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PAN JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2022.141569
2022, No. 54 (VII–IX): 172–176

Compare and evaluate the performance of structural flood risk management options

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RECEIVED 08.07.2021 ACCEPTED 24.08.2021 AVAILABLE ONLINE 28.09.2022

Abstract: One of the most important natural phenomena that causes harmful damage around the world is the occurrence of sudden and severe floods. There are various solutions to deal with floods. Among the structural measures of flood risk management, we can mention the construction of levee, detention basin, channel modification, and a combination of the mentioned measures. Manafwa is a flood-prone area in Uganda currently protected by a 6.6 m high levee. Unfortunately, the existing levee does not have ideal performance, and the probability of failure is very high. Therefore, the main purpose of this study is to compare seven flood management measures in the flood-prone area of Manafwa and to select the best flood risk management proposal. These management measures are: 1) construction of a levee with a height of 6.5 m, 2) construction of a levee with a height of 7 m, 3) construction of a levee with a height of 7.5 m, 4) construction of a levee with a height of 8 m, 5) channel modification, 6) detention basin and 7) a combination of structural measures of channel modification and detention basin. The results show that although building a levee with a height of 8 m is more expensive than other options, but it reduces the expected annual flood damage to about USD30.5 thous.

Keywords: annual expected damage, assurance, flood, risk management

INTRODUCTION

Structural and non-structural methods are used to manage flood risk. Structural flood management methods are a subset of flood management which includes the role of the structure and its operation [Liu *et al.* 2019; Khosravi *et al.* 2022]. Many of these methods have a history of several thousand years [Afshar *et al.* 2021; Hajibabaei, Ghasemi 2017; Lodge 2019; Yavari *et al.* 2022]. Structural methods of flood management include flood walls and levees, channel modification, and detention basin. Restriction of flood flow in a certain width of the river is done with the help of structures such as levees and floodwalls [Koszewska, Kuzak 2021]. These structures prevent the spread of floods in the lands around the river, directing it in a specific and limited path and channel. The construction of these structures has been the oldest, most common, and also one of the most important methods of flood control since ancient times [Filz *et al.* 2012]. By improving the riverbed, the river's capacity to control floods increases, and hence the risk of flooding is reduced [Nkwunonwo *et al.* 2020]. By constructing a detention basin and storing water behind this reservoir, peak floods decrease and peak flood times increase [Sharior *et al.* 2019].

It makes sense that flood risk assessment should be done before any structural or non-structural action. Flood risk assessment is a qualitative or semi-quantitative method for measuring flood risk [Lyu *et al.* 2019]. In flood risk assessment, valuable information for flood risk management is provided by examining the extent of vulnerability and exposure to risk. Flood risk assessment is performed in four stages: 1) damage assessment, 2) exposure assessment, 3) vulnerability assessment, and 4) risk assessment.

In step 1, the damage assessment provides information about flood characteristics (water depth, flood zone area, flow area, etc.) with different return periods, summarised in the flood map [Romali *et al.* 2018]. The purpose of step 2 is to determine the location of flood-affected elements such as residential and non-residential land uses, agriculture, and human population. In step 3, the vulnerability assessment identifies how the flood damages these elements. In step 4, finally, the risk assessment involves generating a "damage–exceedance probability" curve. In fact, it expresses the amount of damage caused by floods with the exceedance probability / different return periods [Liu *et al.* 2013].

The main purpose of this study was to compare the performance of several structural measures: 1) construction of levee with a height of 6.5 m, 2) construction of levee with a height of 7 m, 3) construction of levee with a height of 7.5 m, 4) construction of levee with a height of 8 m, 5) channel modification, 6) detention basin and 7) combination of structural measures (channel modification and detention basin) in the study area in order to evaluate and compare the performance of these structural measures, flood risk assessment has been done by considering a wide range of existing uncertainties.

MATERIALS AND METHODS

ANNUAL EXPECTED DAMAGES

The amount of damage per specific stage must first be found from the "stage–damage" curve [Alian, Ahmadi 2019]. Then, from the discharge-stage curve, find the flow rate corresponding to the specified stage. In the next step, the amount of exceedance probability related to the specified discharge should be determined from the discharge– exceedance probability curve. Finally, by repeating these steps for different stages, the damage-exceedance probability curve can be found. The area below this curve indicates the expected annual damage.

