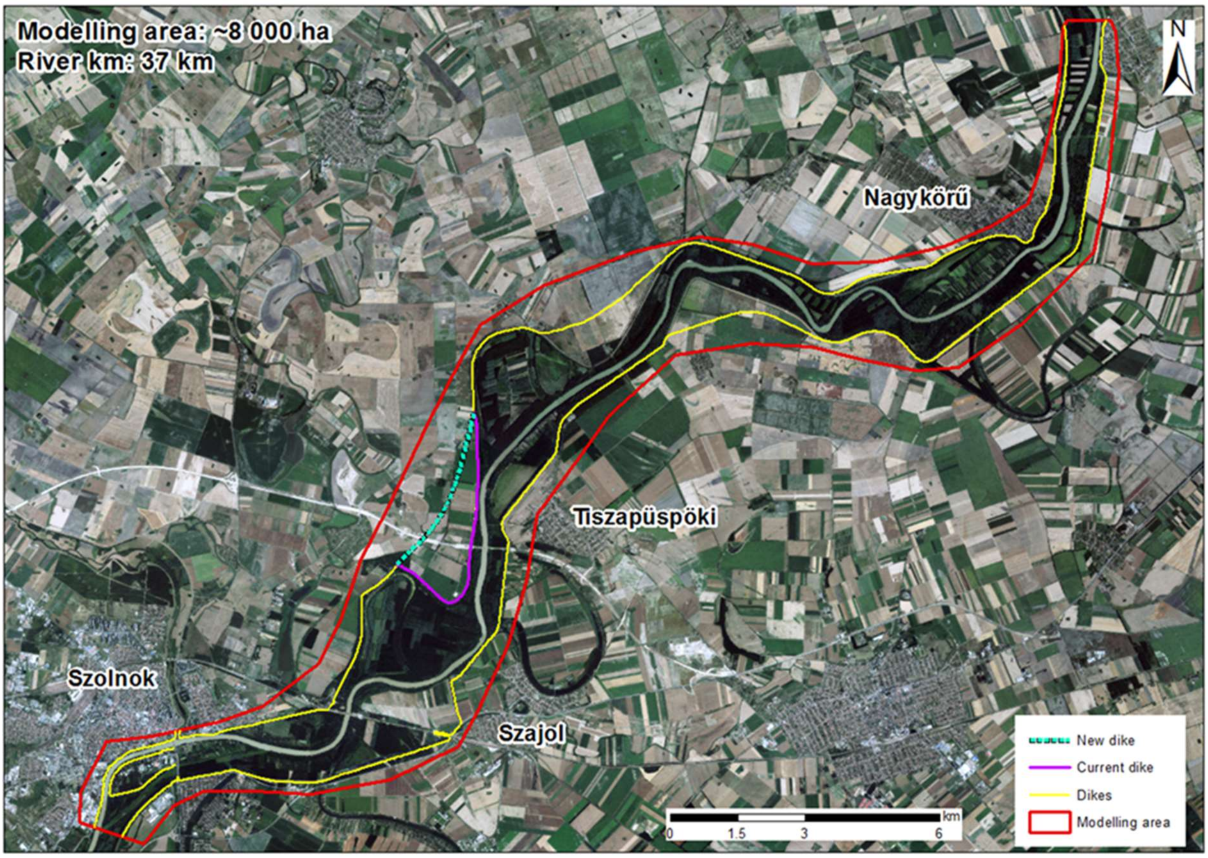
Under the assumption of lower damage exposure in the polder, the economic breakeven point also shifts downwards, providing an additional risk reduction effect for opening at lower flood levels. However, as flood waves decline the additional risk reduction effect also contracts. In a special case with zero compensation all floods can be released into the polder. In this case, however, current agricultural activities would no longer be viable in the area. The question arises as to whether the additional risk mitigation that could be gained by releasing minor floods would cover the cost of purchasing the land? (Land price is considered as a clear indicator of the economic space for bargaining with a landowner for mutually acceptable land-use terms and no policy considerations of expropriation are attached.) The fourth and fifth columns represent only the value of this additional benefit from minor floods. Its relation to the land price in the area, the sixth column, reveals the economic viability of such an approach. The last column is sensitive to the length of lifecycle and the discount rates that are close to but lower than one. In other words, the additional risk reduction benefit from floods below the breakeven point is lower than the costs of investing in the possibility to curb them.

From a narrow flood protection point of view, therefore, the solution currently applied is confirmed by these ex-post calculations. Taking only flood risk into consideration, it is not economically rational in the current situation to change land-use, i.e. to invest in the purchase of land in the polder to further reduce the cost of flood events. At the same time, in order to reveal the full potential for additional public and private benefits, the bundle of benefits is necessary to be considered that the following two analyses pursue.

3.3 Multi-purpose cost-benefit relationships of dike relocation at the Fokorú-puszta river section

The (REKK, 2021) study carried out an ex-post evaluation of the dike relocation development at the Fokorú-puszta site. The flood risk reduction effect of the dike relocation overlaps strongly with the area of reduced flood risk by the flood-peak polders. While not substitutable, the flood risk reduction performance is comparable.

Figure Art.2.3 Map of the Fokorú-puszta dike relocation site



Legend: The map shows the change in the line of the dike and the area incorporated into the floodplain. Source: (REKK, 2020)

The REKK study (2020) was based on the flood risk calculation methodology for polder use and complemented by an assessment of ecosystem-service-based benefits enabled by integrating the area into the floodplain.

The floodplain was extended by 325 hectares, converting what was previously arable cultivation into grassland, wetlands, and a forested strip to protect the dike (see Figure 3.) The extended cost-benefit analysis of the investment and the multi-purpose use of the area quantified the flood risk reduction, the maintenance costs of the area, the revenue from the timber extraction and carbon sequestration balance from the forests, and the use of the wetland as a fish spawning area. These benefits from the full ecosystem service package are monetized and presented in Table 2.

Table Art.2.2 CBA results for ecosystem service elements

	Size of the delineated ES service area	**Net Present Value of the ES service**
CBA elements	hectare	million EUR
Investment costs		-15.8
Flood risk reduction as benefit	325	18.0
CO2 sink (forest)	20	0.8
Fish spawning area	35	0.9
Meadow maintenance	270	-0.5
SUM		3.4

Legend: Source of data (REKK, 2020)

Flood risk reduction has by far the largest impact, itself bringing the equation into positive territory. The ecosystem services provided by the floodplain under current conditions (excluding flood risk reduction) would not cover the cost of the dike relocation project, but have a strong, positive supplemental impact.

The benefit of dike relocation and the polder development can also be expressed per hectare of land used. Table 3 shows the specific flood risk reduction impact per hectare of the three polders and the dike relocation.

Table Art.2.3 Flood-peak polders and dike relocation land service productivity comparison

		Impact of the Fokorú-puszta dike relocation	
		Flood risk mitigation impact	Flood risk mitigation and other ESS impacts
		EUR/ha	EUR/ha
		6,857	10,475
Flood risk mitigation impact of the flood-peak polders		Ratio of per hectare efficiency: dike relocation / flood-peak polder Only flood risk mitigation	Ratio of per hectare efficiency: dike relocation / flood-peak polder Including ES service of dike relocation
Nagykunsági flood-peak polder flood risk mitigation impact, EUR / ha	18,128	0.38	0.58
Hanyi-Tiszasülyi flood-peak polder flood risk mitigation impact, EUR / ha	18,279	0.38	0.57
Tiszaroffi flood-peak polder flood risk mitigation impact, EUR / ha	34,818	0.20	0.30

Legend: Source of data (REKK, 2018 and 2020)

Table 3 shows that the dike relocation risk reduction capacity per unit area is much lower than that of the polders, a consequence of the controlled release of water. By opening flood gates, the top of the flood wave – which carries the most risk - is discharged into the area of the polder. In the case of dike relocation, the flood reduction effect comes from a local increase in cross-sectional runoff capacity, which becomes partly occupied by the volume of water ahead the peak of the flood wave. Therefore, the newly integrated area is not fully utilized to treat the most dangerous section of the flood wave. The last column shows how the differences contract when ecosystem services are included in the impact of the dike relocation. Although the inclusion of additional ecosystem services does not overcome the initial difference, the results confirm the conclusion that the potential for developing multi-purpose use packages rather than considering single-purpose use.

