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Decision Analysis for Robust Long-Term Flood Management: Uncertainty Exploration Using Probabilistic Approach and Information-Gap Decision Theory

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ABSTRACT

Decision making for flood risk management involves comparing options based on their benefits and costs. These choices always involve considerable uncertainties, especially when long-term projections are being developed, taking climate change into account. The aim of the study is to reveal what is the uncertainty robustness of alternative flood defense measures. The treatment of different sources of uncertainty is carried out by using probabilistic analysis of net present value (NPV) as well as using information gap decision theory (IGDT). The focal point of the study is a settlement in Nord Bulgaria with a record of severe flooding in the past, for which divergent climate change projections have been generated under the RCP 4.5 and RCP 8.5 scenarios. The behavior of three civil defense options under these uncertainty conditions is explored over an extended 30-year time horizon up to 2050. The paper shows sequentially Probabilistic Performance Analysis with NPV performance criteria, and then how Information-Gap Decision Theory can be formulated and used to analyze same options. After discussing the results, we conclude that facing deep uncertainty in long-term flood protection decision making, it is advisable to use multiple methods that differ in data and assumptions, necessarily taking into account hydrological uncertainty from climate change, that could dramatically change our choices.

1. INTRODUCTION

In the face of climate change, our society is already exposed to increasingly extreme hydrological events, and this will continue. In that context, an assessment of the hazard of flooding with a mid- and end-of-century horizon becomes particularly important. Reliable long-term flood risk management is based on good flood hazard fore-casting, constrained by the uncertainties of flood patterns, river morphology, changing land use, etc. Here the hydrological uncertainty of flood hazard forecasts due to climate variability has a particularly large impact. Working with projections made under possible scenarios of the path of greenhouse gas concentration is laden with an uncertainty that can be described as deeply uncertain [1].

To overcome the limited ability of deterministic models to adequately reflect uncertain behavior in the real world, a wide range of stochastic approaches have been developed [2]. This way, in cases where the decision maker is confident in the underlying probability distributions, a reliable result can be achieved. But for situations of deep uncertainty, other types of decision methods are available. These methods look for the robustness of the decision to uncertainty instead of the optimality of the decision. A robust management strategy performs adequately over a wide range of plausible future events [3]. Under these conditions, it may be better to plan flood protection in the long term for robustness rather than optimality [4] and to adopt mechanisms for analyzing the robustness of design options under uncertainty.

In deep uncertainty, there is no consensus in the scientific community in favor of a unified approach to support decision-making practice in long-term flood management. Therefore, a motivation for this study is the principle that any complex scientific problem can be investigated with multiple methods that modify data and hypotheses to make conclusions more certain. Here we propose a combined approach using Info-Gap Decision Theory (IGDT), a non-probabilistic method that is a quantified theory of robustness [5], and probabilistic performance analysis.

Both approaches aim at providing a different view of the incomplete information in decision-making for long-term flood risk management in the town of Sevlievo, Bulgaria.

Following the structure or the paper, the second section (Methods) gives a brief description of probabilistic performance analysis with Net Present Value performance criteria and Information Gap Decision Theory.

The third section (Case Study) discusses the assumptions, flood discharge-damage function for the city of Sevlievo, flood protection options and flood scenarios.

The next fourth section (Results) analyzes and compares the choice of flood protection option by deterministic and probabilistic evaluation of the cost-effectiveness as well as by Info-Gap analysis.

The last section presents conclusions including that the decision making in flood risk management, based on deterministic and probabilistic cost-effectiveness assessment models can be different when the uncertainty of the hazard assessment is considered using the Info-Gap method.

2. METHODS

2.1 General Remarks

The study is based on previous hydrological research on the effect of climate change on water resources and on floods in Bulgaria [6-8]. The present paper examines the impact of uncertainty in runoff projections to 2050 for the low (RCP 4.5) and high (RCP 8.5) greenhouse gas concentration scenarios for the climatic area in which the catchment of the Rositsa River to Sevlievo falls.

In support of current work, 1D and 2D unsteady hydrodynamic models of flood hazard in the area of interest were created to determine flood depth, velocity, and duration, and then to estimate damages and determine the number of citizens potentially affected.

The paper shows the extent to which the behavior of alternative flood protection options is robust and resilient to uncertainties with the application sequentially of probabilistic performance analysis with Net Present Value performance criteria and Information Gap Decision Theory.

2.2 Net present value

The assessment of economic efficiency includes the determination of the direct result of the implementation of an activity, using generally accepted financial values such as revenues, costs, income, profit, etc. In addition, the direct financial result and the complex effects of a project are assessed, based on the specifics of the project - environmental, social, cultural, etc. The method of Net present value (NPV) is widely used in determining the current value of all future cash flows of a project. Herein, the observed aspects are the initial capital investment, and the question of which projects are likely to turn the greatest profit.

