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Reducing flood risk by effective use of flood-peak polders: A case study of the Tisza River

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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 into the efficiency gains that a more informed, quantitative economic analysis can offer in risk reduction. The analysis reveals the potential for 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.

KEYWORDS

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

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 (Ungvári & Kis, 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 (Davis et al., 2008; Lorente, 2019; Tollan, 2002). 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 subcategories 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 judgment. 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 (Ungvári & Kis, 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 km of dikes (Somlyódy & 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 10-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 six 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 1). 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 1 will display, the maximum mitigating impact of polders on the Tisza ranges between 20 and 60 cm, on the tributaries it is in the 43–152 cm range (Figure 1).

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 cropland 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.

FIGURE 1 Overview map of the region with polder areas along the Tisza and its tributaries. Flood-peak polder name, capacity, and area coverage

As described, the question of quantifying flood risk change played no decisive role in the infrastructure development during the 2000s, but the issue emerged during the late 2010s 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 (Ungvári & Kis, 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 & Balogh, 2010).

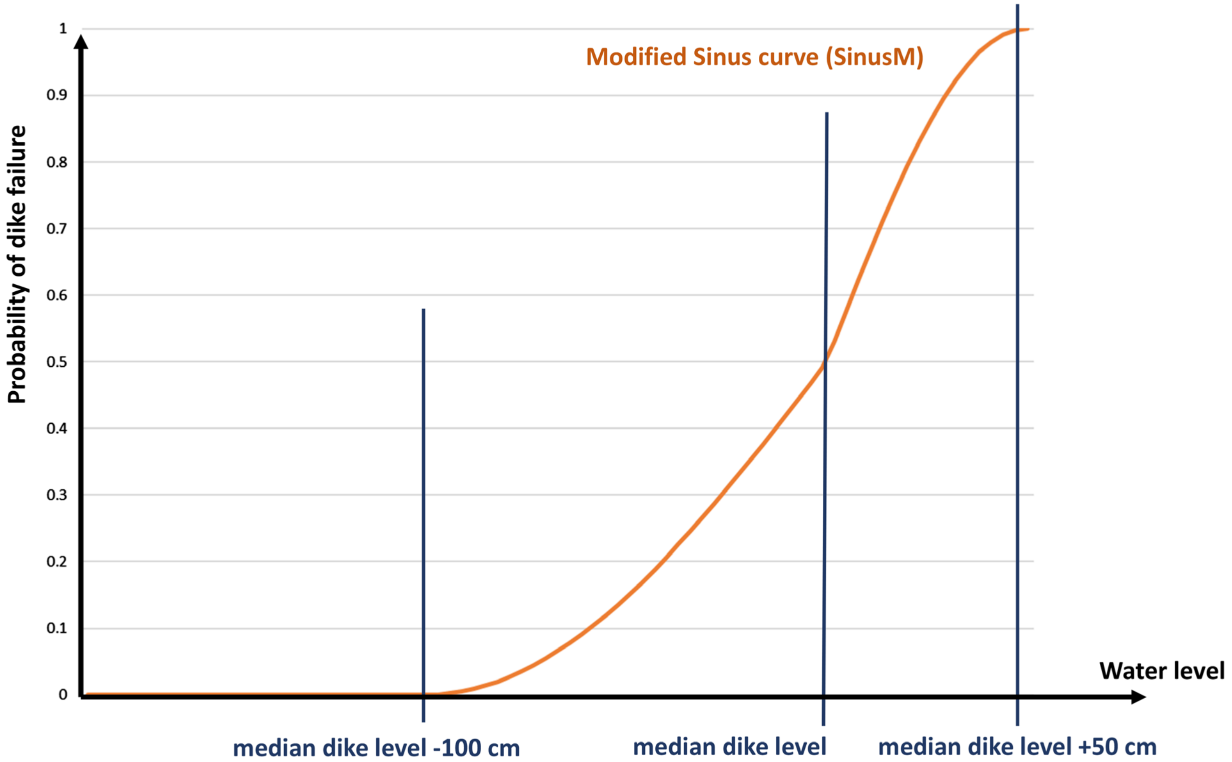

FIGURE 2 Dike failure probability as a function of water level. Vertical axis—probability of failure; horizontal axis—water level in relation to the dike level

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

$$TC = C_c + C_d \quad (1)$$

$$TC' = C'_c + C'_d + C_p \quad (2)$$

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[1] (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 (Ungvári & Kis, 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 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.[2]

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 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 (Ungvári & Kis, 2018). This data was used by the Monte Carlo simulation to estimate C_c and C_c' in Equations (1) and (2)).