CALCULATION OF EXPECTED ANNUAL DAMAGES IN TERMS OF UNCERTAINTIES

In order to calculate the expected annual damage in terms of the three types of uncertainty, it is sufficient to use the Monte Carlo simulator to create a large number of discharge- exceedance probability curve, discharge-stage curve, and stage-damage curve and the expected annual damage for each realisation found [Nathan *et al.* 2003]. Then, the average annual expected damage of all realisations represents the expected annual damage, taking into account uncertainties [Xu *et al.* 2007].

ASSURANCE

In order to calculate the assurance against floods with different return periods, it is first necessary to produce a large number of discharges due to the uncertainty of floods with a return period of t years. Then divide the number of times that the flood characteristic (such as stage, discharge, etc.) is less than the desired stage by the total number of samples [Lai *et al.* 2011].

THE EXCEEDANCE PROBABILITY AND LONG-TERM RISK

In order to calculate the annual exceedance probability (AEP), due to the uncertainty of floods with different return periods, a large number of discharges should be produced. Then divide the number of times that the characteristic of floods has exceeded the desired limit by the total number of samples. Long-term risk (LTR) indicates in a given period of time (t years), what is the percentage of probability that a flood will occur at least once if its characteristic exceeds a certain limit? This parameter can be calculated from Equation (1):

$$LTR = 1 - (1 - AEP)^t \tag{1}$$

IMPACT OF STRUCTURAL MEASURES ON FLOOD RISK

Each of the flood risk management instruments measures reduces flood risk by changing at least one of the curves of discharge–exceedance probability, discharge–stage, and stage-damage. Levee reduces damage by changing the stage–damage relationship. Channel-modification changes the discharge–stage relationship. The main effect of building a detention basin is on the discharge–exceedance probability curve. It is clear that by performing two structural measures of channel-modification and construction of a detention basin simultaneously, the discharge–stage and discharge–exceedance probability curves will change.

APPLYING UNCERTAINTIES

As mentioned earlier, to calculate the expected annual flood damage, one must obtain the uncertainties in the discharge–exceedance probability, discharge–stage, and stage–damage curves [Davis 2003]. The following describes the method of calculating the uncertainty in each of the curves.

- **Uncertainty of the "discharge–exceedance probability" curve**

Errors in the mean and standard deviation of the logarithm of the middle discharge data have created significant errors in fitting the discharge–exceedance probability ratio. As recommended in Bulletin 17B, these errors are described by a possible non-central t-distribution model [Stedinger, Griffis 2006]. Appendix 9 Bulletin 17B provides an explicit estimation method for determining the uncertainty of the Log-Pearson type III distribution function, assuming that the errors follow a possible non-central t-distribution model. In fact, by using this method, confidence intervals can be found for each of the middle discharges with confidence level c.

- **Uncertainty of discharge-stage curve**

In this project, the uncertainty of the discharge-stage relationship with the method provided by HEC has been quantified. According to this method, the errors in predicting the water level in the river for a given discharge have a normal distribution with a mean of zero and a standard deviation which is presented below.

For discharges greater than 100 years of flood, the standard deviation of the error is assumed to be equal to the standard deviation of the 100-year flood. For discharges smaller than 100 years of flood, the standard deviation of the error is calculated as follows:

$$SD_t = SD_{100} \frac{Q_T}{Q_{100}} \tag{2}$$

where: SD_t = the standard deviation of the t-year flood error, SD_{100} = the standard deviation of the 100-year flood error, Q_t = amount of the t-year flood discharge, and Q_{100} = the amount of the 100-year flood discharge.

- **Uncertainty of the stage–damage curve**

Uncertainty in the stage–damage relationship arises from three main cases: 1) errors that exist in estimating the height of structures, 2) errors that exist in damage to structures, and 3) errors that exist in the assessment of damage to contents. In the present study, these errors have a normal distribution with a mean of zero (standard deviation values must be specified).

RESULTS AND DISCUSSION

Figure 1 shows the flood discharge distribution function, flood stage distribution function, and flood damage distribution function with different return periods (exceedance probability) in the current conditions. In fact, the values presented in Figure 1 indicate the upper and lower discharge rates, stages, and average losses, taking into account the values of different confidence intervals. For example, for floods with an exceedance probability of 0.002 (500-year floods), the average discharge values, with 99.8% confidence, are between 518.6 and 2224.9 $m^3 \cdot s^{-1}$ and the mean stage values are between 7.26 and 9.12 m and the average damage values are between USD4,218.1 and USD6,339.1.