The topic of this study is the management of regional flood protection for a 30-year period with a 2050 horizon under hydrological uncertainty associated with climate change. To analyze a such longer-term project with multiple cash flows, then the NPV formula for the project is defined as Eq. (1):

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r)^t} \quad (1)$$

where:

B_t – all project benefits generated in period t,

C_t – all project costs in the period t,

r - social discount rate (SDR), %;

n - number of periods (years) of useful life of the project.

NPV is calculated under certain assumptions at the present moment and does not take into account the possibility of later changes in the situation.

A basic premise of this study is that proposed protection measures will be planned for now but must serve into the next 30 years without budget increases. The benefit associated with each option is the present value of the reduction in flood risk it achieves relative to the case Do nothing. The benefit is in terms of avoided potential material damage, avoided expenses for the number of injuries, and the number of fatalities prevented, determined by the methodology of Civil protection-Bulgaria. In the case of flooding with a depth of more than 1 m and the presence of people who are not mobile easily (disabled, elderly), they are considered potential fatalities. The number of injured is the number of residents subject to evacuation (excluding the number of those who are difficult to move) in flood zones with depths of more than 1 m. Injured also means cold, frostbitten, frightened - all conditions outside the normal range where medical attention is needed.

2.3 Probabilistic performance analysis

Investing in projects with a long lifetime, such as flood defense projects, is characterized by a high degree of uncertainty in some of the variables used in the NPV method. This applies especially to the investment period, the discount rate, the number of fatalities and injuries before and after the introduction of the measure, the material losses before and after the introduction of the measure, the cost of implementing the measure, the operating costs, the cost of evacuating people, the cost of compensation for damages, the benefits, etc. that are expected over the effective lifetime during and after the introduction of the project. This is the first set of probabilistic variables we are going to model. In the second step, we will add to the above group the hydrological uncertainty from climate change in determining the flood hazard: river discharge with 1% annual probability of exceedance, or Q100.

Assessment of the risk of an investment decision, i.e., obtaining the probability distribution of the selected NPV efficiency criterion of an in-vestment project, is performed with Monte Carlo simulation analysis. To select the most economically viable among several competing options, the risk is assessed by the statistical properties of NPV.

2.4 Information Gap Decision Theory

Info-Gap Decision Theory (IGDT) is used for supporting model-based decisions with a lack of information. Info-gaps are non-probabilistic. Examples of common info-gaps include uncertainty regarding the shape of a probability distribution, the functional form of a relationship between entities, or the values of some key parameters.

According to the study of Ben-Haim [9] the info-gap analysis of a decision is based on three elements: an info-gap model of uncertainty, a model of the system, and a set of performance requirements.

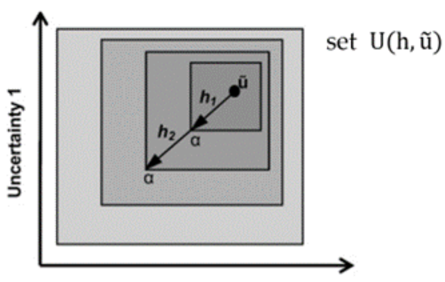


Figure 1. Schematic of an Info-Gap uncertainty model showing the scaling (h) of each interval (horizon) of uncertainty (α) from a best estimate ($\tilde{u}$). Adapted from [9]

An uncertainty information model is an unbounded family of nested sets that have a common structure depending on the uncertainty information. The IGDT concept is an expanding uncertainty defined with respect to the nominal value (best estimation) of the uncertain parameter $\tilde{u}$. Figure 1 visualizes the idea of an info-gap model of uncertainty where *h*, the 'horizon' represents the increase of uncertainty *α*.

IGDT marks the uncertainty of future flood hazard - the 1-in-100-year flood (Q100) - as a group of nested sets defined by the parameter $\tilde{Q}$, a current best estimate of a future parameter flood discharge Q. The deviation between Q and $\tilde{Q}$, is scaled by h, the 'horizon', which represents the increase of uncertainty. The IGDT uncertainty model is a nested set based on $\tilde{Q}$ and h such as $U(h,\tilde{Q})$. The formulation and selection of an uncertainty model depend on the type and amount of information available [10, 11]. In our case, river discharge under climate change can vary widely over the years of a 30-year horizon, as predicted by the two scenarios: medium RCP 4.5 and high RCP 8.5. Therefore, the deviation α from the nominal value $\tilde{Q}$ is measured relative to the standard deviation σ. We consider a fractional-error Info-Gap model [12, 13] with the constraints of Q100 climate scenario projections for a 30-year horizon to 2050, see Eq. (2):

