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Analyzing investments in flood protection structures: A real options approach

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ABSTRACT

The soaring number of natural hazards in recent years due largely to climate change has resulted in an even higher level of investment in flood protection structures. However, such investments tend to be made in the aftermath of disasters. Very little is known about the proactive planning of flood protection investments that account for uncertainties associated with flooding events. Understanding the uncertainties such as “when” to invest on these structures to achieve the most optimal cost-saving amount is outmost important. This study fills this large knowledge gap by developing an investment decision-making assessment framework that determines an optimal timing of flood protection investment options. It combines real options with a net present value analysis to examine managerial flexibility in various investment timing options. Historical data that contain information about river water discharges were leveraged as a random variable in the modeling framework because it may help investors better understand the probability of extreme events, and particularly, flooding uncertainties. A lattice model was then used to investigate potential alternatives of investment timing and to evaluate the benefits of delaying investments in each case. The efficacy of the proposed framework was demonstrated by an illustrative example of flood protection investment. The framework will be used to help better inform decision makers.

1. Introduction

The socioeconomic impact of natural disasters has substantially increased over the past several decades. For example, the estimated annual costs of damages caused by natural disasters in the world increased from 53.6 billion USD in the 1950s to 778.3 billion USD in the 1990s. In 2008, one of the most destructive years, this estimate reached 200 billion USD [1]. Apart from the socioeconomic perspective and according to storm data from the US National Climatic Data Center (NCDC), floods between 1959 and 2005 resulted in 4,586 fatalities, or an average of 98 deaths per year [2]. These significantly high socioeconomic costs call for developing an effective strategy for flood risk management [3]. In particular, appropriate flood protection structures and related investment plans play a pivotal role in this regard. However, determining an optimal investment plan for such structures can be challenging in terms of investment timing given factors such as climate change and socioeconomic development [4].

The most salient justification for immediate investment in flood protection is preventing the recurrence of fatalities and economic damage. According to recent flood experiences around the world, flood protection funds are generally allocated immediately after a flood. For example, in 2010, Pakistan suffered a devastating flood with a death toll of 2,000 people and damage estimated at more than 50 billion USD [5]. Almost immediately afterward, the World Bank committed 1 billion USD of flood support funding to finance recovery and reconstruction. Similarly, the Asian Development Bank and the Asia Pacific Disaster Response extended 2 billion USD and 3 million USD, respectively, toward Pakistan [6]. During 2006–2008, the U.S. Congress authorized an investment of 160 million USD to palliate periodic flood damage caused to flood-susceptible structures [7]. Such immediate responses toward flood protection generally follow the traditional approach of discounted cash flow (DCF), which is used to evaluate investment projects [8].

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However, despite its wide implementation, DCF is limited in its ability to consider uncertain characteristics (e.g., the magnitude and timing of natural disasters), which renders it unsuitable for investment decision making for flood protection [4,8,9].

An alternative is the application of real option (RO) theory to support robust decision making by financially analyzing the managerial flexibility of options for flood risk management. Unlike the traditional DCF method, which is largely based on constant risk profiles [10], the RO approach enables decision makers to account for uncertainties when exploring managerial options (e.g., phasing and waiting). A distinguishing characteristic and benefit of the RO approach is its ability to analyze the value of delaying an investment. Notably, obtaining a positive net present value (NPV) under the DCF approach does not necessarily indicate the best investment timing from the RO perspective. In addition, since the DCF approach does not adequately account for the dynamic nature of uncertainties, disregarding the value of options could result in an under- or overestimation of project NPV [11,12]. In particular, for projects with high uncertainty levels, unexpected changes in cash flow can cause delays and performance issues [13].

2. Review of pertinent literature

2.1. Disaster management

The United Nations International Strategy for Disaster Reduction [14] defines disaster as “a serious disruption of the functioning of the community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its resources.” Disasters can be largely categorized into manmade and natural disasters, depending on their sources. According to a Federal Emergency Management Agency [15] report, the number of both manmade and natural disasters has increased over time. McDonald [16] argues that the impact of humans on the environment and the increase in population density are primary factors escalating disaster occurrences. For instance, population growth has forced people to move to more disaster-prone areas. Another factor, economic policy, possibly compels construction companies to skimp on infrastructure development, thus increasing the chances of construction failures occurring [16]. Simply put, relocation of population to disaster-prone areas and the lack of resiliency in built environments have significantly increased the extent of damages caused by disasters in recent years [17,18].

Several studies have developed disaster-management models in response to disaster risks and their impacts. Defining comprehensive emergency management (CEM), the National Governors Association [19] lists four phases of effective disaster management, acknowledged by numerous organizations [74], including FEMA [20]; as the cornerstones of disaster management:

- **Mitigation** refers to activities that eliminate or reduce the probability of disaster occurrence.
- **Preparedness** comprises all critical activities undertaken if mitigation measures cannot prevent a disaster. In this phase, governments, organizations, or individuals develop plans to safeguard human life and minimize impact.
- **Response** includes activities aimed at providing emergency assistance for casualties following an emergency or disaster.
- **Recovery** involves activities performed until all public utilities have resumed standard long- and short-term operations.

While many studies dealt with the response and recovery phases in disaster management [21–23], this study is focused on the preparedness phase. The preparedness phase of CEM includes developing flood protection structures such as dams, levees, watersheds, and dikes. Given the growing number of unpredictable floods resulting from climate change over the past decades, the development of such structures must carefully account for multiple factors such as proper locations, materials, designs, and optimal investment [24–26].

2.2. Waiting as an investment option

Decision making for natural disasters plays an increasingly critical role throughout disaster management processes [27]. Bøckman et al. [28] assert that “if and when” to invest are challenging decisions given the irreversibility of such decisions in terms of sunk costs. Dixit and Pindyck’s study [9] investigates the influence of irreversible investment, ongoing uncertainty, and timing flexibility on investment decisions. They define timing flexibility by stating “if the investment project is not undertaken today, the firms retain the option of undertaking the project tomorrow” and accordingly, they propose a model indicating the importance of optimal investment timing. Similarly, Chirinko [29] suggests that “waiting” is a valuable option when making investment decisions if postponing investments allows decision makers to acquire useful information about their investments and potential future payoffs. In the same vein, McDonald [30] and Chirinko [29] report the implications of waiting by highlighting that the option is no longer available once an investment action is taken.

