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The Economics of Investment in Flood Risk Reduction in Developing Countries: An Application to the Rocha River Basin of Bolivia

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Abstract

Existing and projected economic losses caused by floods all over the world have generated a growing consensus about the need for investment in flood risk mitigation. Most of the evidence on the returns to risk reduction is based on cost-benefit analysis performed for specific measures, lacking a comprehensive appraisal of alternatives. This paper presents an integrated approach to consistently prioritize potential flood mitigation measures in a river basin and determine the economically desirable investment level in flood risk reduction. An optimization model is developed to select the type, size and schedule of flood risk mitigation measures over a planning horizon. The model is formulated as a dynamic mixed integer linear program and applied to a river basin where severe floods have occurred historically. A variety of individual and combinations of risk reduction measures are used as inputs for the model. Initial analysis is conducted for different scenarios of flood damage growth, investment financing constraints, and decision-makers' preferences towards extreme and future losses. Results show that investment in flood risk reduction is economically justified in the basin. Investment is greater for higher rates of damage growth and aversion to extreme flood losses. Financing constraints only affect the rate of implementation of risk reduction measures in the initial periods. The proposed integrated approach can inform the design of investment plans for flood risk reduction based on sound economic principles, providing valuable support to decision-makers.

Keywords: decision support-systems, economics, flood risk management, investment analysis, optimization model, Bolivia

JEL codes : C61, Q54, Q25, O21

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1. Introduction

The economic losses caused by floods have been studied and quantified in the past decades in detail (Cavallo and Noy, 2011; Kousky, 2014). Floods are the costliest of natural disasters[3] (Miller et al. 2008), and their cost is expected to increase due to the negative impacts of climate change and increasing socioeconomic exposure (Milly et al. 2002; Hall et al. 2003; Hoeppe, 2016). Furthermore, flood frequency has been projected to increase (Hirabayashi et al., 2013; Ward et al., 2013). While evidence exists on the returns to flood risk reduction measures[4] (World Bank, 2010; Hawley et al., 2012, Mechler, 2016; Kousky and Shabman, 2017), comprehensive economic appraisals of investment strategies are limited. Most of the economic analysis of investments has focused on evaluating the economic desirability of specific measures (Krull et al., 2013; Michel-Kerjan et al., 2013; Aerts et al., 2014; Garcia-Alonso et al, 2016; Haer et al., 2017). These studies analyze investments based on the costs and benefits of alternative designs of measures such as dikes or embankments. While providing valuable insights, further analysis is needed to provide a consistent and systematic economic analysis of investment in flood risk reduction at the floodplain level. From a planners' perspective, the appropriate mix and size of measures and the timing to implement them must be analyzed considering a reasonable range of alternative measures and their interactions with one another.

A wide range of decision frameworks has been used in the analysis and formulation of investment strategies for flood risk reduction. Thampapillai and Musgrave (1985) provide a comprehensive review of previous work on the analysis of structural and non-structural measures, the criteria used to determine optimal investment strategies, and the pros and cons of different optimization methods. A considerable part of the approaches has focused in finding the economically efficient combination of flood risk reduction measures that minimize the expected value of flood losses[5] and investment costs. Earlier optimization approaches have used enumeration (James, 1967; Ford and Otto, 1989), classical optimization (Van Dantzig, 1956), linear programming (Weisz and Day, 1977), dynamic programming (Morin et al. 1989, Olsen et al. 2000), and two-stage linear programming (Lund, 2002). More recently, studies have used genetic algorithms (Karamouz et al., 2008; Yazdi et al., 2013 and 2016; Woodward et al., 2014) and integer programming methods (Zwaneveld et al., 2018).