$$U(h,\tilde{Q}) = \left\{ Q : \max_{Q \in U(\alpha,\tilde{Q})} (\tilde{Q} - \sigma\alpha) \le Q \le \min_{Q \in U(\alpha,\tilde{Q})} (\tilde{Q} + \sigma\alpha) \right\} h \ge 0,$$
$$(\tilde{Q} + \sigma\alpha) \le Q100_{RCP8.5}$$
$$(\tilde{Q} - \sigma\alpha) \ge Q100_{RCP4.5} \quad (2)$$

When the uncertain parameter is equal to the nominal value $\tilde{Q}$ then the uncertainty is zero. The Info-Gap analysis starts with the "best" (current) estimate of the uncertain parameter "the 1-in-100-year flood Q100" and determines the value of the NPV objective function at this nominal value. This base value of the NPV function can be used as a reference to quantify the cost of reliability.

Different competing management options are available in flood risk defense planning. For the alternative q_i, there is a range of rewards for each horizon of uncertainty, which is defined by $U(h,\tilde{Q})$. In IGDT the minimum and maximum levels of performance for each *h* are defined as *robustness* and *opportuneness* [9]. In a process known as robust satisficing [4], the theory determines alternatives, which perform acceptably well under a wide range of conditions, thus seeking robustness rather than optimality [12]. This needed level of performance is characterized as the minimum level of system performance Π which has to be achieved. The resulting *robustness* (Eq. (3)) is defined by the maximum amount of uncertainty α (the maximum horizon of uncertainty) that can be tolerated while still ensuring a level of performance Π, greater than a critical level Π_c [12]:

$$\hat{h}(q_i,\Pi) = \max\left\{ h : \min_{Q \in U(h,\tilde{Q})} \Pi(q_i,Q) \ge \Pi_c \right\} \quad (3)$$

To perform Info-Gap analysis we use two performance criteria of the protection option to define the maximum achievable robustness: NPV and number of Potential flood fatalities. NPV=0 is a failure, the highest NPV is the winner; The severity and duration of floods are used to calculate the number of Potential flood fatalities for each simulation, based on the Civil protection-Bulgaria method, described above in subsection 2.2.

The robustness ($\hat{h}$) is the maximum allowed deviation α that still ensures the level of performance and gives the decision maker information about how bad the future estimate of Q100 might be, while still providing a minimum level of efficiency of flood protection.

If the decision maker is interested in what performance windfall (reward) R might occur in the event of a flood that is less than the expected nominal $\tilde{Q}$, Eq. (4) is defined as an *opportuneness* function with a performance windfall Π_w [9]:

$$\hat{\beta}(q_i,\Pi) = \min\left\{ \alpha : \max_{Q \in U(h,\tilde{Q})} R(q_i,Q) \ge \Pi_w \right\} \quad (4)$$

3. CASE STUDY

3.1 Quick review

The town of Sevlievo is situated in the central part of Bulgaria, at the lowest point of the valley located at the foothills of the northern slopes of Stara Planina under its highest peak - Botev. The Rositsa River runs through the town, making a meander within the populated place. The catchment of the river has a torrential character.

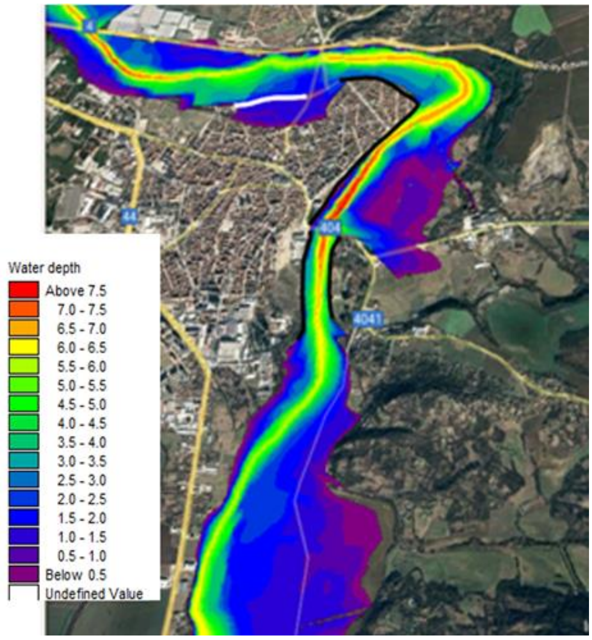


Figure 2. Flood with an annual probability of exceedance 1% (Q100) and protection dikes in the town of Sevlievo

There are several historical records of flooding occurring in the settlement from floodwaters on the river Rositsa. The catastrophic flood that happened on 28.06.1939 is with the most human casualties. After this event, protective dikes were built in the town: an earth embankment from the beginning of the town to the first bridge and a stone masonry dike (dikes in black in Figure 2) along the meander of the river protecting residential buildings; after the stone masonry dike, a lower earth embankment (dike in white in Figure 2) was constructed which in the past protected agricultural land but today protects residential buildings to some extent.