Unlike the polder solution, relocating the dike includes the expropriation costs of the farmland concerned. The price of the land (present value of future income from its agricultural use) is covered by the total additional benefits raised by the project, mostly concentrated in flood risk mitigation. This can open the way for other uses based on the functioning of the ecosystem for smaller co-benefits that require the replacement of intensive farming.

It is important to highlight the role of forests, which have a significant added value relative to their share of the territory (6%). These benefits are calculated based on a management concept of continuous forest cover in line with the function of dike protection against waves. It is supplemented by the value of the additional carbon sequestration over the 50-year lifespan of the analysis. This follows the (EBRD, 2019) recommendation for a "shadow price of EUR 36 - 72 EUR/tCO2" to increase atmospheric carbon dioxide concentrations (see details in the Annex).

The significant public benefits accrued from forests deserve additional attention in comparison with grasslands and wetlands. A significant obstacle to grassland benefits is the absence of pasture-based economic activities in the area of study where higher value-added benefits of raising and feeding animals could be materialized (REKK, 2020). Maintaining grassland has delivered a near breakeven result with agricultural subsidies, mostly contributing through the reduction of flood risk. For wetlands, the negative balance is owing to the high cost of construction, which is a unique, location specific feature. The value of wetlands is predominately recreational fishing, but the value of the spawning areas would not increase proportionally since anglers would not proportionately increase the time they spend along the river. Under the present circumstances, forestry is the only land use type that would increase benefits in proportion to area expansion.

3.4 Combined impacts of flood mitigation and land use transformation in the Cibakháza-Tiszaföldvár area

This third analysis (REKK, 2021) did not examine the operation of an already implemented infrastructure development like the other two. An additional conceptual study was executed in the Danube Floodplain programme, only this time without anticipating real life implementation. This multi-scenario analysis was carried out for the former floodplain area between Cibakháza and Tiszaföldvár settlements and now the area is protected from flooding. In addition to the current (flood-protected) agricultural land use scenario, two other land use scenarios with different exposures to damage were combined with three flood attenuation scenarios. This later analysis highlights the role of economic incentives driving land use decisions.

Farmland has a special role in managing flood risk, on the one hand benefiting from protection of the infrastructure in place, and on the other constraining the space for flood protection solutions in areas capable of adapting to transient water cover.

The choice on agricultural cultivation is an individual parcel-level decision, whereas flood risk mitigation can only be achieved through coordinated land use of a large area. Conversion would be rational but implementation is hampered by a number of difficulties (Hartmann, 2011). The crucial question for landowners is whether future income will rise or fall (Kis et al., 2022). In the case of lower income, individual compensation must be covered by the wider community benefits. For higher income, only implementation support for the collective conversion process should be covered by the community benefits. In the latter case, individual income distribution imbalances can be smoothed with assigned transaction costs over time. These hidden costs are significant, spread over many actors, and capable of undermining agreements (Ungvári and Collentine, 2022).

In Hungary, the EU agricultural subsidies have an oversized influence on landowner decisions (Kovács et al., 2021). Even in the case of medium and poor-quality crop land, the subsidies provided under the Common Agricultural Policy dictate land use, making it economically irrational to convert land for other agricultural purposes. Agricultural regulation is in a constant state of flux in order to avoid the direct and indirect negative environmental impacts it generates. Therefore, a recurrent analysis on the prospects of agricultural land-use, like the area between Cibakháza and Tiszaföldvár, is necessary.

In the absence of dikes, the area would be regularly flooded by medium flood levels. The aim of the study was to investigate the financial opportunities and constraints for adaptation of agricultural land to flooding, considering both the agricultural damage caused by flooding and the flood risk reduction impact of different flood mitigation solutions. Can land-use adaptation create a positive balance taking into account all costs and benefits? Can benefits be allocated to landowners bearing the costs? The site selection criterion was not to maximize flood risk reduction but to explore the relationship between the land characteristics and its inundation.

Table Art.2.4 depicts the current land-use (Current LU) that is almost entirely arable (94%), with the first scenario (Adapted LU) crop-dominated (59%), adjusted to terrain and acceptable according to current public perception, and the second scenario fully forested (Forest LU).

Table Art.2.4 Land use ratios, combined scenario definitions and names

Land use (LU)	**Current LU**	**Adapted LU**	**Forest LU**
Arable land (crops)	94%	59%	0%
Grassland	5%	28%	0%
Deciduous forest	1%	13%	100%
Total (hectare)	2067	2067	2067
Flood scenarios on LU scenarios			
No flood, the area is protected	Current LU, no flood	Adapted LU, no flood	Forest LU, no flood
All floods, the area is open to inundations	Current LU, all floods	Adapted LU, all floods	Forest LU, all floods
Floods through a sluiceway above the 30 year return period floods	Current LU, spillway	Adapted LU, spillway	Forest LU, spillway
Polder-like operation, only the 100 year return period floods	Current LU, flood gate	Adapted LU, flood gate	Forest LU, flood gate

The modelling scenarios attempt to cover the characteristic elements of the outcome spectrum. The three land-use options were tested in combination with the four flood scenarios. The hypothetical shift in land-use and introduction of inundation patterns is enabled by the construction of a perimeter dike, enclosing the area and connecting to the existing line of the dikes.

In the first scenario all floods reach the area (“all floods”), in the second scenario floods above the 30-year frequency are released through a lowered dike section (“spillway”), and in the third scenario the peak of the rarest floods (100-year return frequency) is cut by the flood gate (“flood gate”). The flood level reduction increases from the first to last scenario, with the latter similar to the operation of the controlled flood-peak polders previously described. The calculation accounts for Middle-Tisza flood-peak polders and the dike relocation since they are already influencing downstream flooding patterns.

Table 5 shows that under all scenarios frequent flooding damage to arable land cannot be compensated by the combined benefits of reduced flood risk, lower exposure, and increased ecosystem service potential from converted land. In other words, the investment costs are not offset by flood risk reduction and land-use change is insufficient in scale. Comparing values from the first and fifth columns, it shows, however, that the adapted land-use scenario is the more favorable without inundation.

Table Art.2.5 Costs and benefits of various scenarios in the Cibakháza-Tiszaföldvár floodplain area

	Land use (LU) and flood mitigation scenarios							
	BAU: Current LU - no flood	**Current LU, all floods**	**Current LU, spillway**	**Current LU, flood gate**	**Adapted LU, no flood**	**Adapted LU, all floods**	**Adapted LU, sluiceway**	**Adapted LU, flood gate**
	million EUR	million EUR	million EUR	million EUR	million EUR	million EUR	million EUR	million EUR
Investment cost	0.0	-20.1	-20.1	-31.8	0.0	-20.1	-20.1	-31.8
Flood risk benefit minus agricultural damage	0.0	-18.2	0.8	8.0	0.0	-10.8	1.2	8.5
Agricultural activities' income	8.7	8.7	8.7	8.7	8.5	8.5	8.5	8.5
Financial transfers for agricultural activities	14.7	14.7	14.7	14.7	14.1	14.1	14.1	14.1
Value of CO2 emission - sink balance	-4.5	-4.5	-4.5	-4.5	-1.5	-1.5	-1.5	-1.5
Sum	18.8	-19.4	-0.4	-4.9	21.2	-9.7	2.3	-2.1

Legend: The “Flood risk benefit minus agricultural damage” row of the table shows relative results, the BAU status has an initial flood risk exposure (-85 million EUR) that is excluded from the „Current LU, no flood” scenario for the better comparability. Source of data (REKK, 2021).