2.3. Real options (RO) theory

Real Option (RO) is a decision-making approach that can quantify the value of managerial options for business investment opportunities. The RO methodology aims to the apply the financial option pricing method to non-financial investments [31,32]. Specifically, a binomial lattice model for RO refers to an options pricing approach based on a binomial tree by displaying the entire potential option pricing paths that might be taken over the investment period [9].

This study specifically adopts the RO theory to analyze managerial flexibility in waiting to invest in flood protection structures. RO is an analytical process that evaluates real investment options—for example, abandoning, deferring, reducing, phasing, and expanding [12]—for financial assets on the basis of investment uncertainties [9]. RO properly accounts for these options since it is largely based on the application of financial option pricing theory to non-financial investments [31,32]. A common RO application is a binomial lattice model comprising a binomial tree that displays the option pricing paths that can be taken across the Project Life (PL) period. RO evaluates irreversible investment possibilities including related uncertainties of a given investment [9].

Once new information is obtained, RO provides investors with various options such as expand, contract, delay, abandon, switch, and a combination of these features. These flexible options render RO a powerful decision-making tool in different fields, including water distribution networks [33], underground infrastructure [34], mine production [35], international construction markets [36], and energy retrofits [12]. These studies suggest that adopting RO for project-related decision making allows stakeholders to better communicate the value of flexibility options. In sum, RO addresses the lack of managerial flexibility features in traditional valuations such as DCF and NPV, which presume a fixed discount rate and cash flow, resulting in an adjusted risk profile across a project’s lifespan [8,10]. In other words, traditional methods may offer inaccurate valuations of investment options under considerable uncertainties [12].

Alternatively, studies have performed decision tree analyses to assess projects with uncertain cash flow [37]. While RO and a decision tree analysis may support similar investment decisions under uncertain conditions, the final value of the same risky asset may differ [37,38]. Damodaran [38]; for example, draws distinctions between the two methods. The author states that while the outcomes of a decision tree analysis are based on probabilities in each branch, uncertainty is the key factor shaping treatments in RO. Further, discount rates used to calculate the present values in a decision tree analysis are risk-adapted and cannot be implemented for a specific branch. Thus, given the abovementioned limitations in traditional methods, the authors have chosen RO to analyze intervention decisions for flood protection.

Previously, a growing number of studies have applied RO to explore interventions for flood risk management. For example, Woodward et al. [4] state that RO could provide flexibility options to mitigate flood risks under various scenarios while accounting for potential climate change. Gersonius et al. [39] apply RO theory to planning urban drainage systems and suggest that adapting the RO flexibility feature to climate change decreases future flood risks. However, while several studies examine investment decisions by applying RO theory to flood risk management, no research focuses on investment timing for flood protection options. Thus, to address this gap in the literature, this study proposes an RO-based framework—evaluation of investments in flood protection under uncertainty (EIFU)—and applies it to a hypothetical case study to demonstrate the evaluation of investment timing options.

In this study, valuating an option of delaying investments in flood protection is a function of the following factors: interest, discount, and depreciation rates; design discharge and floodplain extent.

Interest, discount, and depreciation rates are parameters used to calculate the costs and benefits of options. Market interest rates—that is, the rate at which borrowers pay interest—may be influenced by changes in short- and long-term monetary policy goals [40]. However, unpredictable events influence monetary policy and thus, the setting of interest rates is also subject to uncertainty. On the other hand, depreciation is traditionally defined as the cost allotment operation to meet the project cost with its resultant benefits, and hence deprecation rate refers to a percent rate at which an asset is depreciated over its useful life [41]. More specifically, depreciation can represent cost allocations for a project's damages, deterioration, and obsolescence [42].

Design discharge (DD) is the discharge of water corresponding to a given recurrence interval with a probability density function (PDF). By estimating DD, engineers can evaluate the risk of flood protection hydraulic structures with specific dimensions [43]. The DD is a unique maximum value or a hydrograph of water discharge. Discharge data is obtained from historical records or generated by hydrological methods. Discharges can be represented by a time series record with a common distribution function [44,72]. Thus, ignoring correlation coefficients, probabilistic methods can analyze extreme discharge values [44]. Studies have also proposed stochastic processes to represent water discharge time series (e.g., Ref. [45]). Discharge values are estimated by statistically analyzing historical data [46]. For instance, Apel [47] applies exceedance probability theory to water discharge events to determine DD. The average recurrence interval of the DD is the theoretical return period T [48]. Under the assumption that the peak flows from year-to-year are independent of each other, the occurrence of a T-year event is a random process meeting the requirements of a Bernoulli process. Hence, T can be calculated using Equation (1). Where, c is the probability that the T-year event will not be exceeded in an n-year period [49]. In this paper c is also denoted as confidence level or level of confidence. It can be noted that the probability that the T-year event will be exceeded at least once in an n-year period is 1-c.

$$T = \frac{1}{1 - c^{1/n}}. \tag{1}$$

Floodplain extent determination is necessary to estimate flood damage. Floodplains are areas adjacent to a river's mainstream, and these areas experience flooding during high-discharge periods. Numerous methods using topographical information are employed to establish the extent of inundation [50]. Floodplains extent can be directly recorded during the events and can also be estimated by hydraulic simulations. Hydraulic simulations are basically done by calculating water levels along the floodplain, with its corresponding topographic information, for the estimated DD. Currently, one common source of topographical information is the digital elevation model (DEM) [51]. Many times, DEM data are freely available and can be used to perform initiatory investigations [52]. Another method, to get exclusive data for floodplains, is placing a satellite radar altimeter on a river's mainstream to monitor water level variations for wetlands, rivers, and associated floodplains [51]. Currently, there are tools designed to process large datasets of DEM data for use with hydraulic simulation software [53]. These tools are used in the present study.

3. Statement of problem and objective

Numerous studies to date have leveraged RO theory to develop investment decision-making frameworks across various domains; however, there is little or no research that employs RO for the purpose of planning and assessing flood protection investments. Thus, this study attempts to fill this knowledge gap by developing an RO-based framework: Evaluation of Investments in Flood Protection under Uncertainty (EIFU). Determining an optimal timing of investment options, EIFU specifically quantifies the probability of future flooding events using historical information on river discharges as random variables. EIFU then builds a probabilistic lattice model of options to determine optimal investment timings. EIFU is based on possible payoffs to be achieved by delaying investments in flood protection structures. Project stakeholders can adopt EIFU to explore the options of waiting to invest in flood protection and conduct a RO analysis to determine a phased investment strategy, wherein investment timings are estimated prior to full-scale implementation. EIFU can help decision makers determine (1) the financial value of various investment timings for flood protection; (2) the impact of varying flood risks using historical data, which can offset the value of a defer option (wait and watch); and (3) the influence of various input parameters by performing a sensitivity analysis. The efficacy of EIFU is demonstrated through an illustrative example of flood protection investment.