Over the years, the town of Sevlievo from a small settlement with development mainly in agriculture, today has become one of the most developed industrial towns in Bulgaria. In this connection, the flood zones of the town in case of flooding include both industrial enterprises and residential areas with predominantly residential buildings up to 3 stories.

3.2 Flood discharge-damage function

A one-dimensional hydrodynamic model of the part of the Rossitza river through the town of Sevlievo was elaborated using Mike 11 by DHI. Simulations of flood scenarios were performed with the river discharges up to the catastrophic flood that happened in 1939. Looking for damage in some industrial objects and districts of the town (objects of interest), material losses in each flooded area, caused by discharge, have been assessed by the methodology of Armeec Insurance Company. Next Figure 3 shows a damage function, the relationship between discharges Q in $m^3 . s^{-1}$, and damages in euro.

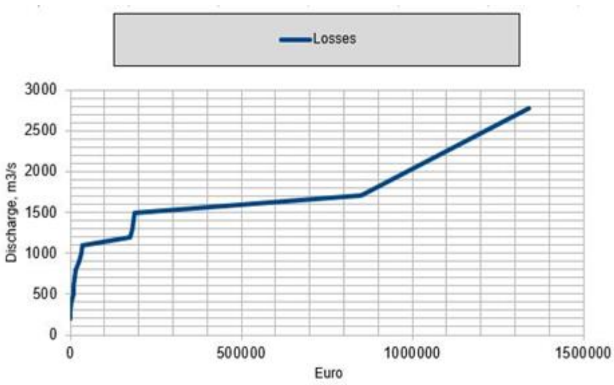


Figure 3. Flood discharge-damage relationship, Rossitza river through the town of Sevlievo

3.3 Flood protection options

Considering the existing flood protection infrastructure, the terrain features of the river valley, and the infrastructure at risk of flooding, three possible flood protection options qi, i=3 are identified:

Panels - Construction of temporary barriers using metal Panels up to 2 m high in places where the terrain allows (total length of 1700m).

Evacuation - Evacuation of the population from potentially affected areas.

Panels and Evacuation - Combined application of the previous two measures - construction of barriers from metal Panels (up to 1.7m high, a total length of 1140m) and Evacuation of the remaining potentially un-protected population.

3.4 Dataset of flood scenarios

The above protection options are designed for the so-called nominal scenario - a flood discharge Q100=1500 m^3/s determined statistically from observations. We examine how effective the flood protection options are under a range of flood scenarios with the hazard bounded at the Q100 climate change projections to 2050: lower bound $Q100_{RCP4.5}$= 1230 m^3/s and upper bound $Q100_{RCP8.5}$=1725m^3/s. This way, a dataset is prepared to assess the impact of hydrological uncertainty on the selection of flood protection.

4. RESULTS

4.1 Deterministic analysis

The economic efficiency of 3 types of protection measures is studied: *panels, evacuation*, and a combined measure of *panels and evacuation*. A constant social discount rate of 3.6% as recommended in the study [13] was used to discount future expected damages, and investment costs. We assume the costs of the panels now and that the benefits of the measure arise at the center point in year 15 of the period of 30 years. The damages without implementing the measures are material and human, the latter being affected people and fatalities. Insurance prices for affected and fatalities are used to calculate the benefits of implementing the measures. Evacuation costs occur at the year 15 and are for travel and accommodation of affected people. The benefits are equal to the avoided damages.

Results are presented in Table 1 and show positive effects and cost-effectiveness for the three options. Evacuation can be ranked first in effectiveness, then panels and evacuation, and least effective are panels as a measure.

Table 1. Deterministic model: NPV comparison of protection options (design flood Q100=1500m^3/s)

Deterministic model	panels	evacuation	panels&evac
NPV	€ 417,104.62	€ 491,653.65	€ 476,257.18

4.2 Probabilistic analysis without considering the hydrological uncertainty associated with climate change

In the probabilistic analysis without considering the hydrological uncertainty associated with climate change, uncertainties associated with prices, SDR, time, methods for estimation of losses, and the number of potentially injured or fatalities were considered. The variation for the period from 1 to 30 years and the range for SDR from 0.8% to 8.13% was assumed. Monte Carlo simulation analysis with 10000 iterations was performed using @RISK 8.2.2. The probability distribution of evacuation option NPV as a histogram and integral probability distribution curve is illustrated in Figure 4.