One clear message from the modelling outcomes is that for crop based agricultural activities transfers substitute rather than complement individual income generation. Although EU-CAP subsidies (transfers) drive individual decisions on cultivation, long-run forestry is more beneficial than crop production, with or without transfers, as shown below in Table 6. In addition to subsidies, lower short-term annual income, lack of management experience beyond crop production, and the cost of replacing assets act as constraints that reduce the attractiveness of an otherwise superior long term financial outcome.

However, the costs of preserving low value-added agricultural production go beyond the individual to the public (as a form of opportunity cost), which is made clear comparing Current LU scenario to the afforestation scenario (Forest LU).

Over several decades forestry would yield 40% more individual income discounted into present value today compared to the current crop-dominated farming system, and it would be 2.6 times higher without agricultural subsidies (transfers). It is clear from Table 6 that the subsidies are the driving force for land-use. In order to unlock the superior public benefits from forestry rather than continue to focus on crop production, the income stream of farmers should be smoothed. Currently the subsidy system disincentivizes farmers from switching to forest management with attractive long-term prospects. In spite of the problem revealed the results mean that not continuous income support is necessary to induce land use adaptation, but a "bridging" type public support is needed to focus on the organization issues and initiation of individual afforestation activities covering all land users.

Table Art.2.6 Forest land use scenarios compared to business-as-usual (BAU)

	Land use (LU) and flood scenarios								
	Current LU, no flood (BAU)	Forest LU, no flood	Forest LU, all floods	Forest LU, spillway	Forest LU, flood gate	Forest LU, no flood	Forest LU, all floods	Forest LU, spillway	Forest LU, flood gate
NPV results of selected items	million EUR	million EUR	million EUR	million EUR	million EUR	ratio x BAU	ratio x BAU	ratio x BAU	ratio x BAU
Individual balance with Transfers	23.4	32.7	32.7	32.7	32.7	1.4	1.4	1.4	1.4
Individual balance without Transfers	8.7	22.5	22.5	22.5	22.5	2.6	2.6	2.6	2.6
Public benefits	-4.5	11.2	12.3	13.1	20.3	-2.5	-2.7	-2.9	-4.5
Sum of all CBA items	18.8	44.0	24.9	25.8	21.3	2.3	1.3	1.4	1.1
Sum without CO2 benefits	23.4	32.7	13.7	14.5	10.0	1.4	0.6	0.6	0.4

Legend: Monetary values are net present values in million EUR. „Ratio x BAU" columns compare scenario results to the „Current LU, no flood" scenario. „Individual balance" refers to the land users' financial position with and without EU CAP payments. „Public benefits" are the sum of the flood risk reduction benefits and the shadow price of CO2 sink. „Sum of all CBA items" includes all individual and public cost and benefits items together with the investment costs. Source: Own calculations

We can see from the modelling results in the last column of Table 6 that without CO2 mitigation the additional flood risk reduction service is not economical. This highlights the importance of the dual evaluation including CO2 sequestration potential, which is 2.33 CO2 tonnes/ha per year averaged over 50 years. This value is the difference between the emission from arable cultivation and CO2 sequestration of a forest, based on Hungary specific coefficients. In Table Art.2.6 the value of CO2 sequestration is calculated using the mean value of the shadow carbon price used by the EBRD (see Appendix for more details). Alternatively Table Art.2.7 shows the breakeven CO2 price for combined land-use change and flood protection (The EBRD methodology calls this the switching price of carbon).

Table Art.2.7 Carbon sink breakeven price in the forest scenarios

	Forest LU, no flood	Forest LU, all floods	Forest LU, spillway	Forest LU, flood gate
Balance: The sum of all items without CO2 benefits compared to BAU (EUR/ha/year)	144.2	-148.9	-136.1	-205.3
CO2 emission difference between forest and arable (ton/ha/year)	-2.33	-2.33	-2.33	-2.33
Monetary value of CO2 mitigation necessary for breakeven economic position of the scenario (EUR/CO2 ton)	-62	64	58	88

Source: Own calculations

All but the first scenario show a positive balance only with high CO2 prices assumed since the flood risk reduction investments are not profitable without a price for CO2. This EUR 64-88 per ton CO2 price range, however, is near to current EU ETS prices ("EUA Futures," 2022) and EBRD and World Bank estimates (€37-74/ton CO2) (EBRD, 2019).

The price orders of magnitude suggest that the public benefit of forestry in terms of CO2 sequestration (excluding the flood risk impacts) is enough for landowners to shift from crop to forest management. However, this theoretical calculation for the Cibakháza-Tiszaföldvár site shows that, if CO2 avoidance prices are assumed, a positive balance of combined flood risk reduction and afforestation in the former floodplain areas of the Tisza River basin can be achieved by more risk- efficiency-focused location and size choices.

3.5 Linking of the research results

The combined analysis aims to reveal the complex territorial and sectoral interrelationships and their potential for joint optimization. The public benefits can be characterized as purely flood risk reduction as current peak polder land-use fails to realize their full potential. Albeit from this risk-only perspective, it is not worth transforming the current polder land-use at the cost of buying the land – the individual and public benefits of afforestation even separately would cover this difference as the calculations of the Cibkaháza-Tiszafüred site show.

The calculations for the Fokorú-puszta dike relocation project indicate that the balance of the floodplain expansion would be significantly improved if new ecosystem service opportunities could be developed to complement the flood risk reduction effect.

The results of the study for the Cibakháza-Tiszaföldvár area makes a compelling case for forestry as opposed to crop-dominated farming. With short-term agricultural incentives, it would be rational to maximize both individual and community benefits. While the forestry brings higher long-term individual income, it is dampened by the short-term incentives of the agricultural subsidy regime. A shift towards the provision of community benefits requires management of the land-use transition, not agricultural income substitution in perpetuity. State funding for farmers should be reassessed to overcome the challenges of the transition and develop the foundation for merging benefits over times.

The economic exploration of trade-offs between flood risk change and afforestation necessitates their joint optimization based on studying out of the box hydrological scenarios without restrictions on river corridor roughness and width conditions and the frequency of polder inundation. These novel hydrology simulations can reveal the flood risk limitations of transforming the space and time distribution of flood wave profiles.

4 DISCUSSION

The quantified flood risk and forestry CO2 sequestration assessments carried out in this study are underused for the implementation of public policy in Hungary. The main problem for flood-peak polders with controlled inundation is the low relative frequency of their use, maintaining arable cultivation (Weikard et al., 2017), which comes with the opportunity cost of the potential for additional benefits. Forest areas can minimize the inundation cost and additional benefits can be obtained. An example of this approach is the decades long experience of the Mályvád polder at the Körös River (Puskás, 2000), where both flood damage prevention and water management infrastructure elements have been technically installed. The area is regularly replenished from receding floods and peaks can be cut-off by flood gates. So far, only ecological studies have been carried out (Puskás, 2010) and a more complex evaluation is needed. There is room for technical innovation from both an engineering and a land management perspective to ensure that water can be safely diverted from regular floods. There is also a need to explore the cost-benefit impacts of flooding on forested areas through empirical studies of local flood and seasonal water inundation conditions. Recently the national methodology for risk mapping under the EU Floods Directive protocol assumes damage functions for both regular and hydrologically affected forests (Szixtin et al., 2020).

The results show that there is a strong public interest in the accountability of the offsetting CO2 sequestration capacity of floodplain forests. A transparent and therefore widely considered accounting system that improves incentives to conserve forests has significant potential for achieving public policy objectives across sectors (Macintosh et al., 2019). At the same time, as in the context of flood risk management, there is a key role for private landowners to play in the development of nature-based solutions (Hartmann et al., 2018). To realize the potential of CO_2 sequestration, it is necessary to clarify who owns the CO_2 sequestered as a climate mitigation service (Merk et al., 2021). At present, CO_2 sequestration from forests contributes to the national obligations, e.g. in Hungary, involving emissions not covered by other regulations, where it is the responsibility of the government to achieve emission levels in line with international commitments. There is no feedback to forest owners to steer their management decisions in a direction that benefits the community or to give them the right to sell CO_2 sequestration. It is not clear whether forest owners can be given the right to sell their sequestration in a voluntary carbon offsetting scheme without creating a double counting with national compliance. Uncertain property right arrangements hamper innovation. The increasingly apparent value of CO_2 sequestration and the scale of the potential areas involved for afforestation suggest a public benefit be harnessed justifies deeper legal focused investigation that (Szigeti, 2021) outlines.