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 Equation (1)) and the one modified by polder use (C_d' in Equation (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 (Ungvári & Kis, 2018). Detailed Tisza flood defense cost data was processed for the period of 1999–2017 to screen defense operations of major flood events. Fifty-five river segments during five 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

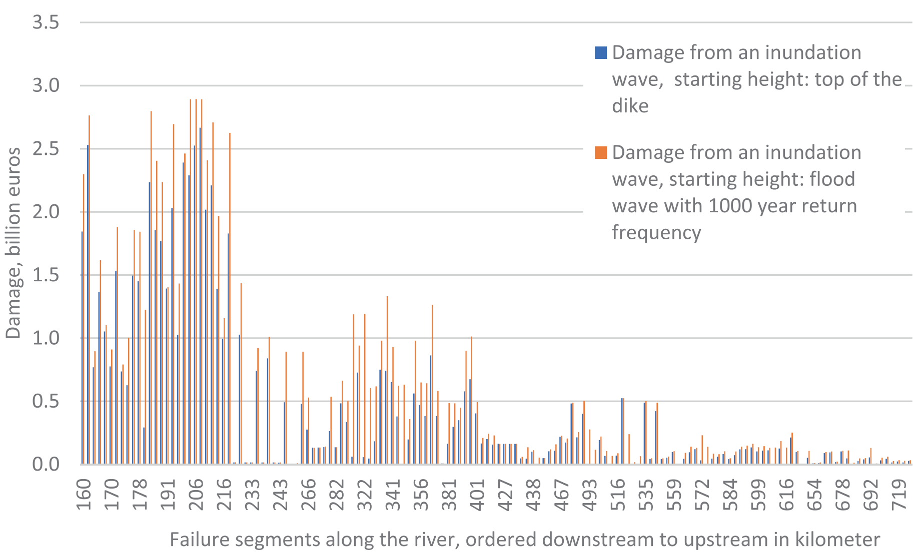

FIGURE 3 Damage values of flood catastrophes at failure segments for two flood wave heights along the Tisza. Vertical axis—inundation damage in billion euros, horizontal axis—failure segments (catastrophe points) along the river ordered downstream to upstream in river-kilometer *Source*: Ungvári and Kis (2018)

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TABLE 1 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 commissioning	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–March)	Maximum (August)
Tiszaroffi	Tisza	2009	20	97.0	2336	1.27	2.02
Cigándi	Tisza	2008	43	94.0	2222	0.64	1.14
Hanyi-Tiszasülyi	Tisza	2012	44	247.0	5437	2.81	4.92
Nagykunsági	Tisza	2013	25	99.0	4006	2.16	3.81
Szamos-Kraszna-közi	Tisza	2014	39	126.0	5068	3.23	5.39
Beregi	Tisza	2015	60	58.0	5857	3.74	4.33
Borsóhalmi	Zagyva	1999	152	23.5	1855	0.92	1.52
Jásztelki	Zagyva	1984	97	13.0	1672	1.29	2.04
Kutas	Berettyó	1966	72	36.5	1633	0.60	1.03
Halaspusztai	Berettyó, Sebes-Körös	1973	43	35.0	2113	0.90	1.32
Mályvádi	Fekete-Körös	1995	127	75.0	3423	0.55	1.16
Kis-Delta	Fehér-Körös	1999	59	26.0	497	0.31	0.54
Mérgesi	Kettős-Körös	1980	83	87.2	1693	1.14	3.20
				1017.2	37,812	19.56	32.42

Source: Ungvári and Kis (2018)

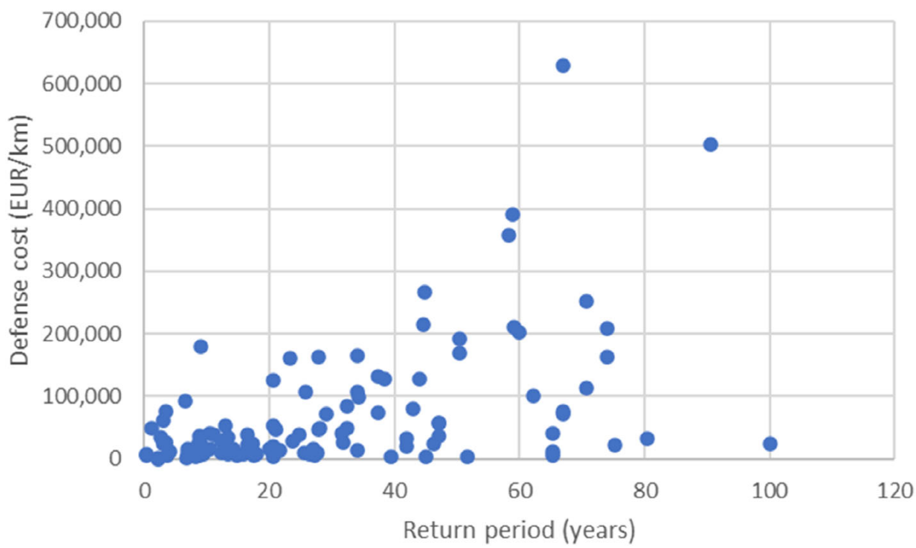

FIGURE 4 The relationship between defense costs and flood return period within the analyzed sample
Source: Ungvári and Kis (2018)