4. Research methods

EIFU, as mentioned, allows decision makers to consider investment timings for flood protection to estimate the financial value of performance risks. The conceptual framework of EIFU is based on the risk and reliability of extreme water discharge events. Risk and reliability data can be derived using the theory of binomial distribution for independent Bernoulli random variables. In other words, sequential data on historical water discharges containing values close to or equal to Design Discharge (DD) is used to estimate the exceedance probability of similar DD events occurring within close intervals of each other following the Project Life (PL) period. In other words, the likelihood of a flood event occurring can be estimated from the historical distribution of the data. This underlying sequence of historical data allows decision makers to estimate the probabilities of near future events. In addition to the discharge historical data, EIFU uses the following as model inputs: depreciation, digital elevation model, design discharge and its return period, property damage unit costs, interest rate, and depreciation rate. Fig. 1 illustrate the steps of the EIFU framework.

4.1. Step 1: Determine Project Lifespan and Return Period

Step 1 involves determining a project's lifespan (PL) by conducting an EIFU analysis. The objective is to estimate an interval time within which the flood protection structure will remain reliable. This interval selection can be challenging because the reliability factor depends on the project's intended function or failure criteria [54]. In other words, a decision maker could also choose to abandon a project during the PL. However, the opportunity to abandon the project is equivalent to put option on a dividend-paying stock, where the salvage value of the project is the exercise price and the dividend payments on the stock are the cash flows at the end of the PL period [32]. The salvage value is correlated with the depreciation rate and as a result, changes in the latter would lead to similar changes in the former value. However, at the end of the depreciation period, the salvage value of a project can be

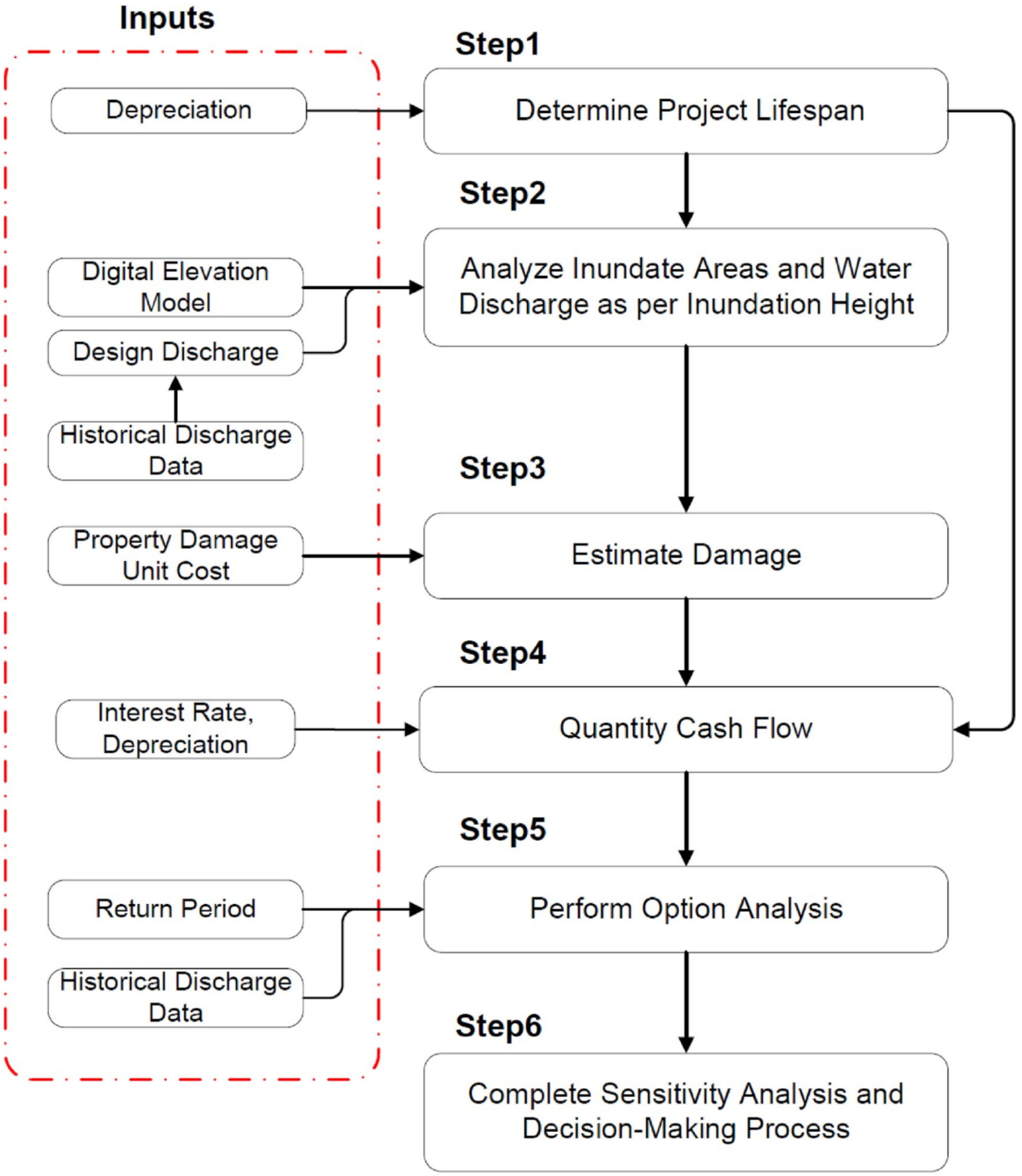


Fig. 1. EIFU steps.

assumed zero. Thus, to simplify the depreciation period and reach a zero-salvage value, the depreciation period will equal the PL period. In addition, in this step, the return period is calculated using Equation (1).