The economic interpretation points to a hitherto unstudied hydrological relationship between more frequent flood-peak polder utilization and higher roughness in the floodplain. Can this flood risk transfer work? The additional risk mitigation capacity of polders may improve management conflicts that arise between the most ecologically valuable riparian gallery forests and the declining cross-sectional capacity. This approach opens new hydrological analysis opportunities for higher frequency polder usage in flood risk regulation considering individual and public benefits of ecological land management.

In the long run, the adaptability of land-use in the former floodplain areas is essential in the context of a landscape that is gradually losing water (Rakonczai, 2021). The multidirectional, dispersed damage of droughts is already more costly than flooding (García-León et al., 2021; Láng, 2021), but detailed, site-related information is not yet available. The quantified benefits of land-use adaptation processes are also important as they facilitate infiltration by the more frequent inundations. With the right tree species, the water tolerance offers flexibility to shift the boundary of the area under protection. This in turn has repercussions on the spatial constraints of flood risk management itself and the ability to expand the cross-sectional capacity of the river, which has been minimized for the Tisza River to this point.

5 CONCLUSIONS

The modelling results show that the improvement of ecosystem service based social benefits of riparian areas must be based on an integrated approach for flood risk reduction and land adaptation rather than fragmented sectorial and location boundaries.

The benefits of the quantified flood risk management method and the benefits of accounting for CO_2 sequestration of forests, even conservatively calculated as two robust and transparent methodologies for quantifying impacts, provide sufficient information to inform about the economics of land use change and adaptation processes. This creates the economic conditions for the necessary agreements between the community of beneficiaries and the cost bearers. With this approach, the issue of agreements on subsequent uses that may potentially arise when ecosystems mature can be left for later.

The community cost of not adapting riparian land-use far outweighs the opportunity costs of individual inaction. The price of land as a switching point for expropriation is a clear indicator in an economic comparison, moreover it indicates a strong public bargaining position on forming future land use, but the displacement of land-users is not the preferable negotiation result. Overcoming the underlying conflict of interests may require a legal mandate for the creation of a compulsory water easement regulation that enable the majority of agricultural landowners of a local flood basin to receive transient water cover that the recent requirement of a unanimous owner agreement would never be reached. Due to the perverse incentives imbedded in the EU-CAP subsidies, there is a need for sufficiently strong and enforceable regulatory instruments to enable community action on long term water management goals.

In order to increase the social benefits from forested CO_2 sequestration capacity, the principles of public and private ownership and a national accounting system need to be clarified and established.

ANNEX

The World Bank and many large international development banks already use the projection of the "carbon price" in their financing decisions for project approval (EBRD, 2019). It is assumed that carbon pricing will become standard practice within the timeframe of the projects analyzed. Until then, there are several ways to estimate the economic value of carbon dioxide sequestration, but they vary widely. The most transparent global CO_2 price is the EU-Emission Trading System (ETS), which is €78/ton at the moment, but has fluctuated between EUR 16/ton and EUR 96/ton over the last two years (*EUA Futures*, 2022). Other non-equivalent carbon markets provide less reliable price information. Another approach is equating the economic value of CO2 emissions (or removals) to a price range that will phase out fossil-based technologies in order to meet the Paris Climate Goals. This approach is used by the World Bank and a number of major international investment banks to assess project economics. The price range is USD 40-80/ton CO2 now, (i.e. EUR 36-73/ton) rising to USD 50-100 per ton by 2030, and then 2.25% per year until 2050.

According to the EBRD methodology, when evaluating projects, the lower and upper values of the price range are used to assess the project's outcome. If the balance of the proposed project is positive even after taking into account the cost of CO2 neutralization at these prices, it is eligible for funding according to its climate protection performance. If the calculation does not show a positive balance with both values, a switching point is calculated, whose value and the specific CO2 abatement costs for the economy in question provide the basis for the financing decision.

Acknowledgements: I thank my colleague András Kis for his enduring support.

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ARTICE 3: SOCIAL, ECONOMIC AND LEGAL ASPECTS OF POLDER IMPLEMENTATION FOR FLOOD RISK MANAGEMENT IN POLAND AND HUNGARY

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Journal: *Journal of Flood Risk Management*, (2023) e12897. https://doi.org/10.1111/jfr3.12897

Keywords: floods, nature-based solution, Golina polder, Tiszaroff polder, social innovation

ABSTRACT

The implementation of nature-based solutions that involve natural processes to mutually decrease flood risk and protect natural ecosystems can be an answer to the demand for resilient flood risk management. As an example of a nature-based solution, flood polders have the potential to deliver those benefits; however, a need for innovation is observed in the field of redefining, combining, and reformulating existing approaches to improve the welfare and wellbeing of individuals and communities.

This paper aims to investigate polder implementation and management processes, perceived as a potential introduction of social innovation in Poland and Hungary, where social innovation in flood risk management is required but where the introduction of innovative solutions stalls at different stages. Based on a comparative analysis, a set of factors for effective social innovation was formulated regarding formal and legal conditions and economic and social aspects of polder management and implementation. Each of identified factors can either allow or hinder public engagement and successful social innovation.

1 INTRODUCTION

Although climate change has had significant implications for flood risk management (FRM) over the years, these have not induced actual action for flood risk mitigation (Wasko et al., 2021). At the same time, the vast majority of long-term FRM actions that have been undertaken have so far relied mostly on technical measures that have often been ineffective in combating increasing flood risk (Ellis et al., 2021). Flood damages, caused not only by the very nature of the flood events (Zwoliński, 1992) but also by negligence in the technical infrastructure of flood protection measures or the establishment of insufficient measures to cope with increasing flood risk, are predicted to increase and expand in the future (Alfieri et al., 2015; Hirabayashi et al., 2013; Jania and Zwoliński, 2011; Kreibich et al., 2022; Wing et al., 2018). While many initiatives emerge in the immediate aftermath of a flood event, there is still a general scarcity of substantial actions undertaken a priori to mitigate such risks (Albrecht and Hartmann, 2021). The frequently observed post-factum approach to FRM action is characteristic of post-socialist countries influenced by their former centralized policies, resulting in certain specific kinds of flood risk perception among authorities as well as in society (Raška, 2015). Substantial transformations in established FRM systems are constantly required, especially in countries that have experienced floods on scales exceeding predictions of possible size of the disaster in the past (Matczak et al., 2018). Even in regions where actions to mitigate flood risk are actively undertaken, new innovative measures need to be implemented in response to social and environmental needs (OECD, 2016).

Due to dynamic societal transformation, more focus is usually dedicated to social innovations born out of new ideas that work to satisfy social goals (Mulgan, 2006) or to innovative services and activities aimed at meeting social needs (Cajaiba-Santana, 2014; Mulgan et al., 2007). An innovative approach to flood risk reduction can be expressed as a shift toward implementing solutions based on natural processes—that is, nature-based solutions (NbS)—to decrease flood risk while simultaneously preserving and maintaining geo-, bio-, and cultural diversity as well as the ability of ecosystems to evolve over time, thus producing societal benefits in a fair and equitable manner (IUCN, 2021; Jakubínský et al., 2021; Raymond, 2017).

One example of an NbS in FRM is polders, which combine the potential of hydrotechnical engineering with nature-derived features and processes to mitigate floods (Daigneault et al., 2016). The effectiveness of polders in flood risk mitigation has been proven in several sites and under various conditions (Budiyono et al., 2017; Gao et al., 2018; Maczalowski, 2015; Mawandha et al., 2018; Nováková et al., 2014; Short et al., 2019; Wahyudi, 2019). However, despite their benefits, the implementation and management of polders is not straightforward and is limited by numerous factors and conditions.