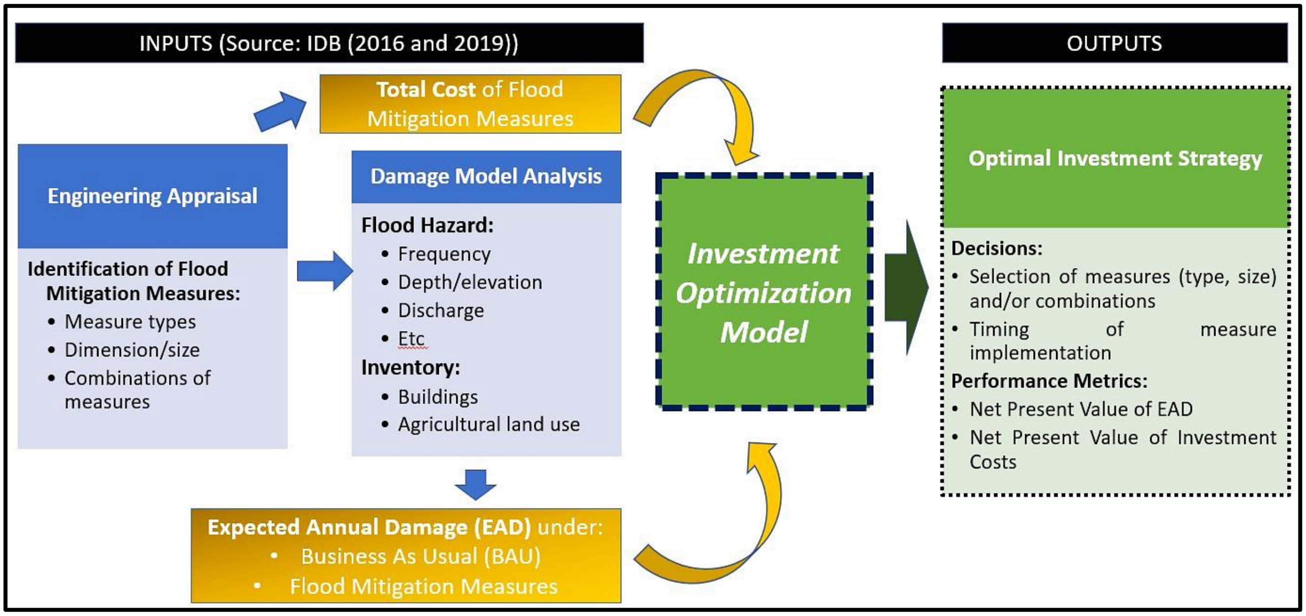
Different aspects of flood mitigation investments have been analyzed as methods and policy needs evolved over time. Studies have advanced from using a specific flood return period to adopting probabilistic approaches for the analysis of flood mitigation investments. Investment analysis has also varied in the treatment of alternatives and possible combinations of mitigation measures. A variety of structural and non-structural measures has been analyzed both jointly and separately (Thampapillai and Musgrave, 1985; Lund, 2002). Static analysis has been

[3] The cost of floods includes both riverine and coastal floods.
[4] Flood risk reduction and flood mitigation are used interchangeably in this paper.
[5] Flood losses and flood damages are used interchangeably in this paper.

complemented with dynamic analysis, where investment timing is considered in relation to changes in economic and hydrologic conditions over time (Olsen et al., 2000; Zhu et al., 2007; Zwaneveld et al., 2018). Studies have also analyzed the optimal location of investments within a floodplain, together with the possible feedback effects between spatially connected areas (Karamouz et al., 2008; Yazdi et al., 2013). Finally, researchers have suggested the need to consider the cost of risk taking into investment decisions (Lind, 1967). To analyze this issue, the variability of flood losses has been considered in addition to the standard expected value approach towards losses (Willis and Aklilu, 1973; Kaul and Willis, 1975). More recently, the catastrophic risk literature has explored the issue of risk taking when considering financial protection measures (Ermoliev et al., 2000; Compton et al., 2013).

The present study constitutes a novel application of an optimization model for investment analysis in flood risk reduction in a developing country. The proposed framework goes beyond traditional cost benefit analysis of specific measures and provides a decision support tool to evaluate possible investment strategies, using different criteria for optimality and feasibility consistently and efficiently. Figure 1 presents a summary schematic of the approach and the data inputs for analysis. An optimization model identifies the optimal investment strategy which is based on the selection of the type of measure to use, the possible combinations of measures, and the timing for implementation. The model relies on the external evaluation of flood mitigation measures identified by experts. While a damage model is used to estimate the expected benefits of the measures, local engineering knowledge is used to estimate the costs and determine additional technical, social and environmental constraints for implementation. The remainder of this paper is structured as follows. Section 2 presents the characteristics of the area subjected to flood risk, the flood mitigation measures identified by the experts, the simulations used to estimate the expected benefits of measures, and the estimated costs for the measures. Section 3 describes the model formulation, its objective function and associated constraints. Section 4 discusses the results obtained with the proposed methodological approach under different scenarios and model specifications. Finally, section 5 presents the conclusions and implications for policy-makers.