4.2. Step 2: Analyze Inundated Areas and Water Discharge as Per Inundation Height

In Step 2, a correlation curve is defined between inundated area and height of inundation (IA–HI) for the floodplain. The curve depicts the potential inundation variability of an area as water levels change. An IA–HI curve at zero height indicates the point at which the water flowing into the mainstream begins to overflow to the floodplain. This point is located at a higher elevation than the mainstream's lowest elevation point. When the height of the IA–HI curve increases, the number of inundated areas may increase or remain constant but will never decrease. The determination of the IA–HI curve must account for the characteristics of flood-prone areas (FPA). A floodplain's inundation height can be calculated by conducting hydraulic simulations with a water discharge. Next, a correlation curve between water discharge and inundation height (WD–HI) of the floodplain must be developed. The curve provides information on changes in inundation height as a result of variations in water discharge levels. A zero-height WD–HI curve indicates the point at which the water flowing into the mainstream starts to overflow to the floodplain. However, it is noteworthy that the water discharge corresponding to zero height is not at zero. Similar to the IA–HI curve, with a rise in the water discharge, inundation height will increase but never decrease.

4.3. Step 3: Estimate Damage

Step 3 constructs a correlation curve between an area's damage costs per unit and inundation height. The hydraulic modeling for various Design Discharge (DD) levels estimates the heights of inundated areas. Hydraulic modeling accounts for both single and multiple breach scenarios and its findings can be illustrated on a map. In addition, it is necessary to consider that multiple breaches could produce greater physical damage [55].

Estimating the extent of damage is vital to the decision-making process for flood protection investments. The estimation can help investors understand the benefits of a flood protection project. In addition, it could be used to define relief assistance after a flood has occurred [56]. Measuring disaster costs highlights related challenges such as determining direct costs, time and space scales for its analysis, and intangible costs [56]. In other words, several factors influence damage estimations, rendering the value of loss uncertain.

In the United States, FEMA has been collecting damage and cost data under its disaster assistance programs since the 1990s [56]. This study uses data on property damage costs (tangible costs) of previous floods available on the FEMA [57] webpage. Property damage costs are commonly presented using plots of average damage costs per unit of area correlated with various inundation heights. In the EIFU analysis, the damage cost of taking no action equals the total damage cost produced by DD flooding.

4.4. *Step 4: Cost-Benefit Calculation (Quantify Cash Flow)*

Step 4 is a cost–benefit analysis on different options of investment timing for flood protection. Costs are the investments undertaken to implement a project designed for a specific DD, whereas benefits are the total damage costs avoided by implementing the project.

The project cost with investment I_j in future year j can be calculated as follows:

$$I_j = I_0 {}^{*}(1+i)^j, \tag{2}$$

where I_0 is project investment at time zero and i is the interest rate applied to investment capital. Time interval m is set at equal or less than the PL: $0 < j \leq m,\ m \leq PL$. Table 1 describes the benefits matrix.

In the table, row j in the matrix denotes the year of probable flooding until year m. Column k indicates the probable year of investment. Benefit B_{jk} is calculated using Equation (3). Time interval n for investment timing is set at equal or less than the PL: $0 < k \leq n,\ \ n \leq PL$.

$$B_{jk} = \frac{b_k}{(1+r)^j} - d_k + S_k, \tag{3}$$

where b_k, estimated using Equation (4), is the benefit corresponding to damage avoided through flood protection, r is the discount rate, and d_k is the depreciation rate.

$$b_k = D_{do\ nothing_k} - D_{after\ investment_k} \tag{4}$$

where $D_{do\ nothing_k}$ is the damage cost for the “do nothing” option and $D_{after\ investment_k}$ is the allowed damage cost of the “after investment” option in year k. Doing nothing produces the highest damage cost. The first step in calculating the benefits of each option is determining the safest choice of flood protection, which also requires the maximum investment. This option avoids all flooding effects and consequently, produces zero damage costs ($D_{after\ investment_k} = 0$). The benefits of the remaining options are estimated for lower investments and differ from the safest design. These options are less secure and allow a certain amount of flooding damage and associated costs. Thus, the calculated benefits b_k of any option is equal to or greater than zero. S_k represents additional sources of benefits in future year k and takes a negative value if the valued source of benefit cannot be considered or is outside the protected zone of investment. Thus, this term is supposed to offer flexibility to decision makers.

Table 1
Benefits matrix.

Flooding year j	Investment at				
	$Year_{k=1}$	$Year_{k=2}$	$Year_{k=3}$	…	$Year_{k=n}$
$Year_{j=1}$	B_{11}	–	–	…	–
$Year_{j=2}$		B_{22}	–	…	–
$Year_{j=3}$			B_{33}	…	–
…					…
$Year_{j=m}$				…	B_{jk}

4.5. *Step 5: Perform Options Analysis*

Step 5 is the calculation of options values. An owner can decide whether to invest in a project. The authors assume the duration of the construction procedure is one period and its cost is I. The owner’s rights can be exercised prior to the maturity date, which is equal to the PL. Here, the authors first construct a decision tree. At date zero, the project owner is faced with two options [11]: invest in the project or wait (Fig. 2). If the owner chooses to invest on date zero, the cost will be I and the decision tree will be terminated. However, if the owner chooses to wait, the decision tree moves to the next period, in which the owner is presented with the same two options (invest or wait). Notably, at any point, the project will have one of two possible statuses: “not started” or “complete.” In Fig. 2, the lighter circles in the decision tree represent the owner’s decision nodes and the darker circles are terminated nodes.

In fact, the opportunity to postpone the decision and having a longer-term call might be more valued than shorter-termed ones because decision makers can exercise their right (but not obligation) to invest in the project before the maturity date. In this case, capital is still available for other investments. However, holders can earn better profits if they exercise their right before maturity. In the case of flood protection, these possibilities correspond with the risk of DD exceedance in the future. Here, discharge is considered an independent random variable. Thus, the following equation derived for a Bernoulli process based on independent random variables [58] is applicable:

$$R_k = 1 - \left(1 - \frac{1}{T}\right)^k, \tag{5}$$

where R is the risk probability that the T-year event will be exceeded at least once in a k-year period. Here, k is defined as the period of the investment. Year k begins when a similar DD value is reported in the past; the DD value can be either sourced or interpolated from historical records. Historical records for EIFU are extracted from chronologically sequenced data, which yields a range of probabilities for future events. For instance, if the selected DD has occurred, then the first value of the lattice model corresponds to the likelihood of an event with the same or greater magnitude occurring within the next year. Similarly, the second value denotes the probability of an event occurring within the next two years. Over time, the exceedance probability of an event occurrence with similar or higher values compared to the chosen DD will increase. Progressing from date zero to maturity, the authors apply the following equation to estimate the option value (OV) at a given node k. OV is defined as the willingness to pay for keeping a public asset or service although the likelihood of actually using it might be low [59]. The time interval to calculate the probabilities is the PL period. The estimated probabilities multiply the benefits for various options obtained in Step 4. Equation (6) calculates the cash flow for various investment timing options:

$$OV_k = \sum_{j=1}^{j=m} R_k\left(B_{jk} - I_j\right). \tag{6}$$

4.6. *Step 6: Complete Sensitivity Analysis and Decision-Making Process*

Finally, a sensitivity analysis allows decision makers to determine the impact of various inputs and assumptions on the results [73] so that they can minimize the chance of biased analysis. In this study, a sensitivity analysis was performed to analyze the effects of uncertainty with regards to three variables: interest rate, time of occurrence for an exceeding discharge compared to DD in the historical records prior to date zero, and level of confidence (c) associated with the return period