This contribution aims to investigate polder implementation and management processes, perceived as a potential introduction of social innovation. A comparative analysis was conducted for two case study polders located in Central-European countries—Golina in Poland and Tiszaroff in Hungary—where similar background conditions were observed, such as their history of former flood events, increasing flood risk, and maladjusted FRM systems and their transformation. However, the implementation of these polders rendered different outcomes. The research also addresses the questions of whether polders, despite their social and ecological benefits, may be assessed as social innovation and, if so, to what extent they contribute to the improvement of societal wellbeing.

To address these questions, a set of factors influencing the effectiveness of social innovation was identified.

2 POLDERS AND SOCIAL INNOVATION

Ensuring flood safety is considered one of the basic needs of communities in flood-prone areas (Yusoff and Yusoff, 2021). As the negative consequences of flood events increase and expand over the years, new innovative solutions are required to cope with increasing flood risk and constantly changing background conditions (social, environmental, economic, and formal). In that context, polders, as regulated areas along rivers for the multiple goals of flood defense and a bundle of other public and private benefits, can be perceived as an innovation when compared to hydraulic infrastructure, such as dikes or dams (Bark et al., 2021; Moreau et al., 2022; Vingre, 2017). This reflects a general shift in FRM that emphasizes the role of protecting nature and human beings (Wesselink, 2016).

Polder implementation requires new arrangements, methods, and approaches, the introduction of which is both a necessity and an opportunity for different groups; land owners, land users, public administration, and indirect beneficiary groups activate themselves to defend interests or mobilize for new goals. As the role of citizens in decision-making processes gains importance (Guerriero and Penning-Rowsell, 2021), especially in post-communist countries (Raška, 2015), there is a strong need to investigate the process of designing and implementing new solutions that imply conceptual, process, product, or organizational change, ultimately aiming to improve the welfare and wellbeing of individuals and communities, defined as social innovation (OECD, 2016). Presented research perceives polders as an innovative solution with the potential to induce those changes, but the implementation and management of polders manifests as a host of intertwined and complex processes, and this potential is untapped.

The concept of social innovation provides an analytical perspective for these complex processes (Cajaiba-Santana, 2014). This approach acknowledges the proactiveness of all actors in decision-making processes and addresses the contingencies of historical and local situations while allowing the exploration of patterns across cases (Christmann et al., 2020; Mumford, 2002). The novelty of the concept of social innovation is expressed in its applicability to multiple socio-environmental problems that are not addressed by traditional innovation (Solis-Navarrete et al., 2021). Social innovation is however an answer for context-specific challenges as the background conditions determine the emergence and development of local social innovations (Brandsen et al., 2016; Domanski et al., 2020)(Brandsen et al., 2016, p 8; Domanski et al., 2020) that can be upscaled and transferred to different applicable contexts (Thaler et al., 2019). Social innovation proposes new and better ways of solving social problems and fostering positive social change (The Young Foundation, 2012). Presented study focus on process oriented innovation that may however lead to an innovative results (EC, 1995).

The literature describes the preconditions of social innovation as the satisfaction of basic needs, reconfigured social relations (social transformation), and socio-political empowerment or mobilization (Moulaert et al., 2005). Transformation, leading to social innovation, can be triggered by deviations that create the need for a system to change (Thaler et al., 2019). Social innovation has its starting point in notions of social beneficence and public good that support people in organizations, communities, and society in general (Dawson and Daniel, 2010). A driver for change is a so-called window of opportunity, often referring to natural disasters (such as flood events) as a starting point of transformation (Few et al., 2017; Tortajada et al., 2021).

3 CASE STUDIES

A comparative analysis of polders located in two purposively chosen Central European river basins in Poland and Hungary was performed. In recent decades, both countries have faced severe flood events (Kundzewicz, 2012, 1999; Szlávik, 2003). In Poland, floods endangered the majority of society, caused dozens of deaths and induced significant economic losses estimated at billions of euros (Kundzewicz, 2014). In Hungary, apart from inducing significant defence operations, a series of major floods in the Tisza river basin resulted in a dike breach and, consequently, a large-scale inundation of settlements (Szlávik, 2003), which, until now, were considered events of the past and largely forgotten. For both regions, as well as for the whole of Europe, flood risk and flood damage are predicted to increase in the next decade due to the highly dynamic nature of climate change (IPCC, 2021). Because of the constantly increasing flood risk in both river basins, attempts are being made to find and implement innovative flood protective measures. In both regions, polders play an important role in FRM. Although the background conditions for both regions appear to be similar, the processes adopted by the two countries to achieve the same goal, i.e. implementation of polders for flood risk reduction, were different and brought about different outcomes. The location of case study areas is presented on Fig. 1. and all basic information are presented in table 1.

Figure Art.3.1 Location of selected case studies - Tiszaroff and Golina polder.

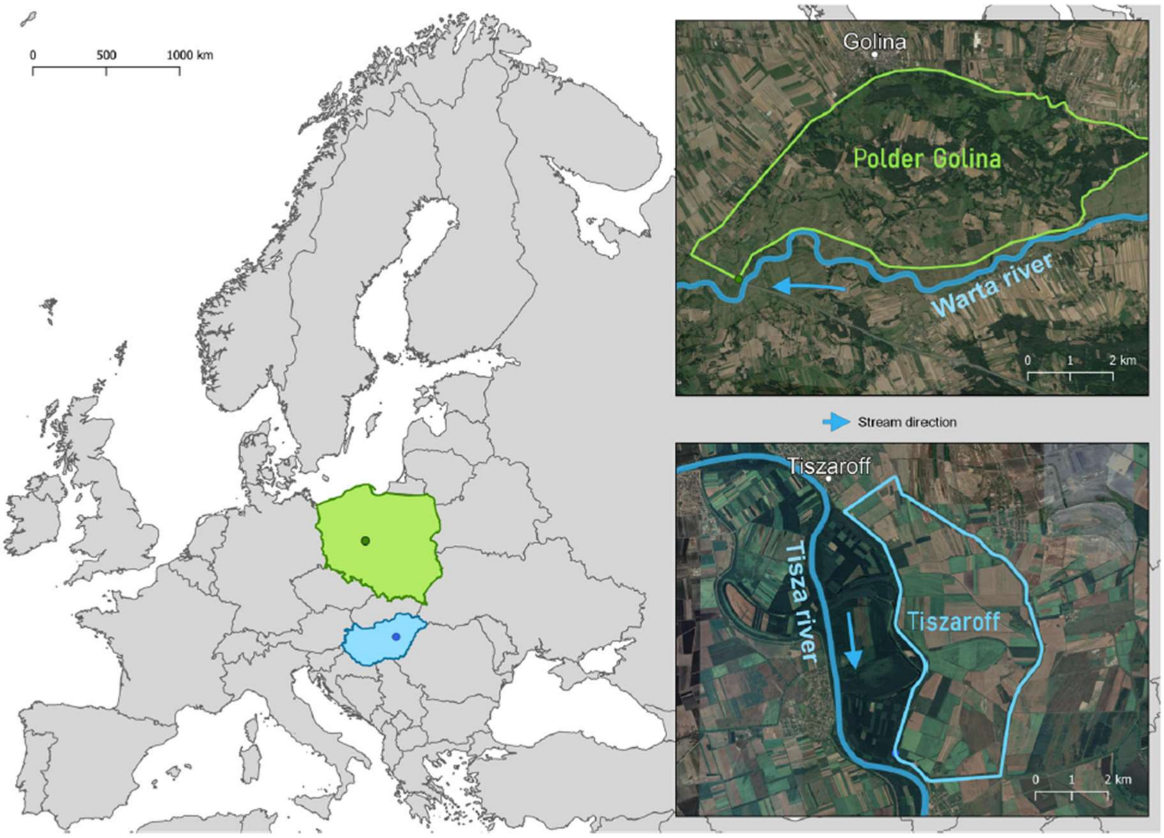

Table Art.3.1 Description of Tiszaroff and Golina polders.