The values presented in Figure 1 are used to calculate the expected annual damage in the current situation. For this purpose, using Monte Carlo simulation, it generated 1000 times random discharge–exceedance probability, discharge–stage, and damage–stage curves, and the damage–exceedance probability curve has been generated 1000 times. Then, the expected annual damage is calculated by averaging the expected annual damage of all samples. By performing the above steps, the expected annual damage was calculated at USD69.9 thous. It should be noted that the amount of damage is zero for $p \geq 0.2$ (Fig. 1).

Table 1 shows the economic factors of the options for reducing flood damage without considering flood uncertainty and flood uncertainty. Given that the normal distribution of flood damage error has been adjusted with different return periods, we expect that the expected annual damage, taking into account uncertainty and without taking into account flood uncertainty, will lead to almost similar results. By comparing the values shown in Table 1, it can be seen that this has been met. According to the results of this Table, the order of selection of options in terms of expected annual damages is as follows: 1) levee 8 m, 2) levee 7.5 m, 3) levee 7 m, 4) levee 6.5 m, 5) channel modification, 6) mixed-measure, 7) detention basin.

As you can see in Table 1, the damage reduction by the levee 8 m is much greater than the other options. In addition, the construction of the 8 m levee provides greater assurance against very large floods, such as floods with an exceedance probability of 0.004 (Tab. 2). Therefore, levee 8 m will be more acceptable than other levees and options in case of very large floods. Also, the long-term risk (50 years) of the levee 8 m is lower than all available options (Tab. 3). According to these explanations, the best option in terms of engineering performance is levee 8 m.

The choice of a combination of detention basin and channel modification (mixed measure option) compared to the channel modification option did not make much difference in increasing net profit. Because both detention basin and channel modification options work very well in large silos. Therefore, in the case of

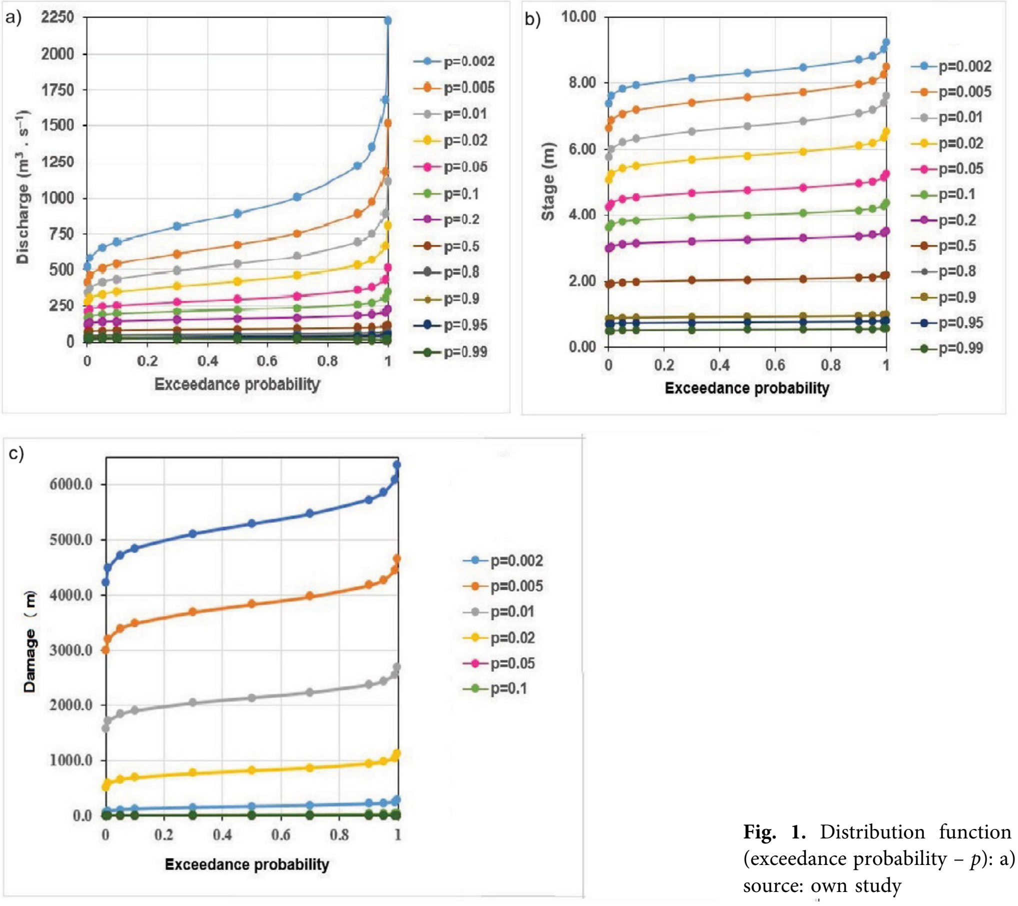

Fig. 1. Distribution function with different return period (exceedance probability – p): a) discharge, b) stage, c) damage; source: own study