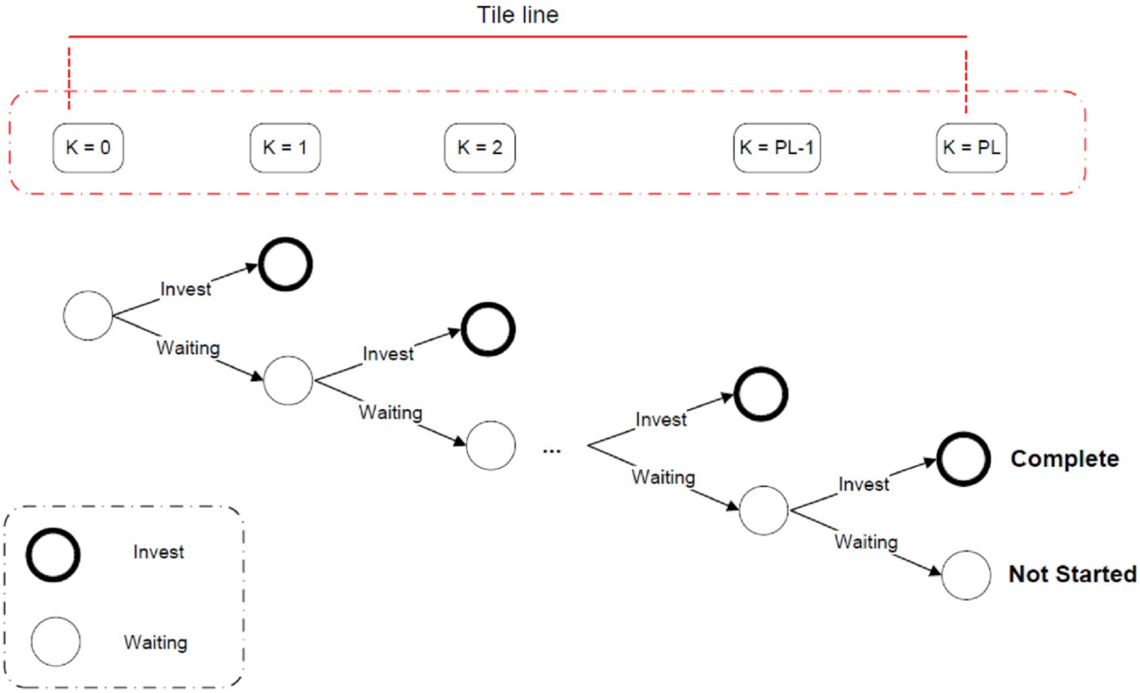


Fig. 2. Decision tree with wait and invest options (one period).

for DD. By determining the significance of performance risks inherent in investments, the sensitivity analysis findings can support decision makers in making better-informed decisions.

4.7. Illustrative example

This section presents a hypothetical illustrative example that was used to demonstrate the application of the proposed EIFU framework to the financial valuation of delaying investments in a flood protection project. This example was specifically selected because it is readily applicable to flood simulations. Data were taken from the Hec-GeoRas example data to develop a hydraulic model for the Baxter River [53]. Some additional spatial information is adapted from GIS data for the City of Modesto in California, United States (Google [60]). The later is only used to illustrate the hypothetical location of the inundated field areas and inundated building areas in the floodplain (Fig. 3).

Following Step 1, the authors set the project lifespan (PL) of the EIFU analysis as 10 years and define it as the reliability duration for the project and the infrastructure to be protected. The authors assume the level of confidence that this example will not exceed a structure's design capacity within the 10-year period to be 50% ($c = 0.50$). The authors apply Equation (1) to estimate the return period and as per the result, set it to 15 years. This means that a 15-year event will not exceed the structure's design capacity during 10-years with a 50% confidence level (e.g. a probability of 50%.)

In Step 2, using information derived from GIS data, the authors conduct hydraulic simulations to create an inundation map. DD is assumed at 4,389 m^3/s (155,000 CFS) corresponding to the 15-year return period. According to the contour lines in Fig. 3, this discharge produces an inundation height of 5.2 m (17 feet). This height causes 0.557 km^2 of inundation in the populated area. It should be mentioned that the HEC-GeoRAS model [53] was used as it offers capabilities to handle complex topographic information like the cases in this study.

As part of Step 3, the authors estimate a correlation curve between the damage costs per unit of area and inundation height. Using flood-related damage costs reported on the FEMA webpage, the authors estimate the damage cost for the do-nothing option to be 51,818,905 USD (Table 2). As explained, this value corresponds to the scenario with no intervention. The damage-loss could be more explicit and include land use zoning, which is actually allowed by the model. However, in this

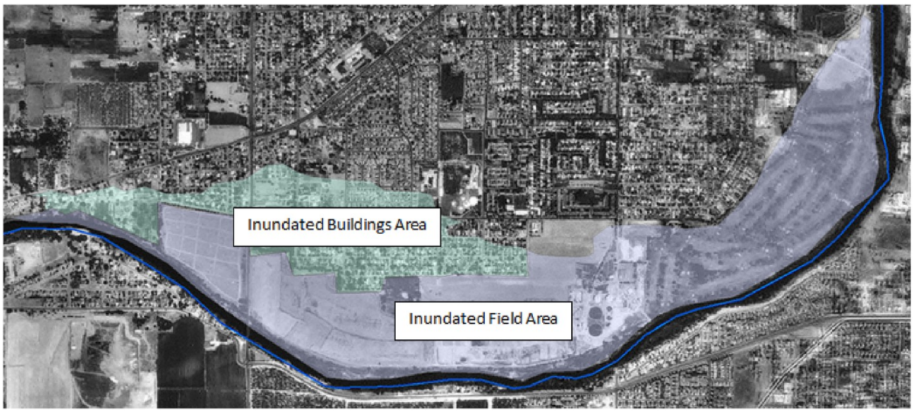


Fig. 3. Simulated Inundated Area near Baxter River (background images are from Hec-GeoRas and Google Earth).