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

TABLE 2 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: Ungvári and Kis (2018)

of the defense cost. Table 2 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 modeling of the flood event with and without the use of a polder.

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 4. Comprehensive retrospective 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.

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 m, 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 plowing 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 (Ungvári & Kis, 2018). These costs are summarized in Table 1 for each of the available polders together with some of the other key attributes of the polders.

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.

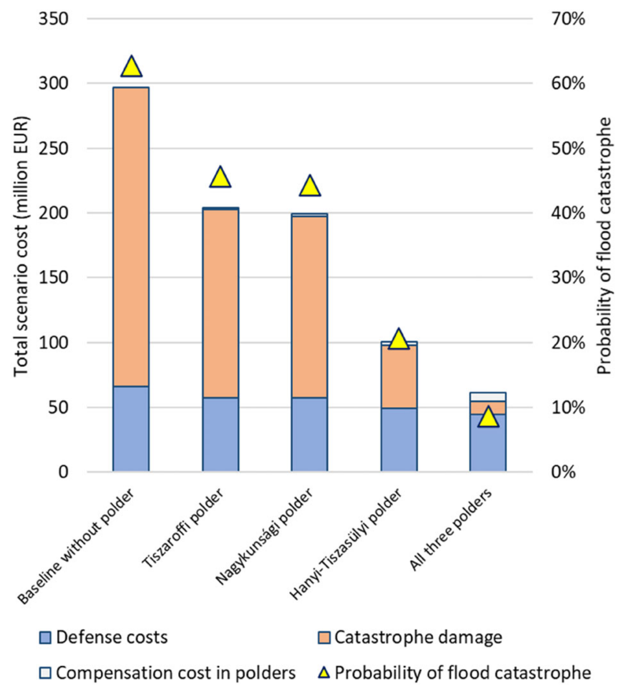

FIGURE 5 Total cost of scenarios and probability of flood catastrophe, year 2000 flood on the Tisza, modeling results. Vertical axis (left) total expected cost of the scenarios in million euros, (right—yellow triangles) probability of flood catastrophe of the scenarios; horizontal axis—flood wave scenarios

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 modeling 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 Figure 5, comparing modeling 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.

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). Modeling results, however, suggested that opening the polders may also be economic for less severe events. The economic break-even point of each