Feature	Golina	Tiszaroff
Location	Warta river (Poland)	Tisza river (Hungary)
Area [ha]	2678,5	2336
Retention capacity [mln m^3]	37	97
Water level reduction [cm]	29	38
Land cover	95% agricultural areas 4% artificial surfaces 1% forests	95% agricultural areas 3% forests 2% water bodies
Share of private land (%)	78	94

3.1 Golina polder

The Polish polder Golina is located in the central part of the country, on the right bank, between 385 and 398 km of the Warta River. The polder was constructed as part of a project to develop the widely spread, natural Konin-Pyzdry valley. This complete project involved the construction of embankments that would divide the valley into nine polders with dedicated hydrotechnical structures designed to protect areas in the lower section of the Warta, particularly the city of Poznan (Laks, 2017). Due to limited financial resources and construction of another flood retention reservoir named Jeziorsko upstream, the initial development plan for Golina was abandoned for almost 40 years, and then narrowed down to two polders (Golina and Zagórów) instead of a complex polder system (Laks and Lewandowska, 2017). Ultimately, only Golina was designed for flood protection purposes, with its area intended for agricultural use and optional flood retention (Laks, 2017). The legal and formal framework for establishing polders in Poland did not specifically define the conditions to set up operational polders and manage water retention during flood events. Hydrotechnical infrastructure (consisting of embankment spillways, weirs, pumping stations and sluices) was built in 1980 to enable the flood water to uncontrollably flow into the polder and mitigate the flood wave peak. However, due to unsettled ownership relatios and lack of formal regulation, the retention potential of the polder was left untapped and social conflicts emerged (Laks, 2017).

Despite the lack of agreement between the local community and the authorities (lack of formal regulations for land reclamation and managing the polder), the Golina polder was flooded several times between 1997 and 2020. During the last severe flooding in 2010, owners of the land located within the polder tried to block the water flow with sandbags, which led to a loss of flow control and severely damaged the hydrotechnical infrastructure of the polder. Damages were also caused by a lack of maintenance. Analysis performed on the impact of the Golina polder on the transformation flood wave revealed that, despite its considerable distance, the polder influenced the water level in the gauging station in the city of Poznań (Laks, 2017; Malinger et al., 2022). During the flood event in 2010, uncontrolled polder retention reduced the water level by 17 cm and water flow by 37 m3/s, thus significantly decreasing flood risk, although normal operating conditions would have caused a reduction of 29 cm and 65 m3/s, respectively. This indicates a necessity for clarification of legal relations, particularly with regard to land ownership and renovation of infrastructure (Laks, 2017).

A concrete decision to build a fully operational flood retention polder was made in 2015, in which implementation of the Golina polder was included in a flood risk management plan for the Odra river basin as a technical strategic investment for flood risk mitigation (Rozporządzenie, 2016). Multi-criteria analysis performed for the purpose of the flood risk management plan included a comparison of three scenarios: (i) building the Golina polder, (ii) embankment relocation in the Golina municipality and (iii) embankments removal in the Golina municipality. Based on economic, social, environmental and flood criteria, the first scenario was selected for implementation.

Due to the fact that the whole area of the Golina polder intended for inundation is protected in various forms, such as Natura 2000 birds and habitat directive sites as well as protected landscape areas, its implementation was preceded by detailed environmental impact analysis. The scope of analysis and environmental monitoring have been defined in detail in the decision on environmental conditions taken in the project involving the construction of a polder (RDOŚ 2020a). During the environmental impact assessment different variants of flow control were compared to select the most effective method for polder inundation that would not negatively influence the environment. Decision on environmental conditions in relation to the Golina polder also included conditions of land use during the implementation and operation phases.

The environmental impact assessment procedure provides public participation in whole decision making process (Ustawa 1960, Ustawa 2008) and local communities actively exercised their rights submitting reservations that were further included in the assessment. However, extensive and detailed environmental impact analyses, constrained by numerous formal defects, led to a significant delay in the factual establishment of the fully operational polder. An environmental conditions decision was issued in 2020, where a specific variant of flow control was settled (RDOŚ 2020a). However in 2022 the appeal proceedings is in progress and polder implementation is still withheld (RDOŚ 2020b, GDOŚ 2022).

3.2 Tiszaroff polder

The Tiszaroff flood peak polder is located in the middle section of the river Tisza in the Hungarian Plain, on the left bank at 375-380 km of the river section. It was completed in 2009 and was inundated during the 2010 flood.

The unprecedented series of major floods on the Tisza river between 1998 and 2001 as well as the dike breach in 2001 at the Hungarian upper section triggered a reconsideration of the prevailing flood defence strategy that had focused on heightening dikes to cope with flood peaks (Szlávik, 2003), albeit the height requirements were not fulfilled along the whole length of the river (Somlyódy and Aradi, 2002). The revision that concluded in the 2004/67 Law (named The Further Development of the Vásárhelyi Plan—VTT by its Hungarian acronym) combined three approaches: (i) strengthening the dikes, (ii) decreasing the roughness of the river corridor and (iii) creating flood peak polders. Notably, the Tiszaroff polder was the first element of the VTT development programme. This polder system provides a total storage volume of 1.5 billion m3 (Dobó, 2019) along the upper and middle sections of the Tisza River.

Its flood wave reduction effect, albeit in a decreasing manner, lasts across the whole Hungarian stretch of the river.

The Tiszaroff polder was built adjacent to an existing dike line on an already protected part of the former Tisza floodplain, dominated with croplands, with no significant environmental value. It is a controlled inundation site where the operation of flood gates controls the timing and discharge volume of the inundation. This technical feature, based on a flood wave forecast simulation, provides the most effective flood peak reduction in what a given storage volume can reach.

During the initial planning phase of the polder development programme according to the 2004/67 Law, it aimed for intertwined land usage based on nature-related floodplain farming activities that would be less exposed to damages in case of inundation and would form high natural value areas. Background documents of the VTT planning process estimated that nature-based farming activities would have higher public benefits than crop-dominated ones. However, the support provided by the EU CAP system for such activities (tailor-made for these flood polders) was not attractive enough to trigger land use adaptation. The bias, induced by the EU-CAP subsidies' crop-friendly preferences was a major driver of sustaining a rigid crop-dominated landscape.

Ex-post simulations showed that the inundation of the Tiszaroff polder in 2010 resulted in a 38 cm decrease in the flood peak at the gates and a 36 cm decrease at the nearby downstream city of Szolnok (Kovács, 2013). The impacts of these reductions were felt in a diminishing manner along the whole section of the Hungarian river. The peak level reduction also nullified the need to build temporary defence structures against extreme pressure from the city section of the river in Szolnok. From an economic perspective, the balance of the 2010 intervention was positive—the flood risk reduction outweighed the damage compensation paid for sacrificing agricultural produce (Ungvári, 2016). A subsequent analysis (REKK, 2018) demonstrated that the 20-year return frequency flood is the breakeven one. In the case of more extreme floods, the use of the polder would be justified from an economic point of view. It is important to highlight that this breakeven flood peak level is much lower than the 100-year return frequency flood that was designed to be the trigger for polder use, based only on the hydrologic conditions outlined by the law under the VTT development program (Ungvári and Kis, 2022). It was concluded that flood risks alone do not provide enough additional benefits, compared to the actual operation, to justify the investment. Financially robust results on additional environmental benefits of a major land management change are necessary to be in the position to investigate whether such a step is justifiable—whether it is worth investing in the socio-economic improvement of the site and whether its users will be able to live up to the expectations of managing a site with higher performance on all three—environmental, social and flood risk reduction—aspects (Ungvári, 2022).

4 COMPARATIVE STUDY OF POLDER IMPLEMENTATION

For this study, a comparative case study analysis was applied (Coletta et al. The analysis relied on content analysis of technical literature and reports and an extensive review of legal frameworks and administrative procedures. The research also includes the results of media coverage analysis and field visits. Data and information were analyzed to identify procedural steps and conditions in the polders' establishment. Moreover, thematic analysis methods were used to identify and report patterns in the themes obtained (Liamputtong, 2010; Yusoff and Yusoff, 2021). Qualitative data and information were studied descriptively and then presented in the form of descriptions and tables to facilitate the reporting of findings. The analysis was performed in three thematic groups relating formal, economic, and social aspects as they overlap in innovation processes (Mumford, 2002).