Table 2
Damage cost calculation.

1	2	3	4	5	6
Ground Elevation (m)	Height of Flood (m)	Flooded Area	Built Area	Built Flooded Area (m^2)	Damage Cost
16.2	5.18	–	10%	–	–
16.8	4.57	2%	20%	2,229	$1,624,277
18.3	3.05	13%	25%	18,114	$11,279,329
19.8	1.52	35%	30%	58,521	$27,861,229
21.3	0.03	50%	35%	97,536	$11,055,070
Total		100%			$51,819,905

Table 3
Example of evaluation of investments in flood protection under uncertainty.

Flooding Year	Cost EV	Risk	Benefits NPV	Cost + Benefits	Option Value
Year 1	−6,798.22	0.292893219	51,819.90	45,021.68	13,186.55
Year 2	−7,022.56	0.340246045	52,107.72	45,085.16	15,340.05
Year 3	−7,254.31	0.384427793	53,743.92	46,489.62	17,871.90
Year 4	−7,493.70	0.425650823	52,192.57	44,698.88	19,026.11
Year 5	−7,740.99	0.464113269	50,690.78	42,949.79	19,933.57
Year 6	−7,996.44	0.500000000	49,236.97	41,240.53	20,620.26
Year 7	−8,260.33	0.533483504	47,829.60	39,569.27	21,109.55
Year 8	−8,532.92	0.564724718	46,467.19	37,934.27	21,422.42
Year 9	−8,814.50	0.593873802	45,148.30	36,333.80	21,577.69
Year 10	−9,105.38	0.621070858	43,871.54	34,766.16	21,592.25

hypothetical example, all of the analyses were based on damage-loss data on built areas driven from the FEMA website [57] without land use zoning.

Next, the authors run a hydraulic simulation to determine the height at different stations of the flood protection structure. The findings will help reduce potential damages caused by a T-year DD to zero. Fig. 4 presents the plan for 22 stations obtained with the HEC-GeoRAS model and its corresponding longitudinal station heights for the retaining walls.

As part of Step 4, the authors calculate the costs and benefits for various investment timing options for flood protection. More specifically, costs are the investments undertaken to implement the project designed for a specific DD and benefits are the total damage costs avoided owing to the project. Using data on building construction costs [61], the authors estimate 6,798,221 USD as the cost of investment for the safest flood protection option, that is, a retaining wall with a total length of 4,030 m. The design accounts for different heights of concrete retaining walls. Fig. 5 depicts the cost per unit length for different wall heights.

For this example, the authors set the discount and interest rate to 3.3% to represent the average value of the annual consumer price index in the United States from 1914 to 2012 [62]. The authors select 10 depreciation values, where the first factor is 3.75% and the subsequent values are 10% for a PL of 10 years [42].

As per Step 5, the authors estimate option values by calculating the risk of exceedance probabilities of future DD using Equation (5). A cash flow analysis was performed concerning the different options available to an owner to exercise the right to invest in each year of the 10-year period. The authors assume that an event with discharge similar to DD was determined on date zero and applying Equation (6), option values were calculated in each node k from date zero to maturity. Fig. 6 depicts the outcomes for the option value of delaying investment at each node. In Fig. 6, the horizontal axis corresponds to investment year and the option values normalized by investment on date zero (OV_k/I_0) appear on the vertical axis. Assuming that no infrastructure or source of benefit will be added or moved outside of the protected zone, S_k takes the value of zero.

The results reveal that EIFU produces a concave curve, indicating the presence of a long run optimum option for investment timing. As shown in Fig. 6, the normalized option value for successive investment options reports steep growth during the initial years. Thereafter, the authors see a smooth gradient zone that infers a low increase in the option value. In other words, exercising during a period of steep growth is an option. In this example, for the investment option to reach almost 80% of the normalized net option value ($NNOV = OV_{10}/I_0 - OV_1/I_0$), the option for investment timing must be the sixth year.

Finally, in Step 6, a series of sensitivity analyses were performed to determine the impact of various parameters on investment payoffs. Applying the same decision tree for exceedance probabilities of DD determined in year zero, Fig. 7 illustrates the impact of annual volatility in the interest rate on normalized option values under four scenarios.

Fig. 7 indicates that for a higher discount rate, shorter delays help achieve a higher percentage for the corresponding option value function. In sum, delaying in the case of low discount rates produces higher benefits.

To visualize the impact of various exceedance probabilities of DD on option values, the authors conducted another sensitivity analysis with an interest and discount rate of 3.3%. Fig. 8 summarizes the sensitivity analysis results for different dates when DD was determinedprior to date zero and was not exceeded yet. First, concave curves are found for the normalized option values and steep growth is observed in the normalized option value of successive investment options during the initial years. Second, the farther away the date for DD, the higher the immediate option values. Compared with immediate investment benefit, delaying an investment marginally increases the option's value.

In addition, the authors analyzed the impact of various levels of confidence associated with the return period for DD. A sensitivity analysis (Fig. 9) was performed to examine the impact on normalized option values under three scenarios using the same decision tree as that of the exceedance probabilities for DD recorded at year zero. As shown in Fig. 9, delaying an investment marginally with a lower level of confidence increases the value of the option.