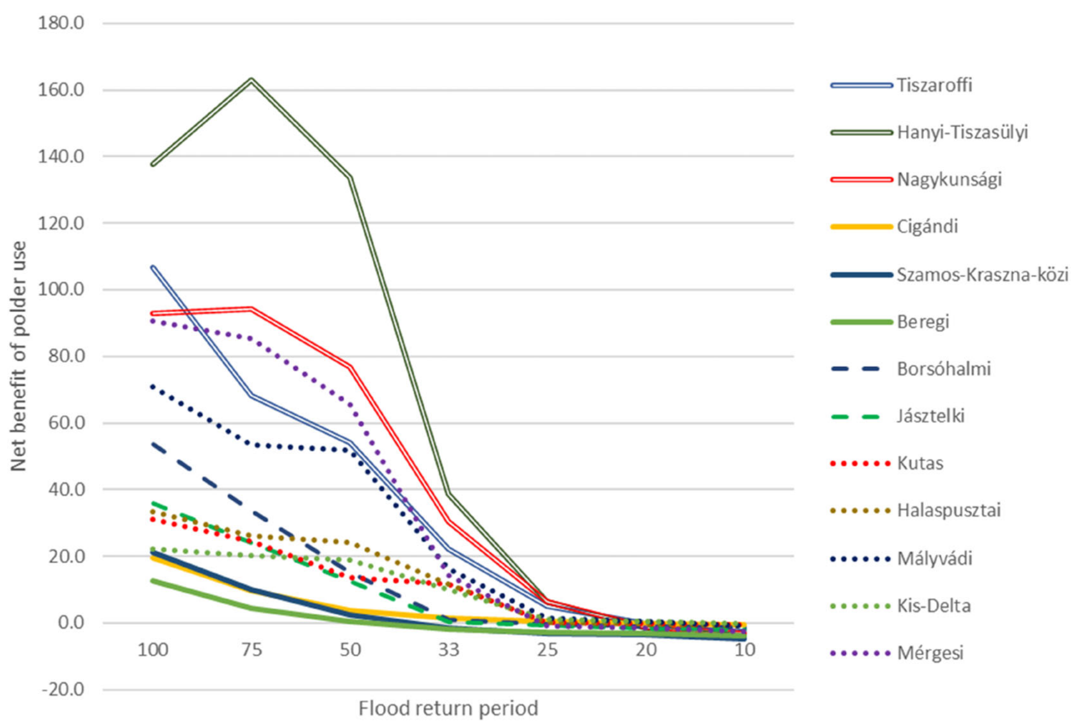

FIGURE 6 Net benefit of polder use for various flood return periods (million EUR). Vertical axis—net benefit of polder use in million euros; horizontal axis—flood return periods in years

polder was calculated in terms of the flood return period above which polder use is economically worthwhile.

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 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 five times in a century.

The results of the exercise for all polders are summarized in Table 3. 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 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: Ungvári and Kis (2018)

3.3 | The coordinated use of multiple polders

Polders used on their own already generate substantial economic benefits, as illustrated in Figure 6. However, they do not fully eliminate the occurrence of flood catastrophes. Hydrological modeling results show that using more than one polder for a major flood further mitigates catastrophe risk (Table 4). Using the cost benefit methodology described in Chapter 3, 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 5 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

TABLE 4 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%

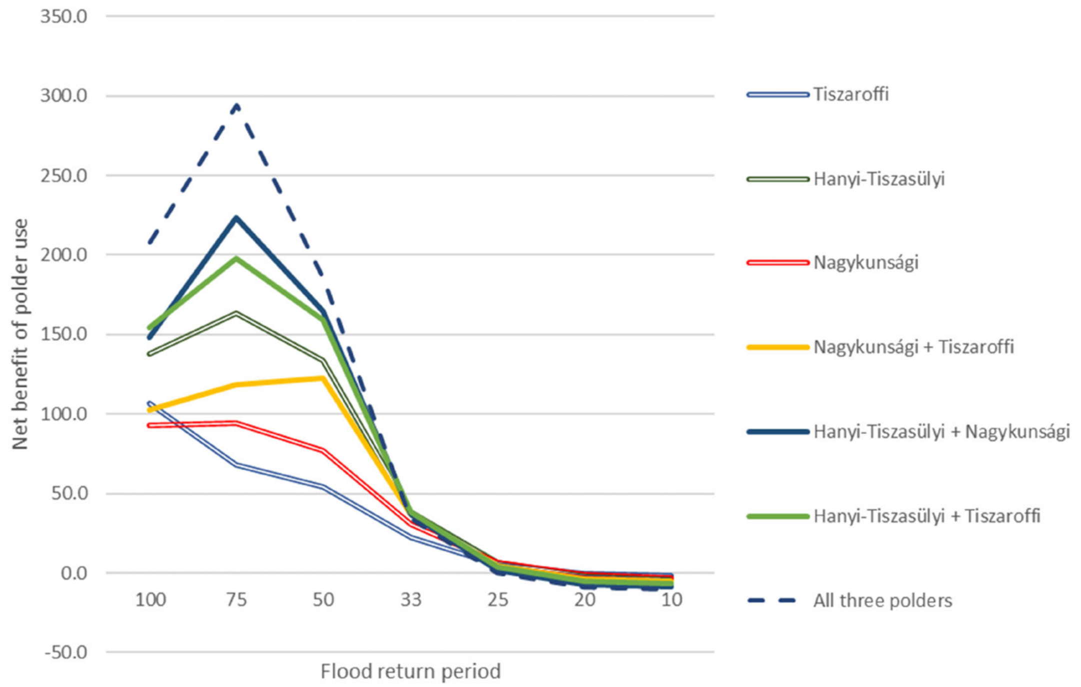

FIGURE 7 Net benefit of the single and combined use of the Middle Tisza polders for various flood return periods (million EUR)

TABLE 5 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: Ungvári and Kis (2018)

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.

The graphical illustration of the net benefit values in Figure 7 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, that is, how much it reduces the likelihood of a catastrophe, also declines. As shown in Table 4 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 probability 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 3, 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.

As illustrated by Table 4, 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 modeling 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.

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 (Adriaenssens et al., 2017; Förster et al., 2005), 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 (Hudak et al., 2018; Przybyła et al., 2011). 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.

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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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ENDNOTES

[1] From here on “ÁKK,” based on its Hungarian language abbreviation.

[2] 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.

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