The results rate the evacuation option with the highest mean NPV and the lowest standard deviation in terms of economic efficiency. Table 2 presents a comparison between variants.

Table 2. Probabilistic analysis without considering hydrological uncertainty associated with climate change: A comparison of results for protection options

Statistical properties	panels	evacuation	panels&evac
NPV-Mean	€ 390,860.37	€ 470,543.26	€ 454,088.25
Std Dev	€ 180,516.59	€ 142,044.83	€ 174,698.60

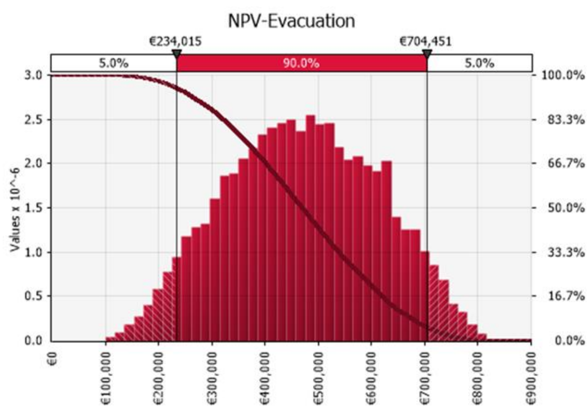
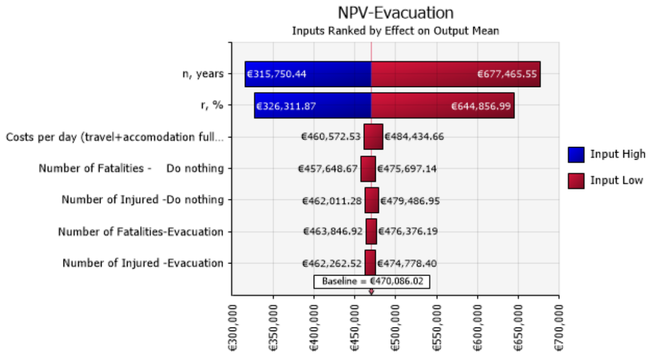
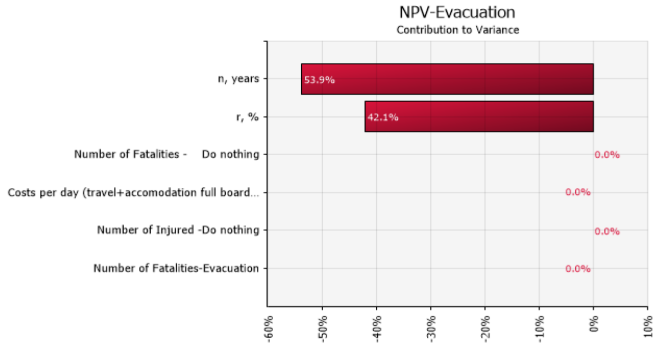


Figure 4. NVP for Evacuation without considering the hydrological uncertainty associated with climate change

Uncertainty of r (SDR) and time show a strong influence on the mean and variance of NPV in all 3 options (Figure 5).



(a) Inputs ranked by the effect on NPV mean



(b) Inputs ranked by the effect on NPV variance

Figure 5. Results for Evacuation option NPV without considering the hydrological uncertainty associated with climate change: Inputs ranked by the effect on (a) NPV mean and (b) NPV variance

4.3 Probabilistic analysis that incorporates hydrological uncertainty associated with climate change

To account for the uncertainty of the flood hazard Q100 due to climate change, a probabilistic analysis was performed introducing a probability distribution of variables considering the whole range of flood scenarios for the period up to 2050, milder and more severe than the nominal scenario described in subsection 3.4.

The uncertainty of the Q100 projections pushes the standard deviation of the NPV to increase, making the forecast less reliable. It changes the average NPV of the options (see Table 3), for example, it reaches a reduction of four times for the panels measure, which is counterproductive and practically dangerous in the case of realization of the RCP 8.5 climate scenario projection.

Under these conditions evaluation of the Number of fatalities before and after implementation of the flood defense option, r (SDR), and time have the strongest influence on the variance of NPV in all options (Figure 6).