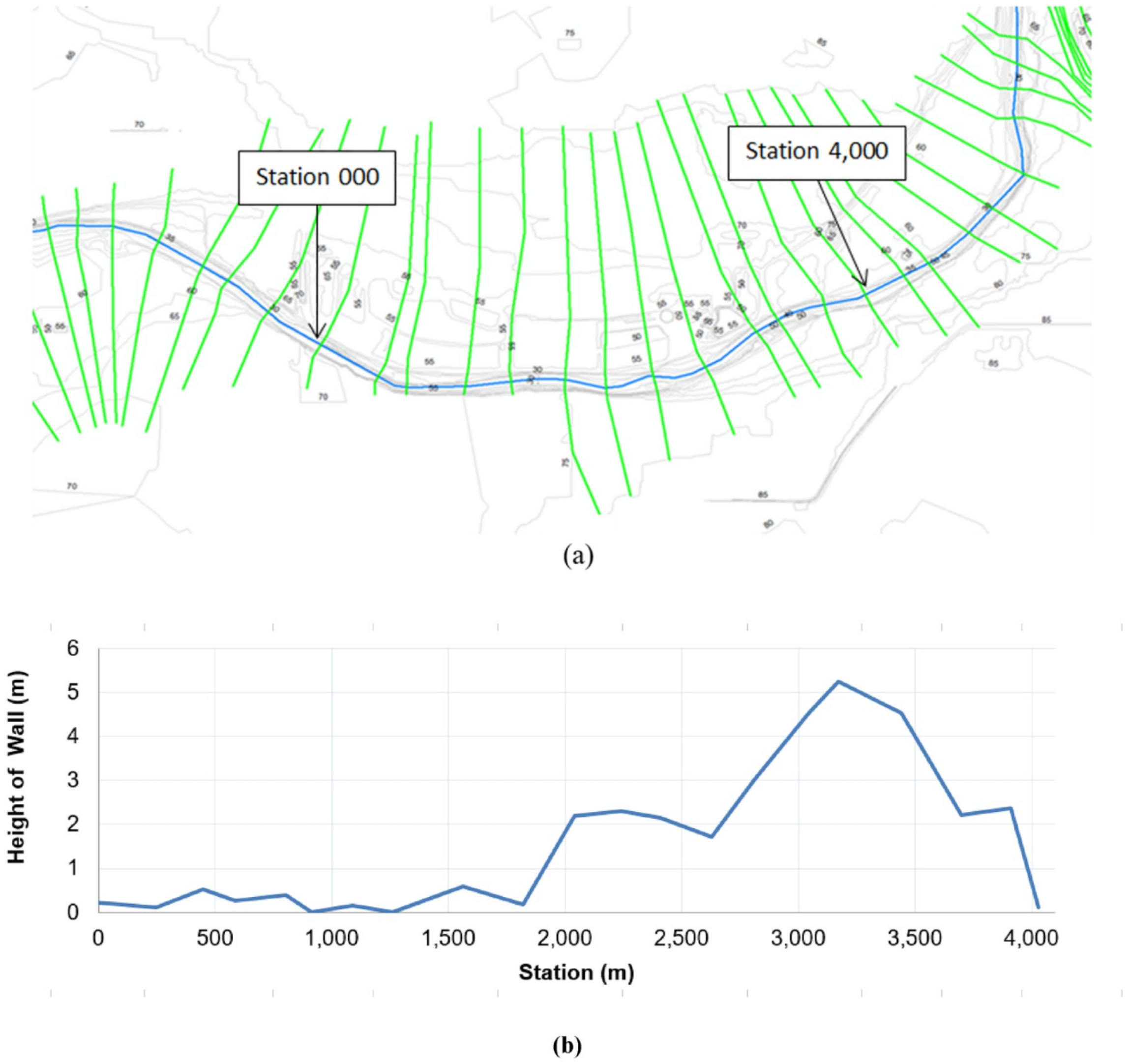
Finally, the authors explored the impact of different levels of confidence associated with the DD return period for different dates prior to date zero assuming an interest and discount rate of 3.3%. Fig. 10 presents the results of the sensitivity analysis. Similar to the previous sensitivity analysis, delaying an investment with a lower level of confidence increases the value of the option. In both Figs. 9 and 10, the higher the confidence level associated with the DD return period, the lower the option values. In other words, safer choices lead to lower option values.

For example, Table 3 summarizes the investment option and their costs to clarify the application and virtuosities of the proposed tool (Flow of the Flood DD = 4,389 m^3/s (155000 CSF), Interest Rate = 3.3%, Discount Rate = 3.3%, year when DD was defined = −5, Damage = $ 51,819.90).

5. Conclusions and future study

The past several decades have highlighted the lack of proper valuations for flood protection investments. Thus, this study proposes a real-options-based framework—evaluation of investments in flood protection under uncertainty (EIFU)—which combines the exceedance probabilities for Design Discharge (DD) and the benefits and costs of various investment timing options. EIFU can assist project owners and stakeholders in making decisions regarding flood protection investments. As a complementary decision tool, EIFU is designed to help determine an optimal timing of investment options on flood protection structures. The suggested framework takes the historical information on river discharges as the main input and provides the optimal timing, with an associated confidence level to overcome a specific event, as the main output.

This study presents the primary analytical EIFU framework using an illustrative hypothetical example of flood protection investment for a



(a)

(b)

Fig. 4. Suggested retaining walls: (a) plan view and (b) height profile.

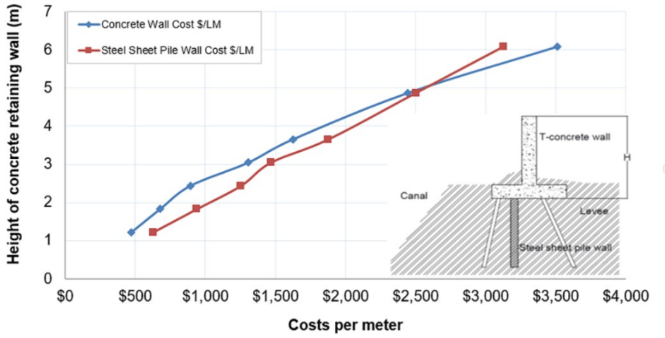


Fig. 5. Cost per unit length for different wall heights.

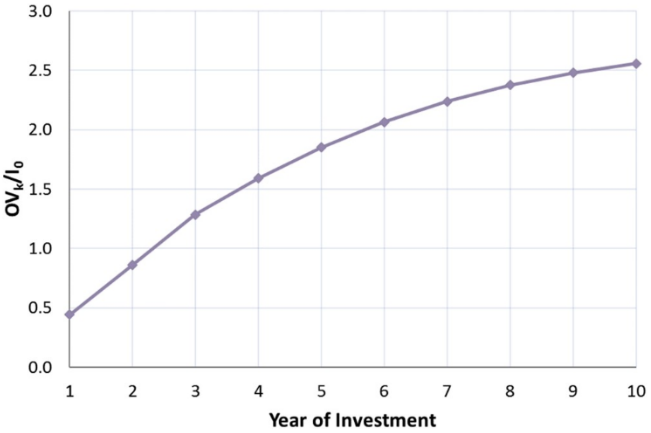


Fig. 6. Normalized option value for various investment timings (interest and discount rate = 3.3%; 15-year DD; confidence level associated with return period for DD, $c = 50\%$).

populated area. The results reveal that EIFU can be used to evaluate the financial impact of performance risks on NPV calculations and RO investment payoffs and, accordingly, to determine the best time to invest under pre-defined scenarios. As input variables, the study adopts historical records of water discharge including DD for a given return period, PL period, unit damage costs, interest rates, and depreciation rate. The authors use historical information on water discharges as random variables to account for a past occurrence of exceedance discharges to the DD value. The authors then use this occurrence to calculate the probability of future occurrences. On the basis of the derived probabilities and cost–benefit payoff, the value of various