Table 1. Economic factors of seven proposed options to reduce flood damage with and without considering flood uncertainty

Proposal	Annual inundation reduction benefit, in USD1000		Annual cost, in USD1000	
	without uncertainty	with uncertainty	without uncertainty	with uncertainty
Levee 6.5 m	33.0	33.0	18.8	18.5
Levee 7.0 m	45.6	46.5	24.5	24.3
Levee 7.5 m	56.4	55.5	31.2	28.5
Levee 8.0 m	61.5	66.7	36.2	36.2
Channel modification	36.6	24.4	36.7	24.2
Detention basin	32.7	32.1	34.9	33.3
Mixed measure	56.5	56.4	44.1	44.3

Source: own study.

Table 2. Assurance values of seven proposed options

Proposal	Exceedance probability		
	0.02	0.01	0.004
Levee 6.5 m	0.999	0.475	0.001
Levee 7.0 m	1.000	0.972	0.085
Levee 7.5 m	1.000	0.998	0.570
Levee 8.0 m	1.000	1.000	0.946
Channel modification	0.020	0.001	0.000
Detention basin	0.009	0.001	0.000
Mixed measure	0.996	0.015	0.000

Source: own study.

Table 3. Probability of annual exceedance and long-term risk of seven proposed options to reduce flood damage

Proposal	Median estimate of annual exceedance probability	Annual exceedance probability with uncertainty analysis	50 year
Levee 6.5 m	0.0101	0.012	0.45
Levee 7.0 m	0.0060	0.007	0.30
Levee 7.5 m	0.0037	0.005	0.22
Levee 8.0 m	0.0021	0.002	0.10
Channel modification	0.0250	0.032	0.80
Detention basin	0.0310	0.046	0.90
Mixed measure	0.0130	0.020	0.64

Source: own study.

a small flood, the existence of one of these two options is enough to control the flood and reduce its damage. Therefore, implementing the mixed measure option only increases costs and has no significant effect on reducing damages. However, it should be noted that in the case of floods with an exceedance probability of 0.02, mixed measure gives a very high assurance, and its long-term risk is much less than detention basin and channel modification. It is noteworthy that the implementation of the detention basin results in a negative net profit since this superstructure has no economic justification [Moglen, McCuen 1990].

A quick look at the results shows that the construction of levees offers more favourable results both economically and in terms of engineering performance. Among the available levees, the economic justification of levee 8 m is more than other levees. In addition, given that the long-term risk of the levee 8 m is much lower and also its assurance against large floods is much higher than other levees if there is no budget limit, this option is offered for selection.

CONCLUSIONS

Structural methods of flood control include construction of levee, channel-modification, and detention basin. In this research, flood risk assessment and analysis in the study area with structural measures of: 1) levee construction with a height of 6.5 m, 2) levee construction with a height of 7 m, 3) levee construction with a height of 7.5 m, 4) levee construction with a height of 8 m, 5) channel modification, 6) detention basin and 7) a combination of channel modification and detention basin structural action is investigated. The evaluation criteria used in this study are: annual expected damages with and without uncertainty, flood assurance with a return period of 50, 100, and 250 years and annual exceedance probability and long-term risk of 50 years. In order to accurately calculate the expected annual damage, it is necessary to take into account all available uncertainties (including uncertainty of discharge–annual exceedance probability curve, discharge–stage, and stage–damage) in calculating this parameter. In the present study, the errors of the discharge–exceedance probability curve with non-central *t*-distribution and the errors of the discharge–stage and stage-damage curves with normal distribution are estimated with a mean of zero. The Monte Carlo simulator was used to randomly generate the above statistical distributions. The results show that if the budget is not limited, the construction of a levee with a height of 8 m has the highest annual expected damage reduction (USD30.5 thous.), the highest flood protection of 250 years (0.95), and the lowest 50-year risk (0.1).

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