Table 3. Probabilistic analysis that incorporates hydrological uncertainty associated with climate change: Comparison of results for protection options

Statistical properties	panels	evacuation	panels&evac
NPV-Mean	€ 89,281.85	€ 417,263.38	€ 474,132.86
Std Dev	€ 412,030.38	€ 322,948.94	€ 321,754.49
Probability of NPV being ≥0	57.8%	92.5%	96.7%

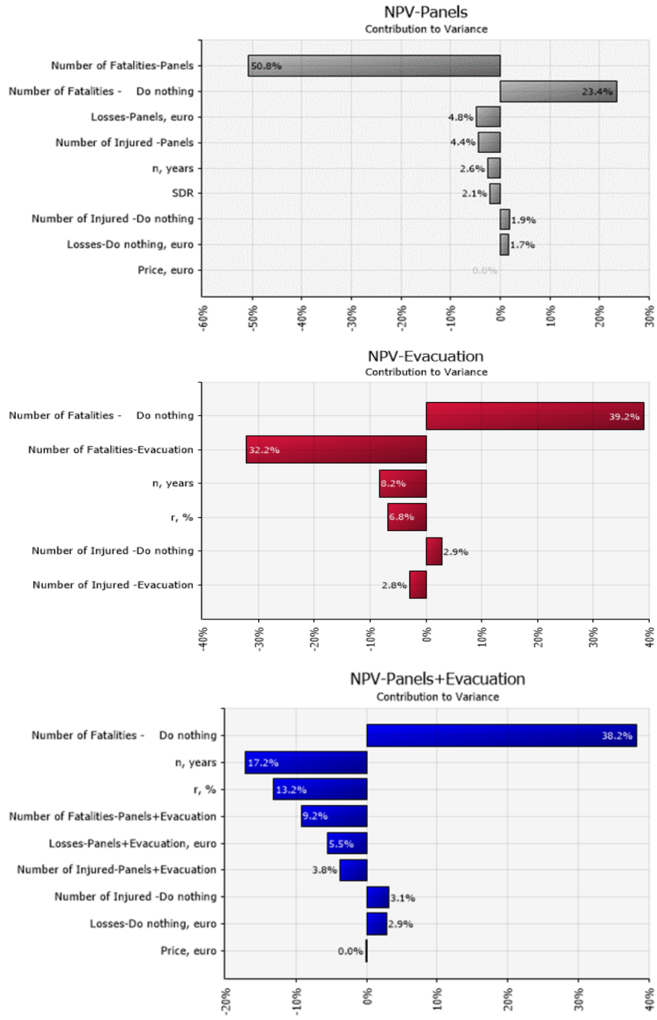


Figure 6. Inputs ranked by the effect on NPV variance, considering the hydrological uncertainty associated with climate change

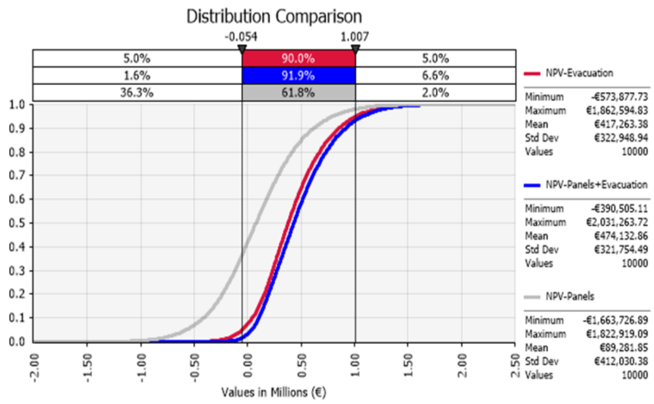


Figure 7. Distribution comparison of options NPV, considering the hydrological uncertainty associated with climate change

In the next Figure 7, distribution comparison shows the three flood defense options are cost-effective with a positive NPV. But taking into account the uncertainty of climate change projections, the winning option is *panels with evacuation*. It has the highest value of mean NPV and the lowest value of standard deviation. The second most cost-effective measure is *evacuation*, and the third is *panels*, which has a significantly lower NPV and the highest standard deviation value. Furthermore, *panels* has a 42.2% probability of having an NPV value of 0 or less, indicating an economically inefficient measure.

4.4 Info-gap analysis

For the next 30 years, we consider 5 flood scenarios specific to the urban environment in the city of Sevlievo. The nominal scenario i.e., the scenario with current evaluation for the 1-in-100-year flood Q100 is used to construct the uncertainty set of the Info-Gap model as detailed in Eq. (2), where the standard deviation of Q100 is σ=184 m3/s, based on climate change projections to 2050 for Q100 from scenarios RCP 4.5 (lower bound) and RCP 8.5 (upper bound). Table 4 shows the NPV values obtained from a deterministic model for the specific scenarios.