4.1 Formal and legal conditions

A significant factor hampering the implementation of polders is related to legal background and institutional settings (Raška et al., 2022). A sufficient legal basis (including land acquisition, compensation and incentives) as well as efficient administrative systems and structures support NbS implementation and management (Brokking et al., 2021; Han and Kuhlicke, 2021; Neumann and Hack, 2019). The above factor is of particular importance in the implementation of polders, because NbS requires significantly more land than hard engineering constructions (Hartmann et al., 2019). Another crucial factor related to implementation is the fact that polder retention is also highly dependent on ownership structures (Brokking et al., 2021). Moreover, if precise methods for land reclamation agreements are not formulated and established, land acquisition and its further management would appear as both time- and money-consuming activities.

Regarding the factors mentioned above, flood risk management systems in Poland and Hungary are characterised by numerous common features. In both countries, due to the introduction of Directive 2007/60/EC for the assessment and management of flood risk (the Floods Directive) by the European Commission, frameworks for flood risk management and flood impact reduction have been implemented (EC, 2007). The implementation of the Floods Directive played a role in stimulating discussions and FRM planning in many member states that lacked a pre-existing national framework, thus positively influencing the creation of legal instruments for FRM (Priest et al., 2016). Also, the implementation of Directive 2000/60/EC of the European Parliament as well as the framework established by the Council for community action in the field of water policy had significant impacts on the water management systems in both countries, while introducing the rules for water management in cross-national river basins.

Issues related to FRM in Poland are regulated by the Water Law Act (Water Law, 2017), in which obligations related to the Water Framework Directive and Floods Directive have been implemented. The amendment to the Water Law Act in Poland in 2017 introduced a definition for a flood protective polder (Water Law, 2017), which focused only on its flood protection function, regardless of the fact that the hallmark of such a measure lies its multifunctionality. This substantially narrowed down the definition of a polder, together with the lack of specific rules for land reclamation and flood damage compensation, directly caused significant social difficulties in polder establishment and its subsequent management.

First, the hydrotechnical infrastructure of the Golina polder was partially built in the 1980s during the realization of a project to embank the widely spread, natural valley for agricultural purposes in the Konin-Pyzdry section. After 1989, the project was re-prioritized. After this, although the polder was never finished as a fully operational flood-protective measure, existing infrastructure enabled flooding of the Golina polder area during the flood events in 1997 and 2010 (Ministerstwo Środowiska, 2012; Przybyła et al., 2011). Because of the lack of formalization in managing the polder and unfinished infrastructure for flood water flow control, the Golina polder could neither be qualified as a flood-protection polder nor could the land located within it be eligible for compensation for flooding (Sąd Administracyjny, 2011a, 2011b), according to the Polish Water Law Act (2001, 2017).

In Hungary, the legal bases of polder establishment and management were steered by a law (2004/67) that declared its development to be of fundamental public interest. It established the hydrological goal (1 metre decrease in extreme flood-peaks along the river) and the legal framework for polder implementation and exploitation that was applied in the Tiszaroff case. The land trail for the new defence infrastructure was expropriated, but the area inside the new polder could still be owned privately. The authorization of polder inundation initiated an upfront payment for the landowners, based on land quality, as compensation for future constraints on land development. It also offered full damage compensation in the case of any future inundation event. Landowners who would decline the offer faced expropriation.

The aforementioned legal instrument (Law 2004/67) called for the multipurpose use of polders as an integration of the flood mitigation function with the agricultural cultivation of the land. It also established that the financial burden of maintenance of the floodplain farming water management infrastructure within the polder lies on the state budget and the connecting water uses are exempted from the Water Resource Fee.

4.2 Economic aspects of establishing polders

Financial barriers related to polder implementation are perceived mostly during the land acquisition process (McCarthy et al., 2018; Raška et al., 2022), while negotiation with private actors appears to be difficult, especially in large-scale projects (Dijk, 2003).

In the case of both polders investigated in this study (Golina and Tiszaroff), the land is mostly a private property. Using private land to decrease the downstream flood level is an intervention to pursue public benefits for a wide range of citizens while imposing its costs on a small group of people situated upstream. With the increasing distance between the two groups (beneficiaries and cost bearers) in terms of localization and communality, there is an urgent need to establish a clear contractual term for such service provisions (Thaler et al., 2016).

From an economic point of view, establishing and exploiting a polder for flood risk reduction purposes is worthwhile if its overall risk reduction impact is higher than the cost of establishing the infrastructure and management of the land within the polder. The public benefits of polder use (expressed as flood risk reduction) must be compared to the total cost related to polder implementation and management in monetary terms in order to justify the use of public financial resources. Also the largest element of performed economic analysis was expenses related to land expropriation what emphasizes the role of economic analysis in FRM bargain.

In the Polish case, the inherited legal definition of polders can be viewed as an ambiguous allocation of property rights concerning the boundary of state responsibilities on protection against floods. Overcoming competitive interests between the state and local communities was attempted through legal actions based on the definition of polder delineation, without accounting for its full economic impact on landowners and their real impact on flood protection in the region. The state tried to limit its financial burden of buying flood risk reduction services by using ambiguous delineations, but the lack of economic bases thwarted the unequivocal execution of what the law authorised. In the Tiszaroff polder case, a cost minimization approach was applied where the expected cost of initial and event-based payments over several decades of polder operation was verified by a threefold difference between the investment cost of the polder system and the large-scale dike height increase along the impacted river stretch downstream from the polder (Ungvári and Kis, 2022). It was assumed that the development alternatives were identical—both fulfil the defined hydrological goal, and the difference between their investment costs provided a basis to verify the decision and the compensation commitments as part of the polder development programme that took shape with the law (Law 2004/67). Up to the mid-2010s, the Golina site was never analysed with similar economic accuracy (KZGW, 2015a, 2015b).

4.3 Social aspects of flood risk management using polders

Several factors that influence polder implementation and management are perceived in knowledge distribution and share amongst stakeholders (Brokking et al., 2021; Chou, 2016; Małecka-Ziembińska and Janicka, 2022). People's knowledge about NbS effectiveness and their awareness of increasing flood risk can influence their general acceptance of NbS (Gray et al., 2017; Han and Kuhlicke, 2021; Martinez-Juarez et al., 2019; Raška et al., 2022). Furthermore, transdisciplinary knowledge transfer between specialists and stakeholders is necessary for the sustainable management of these measures (Neumann and Hack, 2019)(Neumann & Hack, 2020). Common awareness of flood risk and well-established knowledge can foster the involvement of local communities and communication during the entire NbS management process (Neumann & Hack, 2020).

The lack of awareness about flood risk, deficiency in the availability of information on polders—including their real impact on private property—as well as the absence of clear and consistent formal and legal conditions for polder implementation and management (Sosnowska, 2016) may directly lead to the emergence and proliferation of social conflicts. When water flowed into the Golina polder area uncontrollably during the flood events in 1997 and 2010, the local community decided to block the overflow shaft with sandbags to prevent further inundation and protect the private property located inside the polder. Later, as intended, the provisional protection was removed and the polder area was filled with water. However, because of unscheduled water flow, flood peak attenuation was unsuccessful and the polder did not play a significant role in the flood protection system.

Social tensions in Poland were also observed regarding land acquisition, substantial decisions on establishing polders were taken after decades of hesitation and specific rules for land expropriation were not formulated. Also, flood damage compensation rules were unclear, as they referred to an ambiguous formal definition for a polder (Water law 2017, (Sąd Administracyjny, 2011a, 2011b; Sąd Najwyższy, 2020).

The lack of administrative response towards social needs resulted in bottom-up initiatives—several interpellations were addressed at the municipal and national levels, formulating key questions for landowners, such as the course and rules for land expropriation, financial security for eventual claims and possible land use and cultivation of areas intended for inundation.