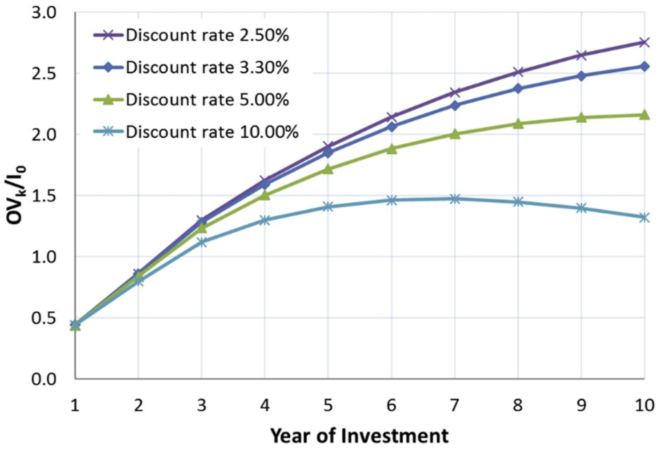


Fig. 7. Impact of annual volatility in discount rate on normalized option values (15-year DD; confidence level associated with return period of DD, $c = 50\%$).

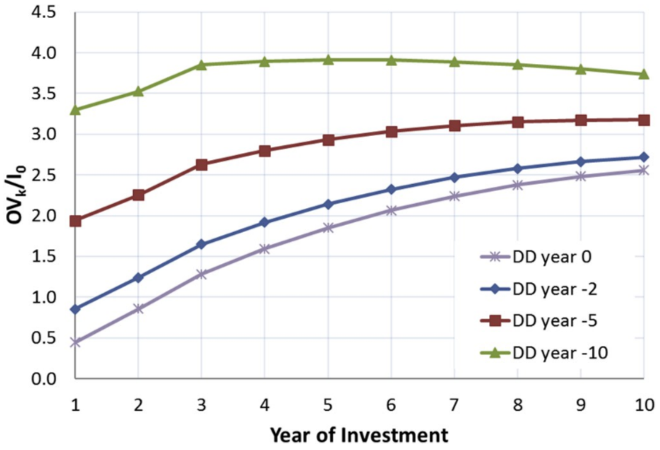


Fig. 8. Sensitivity to different dates when DD was determined prior to year zero (interest and discount rate = 3.3; confidence level associated with DD return period, $c = 50\%$).

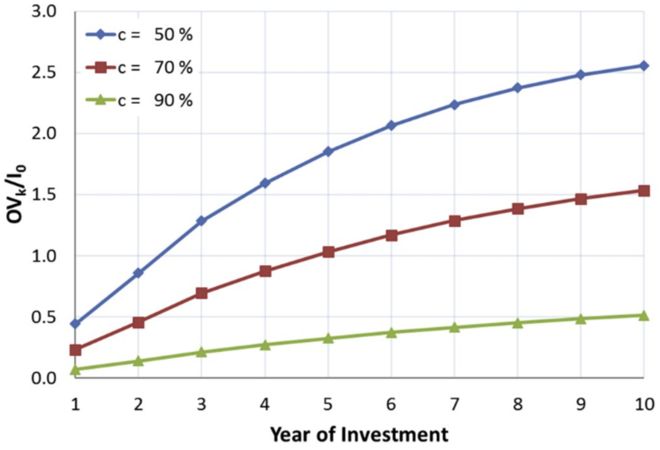


Fig. 9. Analysis of different confidence level, c, associated with DD return period to determine its impact on normalized option values (interest and discount rate = 3.3).

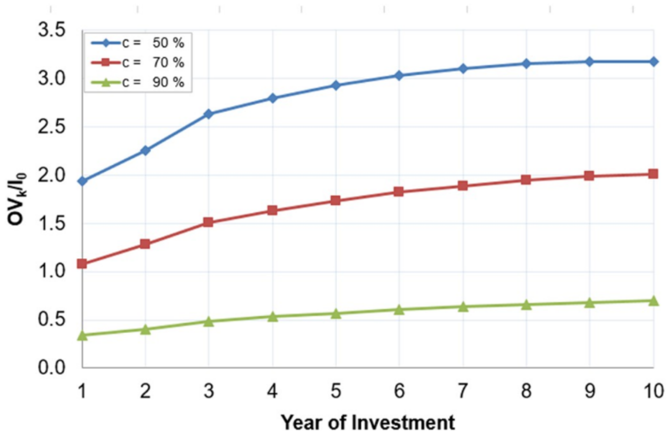


Fig. 10. Analysis of different confidence levels, c, associated with DD return period defined five years prior to date zero (DD year = −5) to determine its impact on normalized option values (interest and discount rate = 3.3).

investment timing options were calculated.

The three key findings from the 10-year project life analysis are summarized as follows. First, using EIFU produces a concave curve for an option value function (Fig. 7- delaying in the case of low discount rates produces higher benefits). Second, retrospectively, the framework presents a concave curve for different water discharge records (Figs. 9 and 10- safer choices produce lower option values). Finally, compared to traditional NPV, RO theory allows for more practical valuations in the case of flood protection projects. By accounting for managerial flexibility, the proposed EIFU and its findings can guide project owners and associated stakeholders in making critical project decisions about flood protection investments. In addition, EIFU helps project owners make better-informed project decisions by evaluating potential risks, barriers, and returns, thus offering them management knowledge about performance risks under various input scenarios.

The analysis demonstrates the feasibility of identifying an optimal investment timing option that produces maximum net benefits, which can be found on a concave curve. As discussed thus far, the authors observed a steep growth pattern for the net benefit value of successive investment options during the initial years. Thereafter, the authors find a smooth gradient zone with a low increase in the net benefit, highlighting an investment option in which it is possible to achieve a certain percentage of optimum net benefit. The sensitivity analysis shows that safer options result in lower option values because the higher the level of confidence associated with the DD return period, the lower the option value.

The authors acknowledge the limitations of demonstrating the application of EIFU to a hypothetical case study, including the need to make a series of assumptions. Nevertheless, the authors believe that the sensitivity analyses contribute to minimizing the subjectivity of these assumptions. Future work can apply EIFU using field data for flood protection projects. Moreover, uncertainty analyses with multiple variables could offer additional findings.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101377.

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