Table 4. Deviation from Q100 and NPV values assumed in the Info-Gap uncertainty model

Deviation from Q100	NPV panels	NPV evacuation	NPV panels&evac
-1.31σ	237,788.79	318,868.02	296,941.35
-0.93σ	327,476.12	405,260.84	386,628.68
0.00σ	417,104.62	491,653.65	476,257.18
0.70σ	-370,990.81	491,653.65	660,713.63
1.38σ	-494,564.59	491,653.65	633,978.63

Note: NPV in euro.

In linear programming with interval uncertainty sets an article [14] shows that the worst optimum solution will be obtained in an extreme scenario of the interval uncertainty sets. In our case, this is either $Q = \tilde{Q} - \sigma\alpha$ or $Q = \tilde{Q} + \sigma\alpha$, where $\tilde{Q} = Q100$.

For the extreme scenario $Q = \tilde{Q} + \sigma\alpha$, the situation in which the hazard Q is heavier than the current estimation for Q 100, the trade-off between robustness and NPV for different flood protection measures is illustrated in Figure 8.

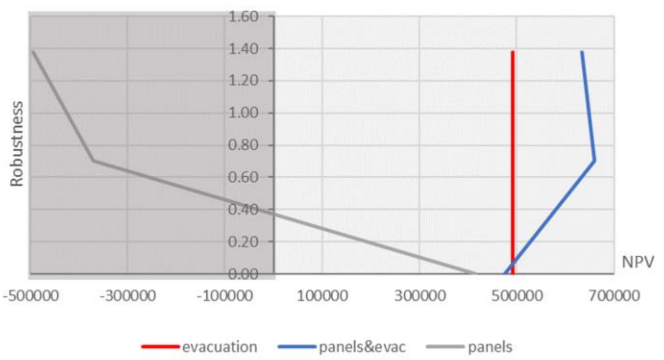


Figure 8. Robustness vs. NPV trade-offs for different flood protection measures

For the nominal scenario, the robustness to the uncertainty of the competing protection measures is zero. In this situation, the *evacuation* measure seems to win with the highest NPV. The *panels* option can tolerate an increase in hazard Q of less than 0.4×σ from Q100, with decreasing economic efficiency, and with a larger deviation, it becomes economically counterproductive and physically dangerous from breach and increase in hazard respectively increase in material damage and casualties.

The *evacuation* can tolerate a deviation in the hazard Q of 1.4×σ=257.60 m^3/s without a change in the cost-effectiveness of the measure (NPV). However, the line crossing shows that it quickly loses its advantage already at the 0.07σ deviation level and falls behind in cost-effectiveness to the *panels+evacuation* option under conditions of greater uncertainty.

The *panels+evacuation* option shows the most robust behaviour, increasing its NPV up to a variance of 0.7×σ=128.80 m^3/s and not significantly reducing it when the uncertainty increases to 1.4σ.

When discussing the protection of the population, in addition to economic criteria, it would be appropriate to analyze the performance of the options in terms of the number of people potentially affected- potential fatalities and potentially injured, that is determined in the context of a specific to the urban environment, existing permanent flood protection and population demographic characterization. Moreover, the probabilistic analysis taking into account hydrological uncertainty due to climate change showed that the number of potential fatalities before and after implementation of the flood defense option has the strongest influence on the variance of NPV in all options. Robustness vs. number of potential fatalities trade-offs for different options is shown in Figure 9.

To prevent potential flood casualties in the city of Sevlievo, the *panels+evacuation* option was found to be more effective. *panels+evacuation* option keeps at a level of a deviation in hazard Q of 1.4×σ=257.60 m^3/s comparable number of potential fatalities with the *evacuation* at a level of a deviation 0.8σ.

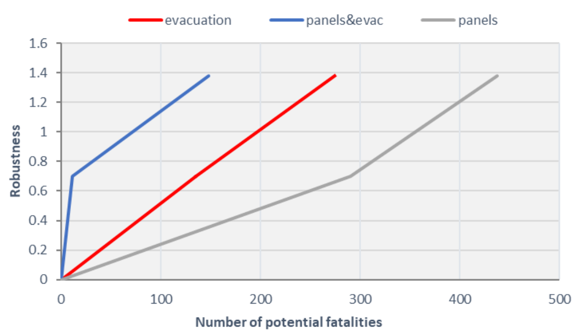


Figure 9. Robustness vs. Number of potential fatalities trade-offs for the options

Opportuneness analysis (Eq. (4)) also allows the decision maker to see what the behaviour of the options will be if the future is more favorable than the central estimate. The extreme scenario $Q = \tilde{Q} - \sigma\alpha$, the case in which the hazard $Q \le \tilde{Q} = Q$ 100, is shown in Figure 10. The uncertainty of the river discharge is simulated in the direction of the projected value for Q100 under the RCP4.5 scenario for the period to 2050, down to $Q = \tilde{Q}$-1.31α.