Polder management and establishment in the Tisza river basin did not induce such social tensions and protests because the VTT law created simple take it or leave it rules for landowners to cooperate. With no other viable solution in sight, strong political support for the development plan was observed. From the perspective of the landowners, the rules for compensation were advantageous—a significant upfront payment and full compensation in the case of uncertain future events (in the case of average or below average quality land, the imposed cultivation constraints were not effectively binding on the actual agricultural activities).

5 DISCUSSION

A comparative analysis of case studies revealed several factors influencing effective social innovation. However, the polder implementation process is complex. It can be observed in the development of both the physical infrastructure and the institutional framework that incorporates agreements between public agents of the beneficiaries (downstream communities) and landowners, who are the service providers for flood risk reduction (upstream communities) (Warachowska et al., 2021). Ultimately, the influence of all formulated factors is ambiguous; they can have both positive and negative influences depending on the context.

5.1 Formal and legal conditions

The evidence from both case studies indicates that the establishment and effective management of polders is impossible unless their formal and legal backgrounds are substantially settled and a set of clear rules for the land negotiation process is formulated and directly communicated. However, it should be noted that the above instances do not prejudge the success of the implementation process of a fully multipurpose, nature-based solution, as shown in the Hungarian case study.

In both case studies, institutional FRM is characterized by several common features, such as geopolitical history, the legacy of centralization, and the dominant role of the state hampering social participation. In both polder implementation processes, the role of local communities was limited. In Hungary, landowners were restricted to choosing between two pre-designed options: participating in a compensation scheme or expropriation of the land. In Poland, complaints from local communities opened a window of opportunity at the beginning but were considered only minimally in the later stages of polder implementation.

A strong legal and formal background can serve as a basis and support for social innovation, but if too strong, it can deter people from undertaking actions.

5.2 Economic aspects of social innovation

Comprehensive economic analysis can significantly enhance the process of polder implementation (Ungvári, 2022), helping to justify the use of public finances and formulate an acceptable financial scheme for landowners. In the Hungarian case, as the land was accessed to fulfill a public goal, seemingly the legitimacy of the compensation was sufficiently established. The case shows that the simple take it or leave it rule limited the role of the people in the decision-making process.

NbS implementation processes require economic justification, but negotiation processes supported by the results of economic analysis (especially land expropriation) hold great potential for innovation. Any agreement with landowners that makes them accept transitional water cover on their land results in nullification of payment of the full price of the land. This arrangement is a reasonable and usual aspiration for implementing nature-based FRM solutions. It is also the preferred option from a social point of view, since expropriation decreases the livelihood prospects of inhabitants, which goes against other development initiatives, such as countryside development strategies.

The implementation of NbS invokes agreements that encourage positive actions instead of obedience to imposed rules. This requires skills, adequate approaches, and perceptions that institutions are yet to acquire, but citizens should demand as well. Implementing these approaches has an indirect positive effect on the social cohesion of the areas concerned, which is also of great importance.

5.3 Social aspects of flood risk management using polders

The analysis showed that facing the disastrous consequences of flood events is a strong driver for undertaking flood risk mitigation actions, yet the responses in local communities differ.

In the Polish case, strong social conflicts emerged after the flood event, and communities actively participated in the initial phase of polder implementation. Then, the bottom-up action collided with the insufficiency of the administrative system and ambiguous rules for polder implementation, resulting in further limitation of public participation. Social conflicts, initially perceived as a problem to be solved, can become a window of opportunity to initiate change in contrast to the status quo. Conflict, in this case, can be seen as an inevitable part of social innovation processes (Schumpeter, 1934). The environmental impact assessment on polder implementation involved public participation during the whole decision-making process, yet active engagement appeared only at the beginning and strong trust in local and national authorities has stopped further efforts. The environmental impact assessment was also a protracted process due to the ambiguity of legal regulation and the complexity of the negotiation process.

In the Hungarian case, the status quo flood defense strategy prevailed for decades due to there being no apparent reason to change track. The disastrous flood event triggered a feedback process, but the reaction of the state was so firm in its invocation of a regional-scale implementation that it also limited public participation—the role of citizens was limited to choosing between two options. This corresponds to a phenomenon often observed in post-communist countries: people mostly rely on the state for long-term flood risk mitigation, and people's engagement, if it extends beyond ensuring their own wellbeing at all, is rather limited (Raška et al., 2020).

5.4 Social innovation

Social innovation can refer to such a changes that aim to improve the welfare and wellbeing of individuals and communities (OECD, 2016). This approach to social innovation is reflected in the concept of nature-based solutions, meaning actions and technologies that are established to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature (IUCN, 2021). The implementation of NbS, involving natural processes to simultaneously protect natural ecosystems and provide human wellbeing (Cohen-Shacham et al., 2016; Fernandes and Guiomar, 2018), seems to be an answer to meet the demand for resilient FRM. Yet, polders, as NbS in FRM, satisfy social needs on the one hand, but on the other hand, their implementation and management require innovation in redefining, combining, and reformulating these approaches to induce successful change.

Assembling multi-purpose land management schemes that include flood risk reduction, among other public and private benefits, in places where it is necessary to maintain a steady and dynamic balance between competing interests requires institutional skills that only states with advanced governance capacities possess. Central-European countries (even after over 30 years since the transition) struggle to restructure governance culture toward such capacities

(Dąbrowski and Piskorek, 2018; Gorzelak, 1996; Sýkora and Bouzarovski, 2012). Without such a shift in governance culture, negotiating NbS solutions is bound to be an uphill struggle. The primary issue here is not the choice of innovations to foster flood risk reduction agreements; rather, it is whether the challenges to FRM can create a pilot field to cultivate better governance solutions.

The case study analysis proved that polders can be perceived as an innovative and effective measure in FRM. Moreover, the implementation of polders meets the preconditions of social innovation. In the implementation of polders to mitigate flood risk, basic needs were satisfied, significant transformative processes were induced to implement polders, and local communities and institutions were mobilized to induce change. However, substantial and long-lasting change in society has yet to be induced.

6 CONCLUSION

The dynamic nature of climate change, together with intensive floodplain development, have resulted in flood damage of an enormous scale. This has fueled discussions on the implementation of innovative flood-protective measures capable of coping with constantly changing environmental, social, formal, and economic conditions.

Depending on context polders can be seen as an innovation, especially when compared to hydraulic engineering solutions in FRM. They also bring benefits to the environment by protecting natural ecosystems, as well as to people by decreasing flood risk and ensuring safety. Although their innovativeness and effectiveness seem evident in terms of flood risk mitigation, the potential in introducing social innovations is untapped. The evidence from the comparative analysis shows that facing the disastrous consequences of flood events is a strong driver for undertaking flood risk mitigation actions. Yet this does not always evoke a change aimed at improving the welfare and wellbeing of society. Effective introduction of social innovation is bounded by several factors that are full of contradictions—the same aspect can either allow or hinder public engagement and successful social innovation. Furthermore, there are hardly any necessary conditions, while several combinations of sufficient conditions can lead to success.

Lack of systematization of the formal and legal frameworks precludes the introduction of innovation in FRM systems and at the same time significantly complicates the flood damage compensation process. Moreover, clear and simplified rules for land reclamation and polder implementation can help people engage in decision-making processes but can also significantly limit their factual active engagement. Furthermore, formal and legal ambiguity, along with its consequences, leads to social conflicts, which can be seen as a complication in FRM measure implementation but often becomes a window of opportunity as well. The implementation of polders was induced in response to the context-specific challenges such as social pressure to undertake effective flood risk mitigation actions. Local communities anticipated innovation in FRM that the authorities were expected to deliver. Social transformation is a continuous process, and as flood risks increase dynamically, constant adjustments in the formal, economic, and social variables are required. Thus, the introduction of social innovation requires the optimization of those variables as they overlap in the process of innovation.

Acknowledgements

The study was conducted as part of project supported by 'GEO+' – high quality interdisciplinary doctoral studies programme conducted at the Faculty of Geographical and Geological Sciences of the Adam Mickiewicz University in Poznań (no. POWR.03.02.00-00-I039/16).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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