As might be expected for Q<Q100, below the Q100 flood flow for which protection options are designed, the total benefit decrease, and it follows from this that all options decrease in their cost-effectiveness with increasing the deviation. With worse performance for the *panels* option, *evacuation* shows the best behavior, followed closely by the *panels and evacuation* option.

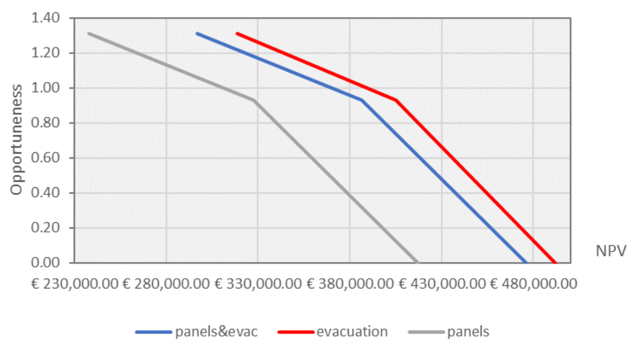


Figure 10. Opportuneness for different flood protection measures

5. DISCUSSION AND CONCLUSIONS

The densely built environment around the river in the City of Sevlievo precludes feasibility for many of the potential flood protection alternatives. The aim of this study was through simplified examples of flood protection measures, to demonstrate a multi-method approach for selection among options compared simultaneously in terms of potential effectiveness and sufficient reliability. The approach combines deterministic and stochastic NPV analysis with Info-Gap Decision Theory to illustrate how useful and illustrative the info-gap theory approach is, especially in combination with completely different approaches such as probabilistic cost-effectiveness analysis, for example. The Info-gap approach enables the decision maker to explore the trade-off between the degree of robustness of each protection option under flood hazard uncertainty and the NPV, or the number of people potentially affected, injured, or any other variable relevant to the analysis.

Through the measure evacuation, protection of human life and small material valuables that can be easily carried is achieved. While the 'mobile barrier protection' measure provides protection for infrastructure and saves lives, its application also carries the risk of greater damage in the event of a breach. In practice, the two measures are often applied in combination. Combining structural and non-structural flood risk reduction measures makes decisions more robust in the face of uncertainty. In a subsequent study, variants of the panel-evacuation combination could be explored, among other flood protection options such as riverbed widening, etc.

This research aims to influence the style of decision making in practice. The results suggest that the choice of flood risk management option can be changed when the uncertainty of the hazard assessment is considered. If decision-makers are not risk averse may prefer the option of maximizing the uncertainty that the protection measure can tolerate under extreme hydrological scenarios. We see that the introduction of hydrological uncertainty due to the impacts of climate change transforms the decisions which would be taken based on both deterministic and probabilistic models to assess economic efficiency.

In the case of a distant horizon and highly uncertain future, hydrological uncertainty can be represented with the help of Info-Gap Decision Theory using the concept of uncertainty sets. We focus on the robustness of solutions here since for now, the opportunity function looks less applicable in this particular hydraulic engineering problem. A future study should include variations on the application of the approach as well as testing alternative sets of uncertainties within the Info-Gap methodology.

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NOMENCLATURE

B_t	project benefits in period t, euro
C_t	project costs in period t, euro
h	horizon of uncertainty
$\hat{h}$	robustness
n	number of years of useful life of the project
NPV	Net Present Value, euro
Q	flood discharge, $m^3. s^{-1}$
$\tilde{Q}$	a current best estimate of a future parameter flood discharge Q, nominal value, $m^3. s^{-1}$
$Q100$	the 1-in-100-year flood, $m^3. s^{-1}$
$Q100_{RCP4.5}$	RCP4.5 scenario Q100 projection to 2050, $m^3. s^{-1}$
$Q100_{RCP8.5}$	RCP8.5 scenario Q100 projection to 2050, $m^3. s^{-1}$
q_i	i-th flood protection option
r	social discount rate (SDR),%
t	period, yrs.
$\tilde{u}$	best estimation of the uncertain parameter, nominal value

Greek symbols

α	amount of uncertainty, deviation from the nominal value $\tilde{Q}$
$\hat{\beta}$	opportuneness
Π	system performance
Π_c	critical level of system performance
Π_w	performance windfall
σ	standard deviation

Subscripts

c	critical
w	windfall