Figure 1 Schematic of Investment Analysis Framework for Flood Risk Reduction



2. Case study: the Rio Rocha River Basin

2.1. Flooding in the Rocha River Basin

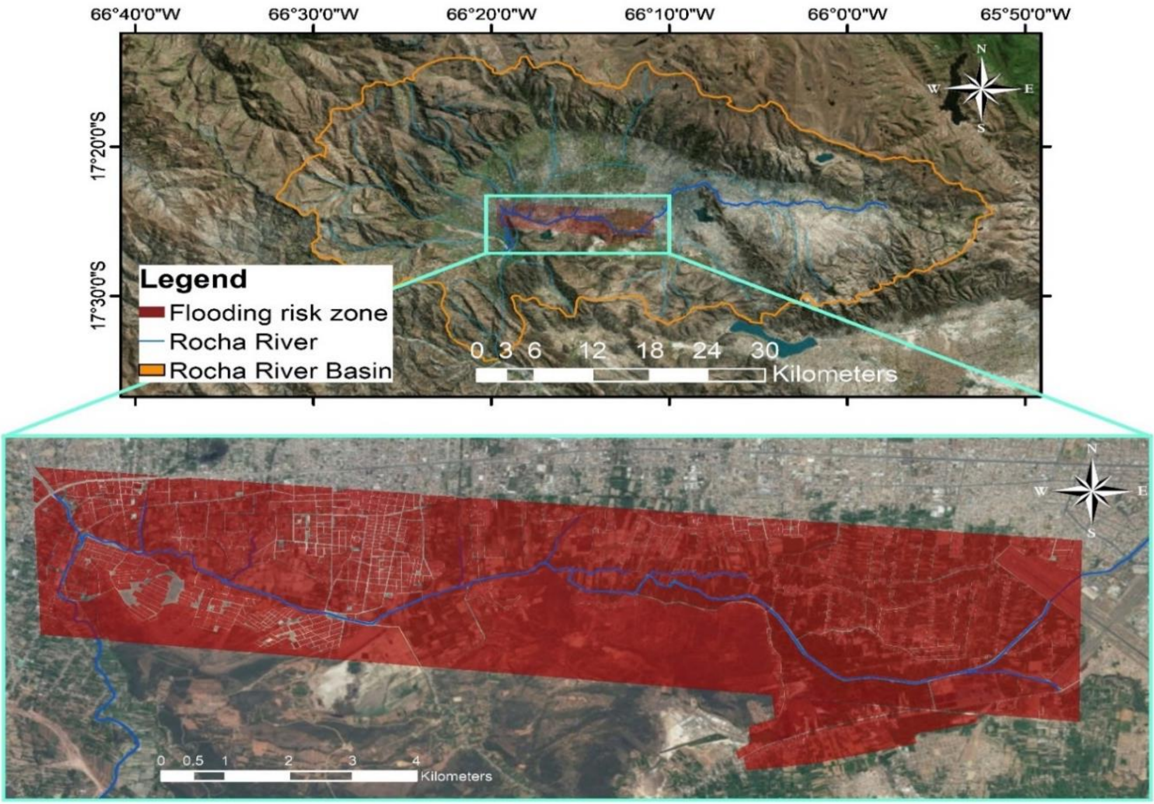
The Rocha River basin, located in Bolivia, is used as a case study for the flood mitigation investment framework. This watershed drains a total area of approximately 1,616 km^2 with an elevation that ranges from 2,400 to 2,600 m above mean sea level. The study area includes 75 km^2 of potentially inundated area with approximately 71,000 inhabitants. The basin is home to Cochabamba, the fourth largest city in Bolivia, with almost one million inhabitants. The lack of appropriate flow regulation and river channeling has resulted in frequent overflows and flooding in the lower part of the basin. Figure 2 illustrates the location of the study area and the zone susceptible to inundations. Flooding events occur frequently in this area during the rainy season, which normally goes from December to February.

Infrastructure exposure in the potential inundation area has increased over the years as new housing and industrial constructions have occupied terrain near the main river-flow channel. Regional GDP has grown for an average of 4.5% per year in the last decade[6], and uncontrolled urban sprawl has increased population density from 65 to 98 inhabitants per hectare[7] in the last two decades. Agricultural production has also expanded in areas subjected to flood hazards. Historically, several

[6] Based on Instituto Nacional de Estadística (INE), 2019.
[7] Based on projections contained in “Plan Director de la Cuenca del Rio Rocha – 2014”

flooding events[8] have affected buildings, agricultural crops and industries in that area. IDB (2016) estimated the maximum probable economic losses of US$ 657 thousands for a 1-in-2 year flood, US$ 1 million for a 1-in-10 year flood, US$ 6.7 million for a 1-in-a-50 year flood, US$ 12.8 million for a 1-in-100 year flood, and US$ 71 million for a 1-in-1000-year flood[9]. This event would affect more than 50,000 inhabitants, 3,700 buildings and 774 hectares of cultivated agricultural land.

Figure 2 Rocha River Basin and area subject to flood risks[10]



Source: IDB (2016)

2.2 Estimation of Flood Risks

The estimation of existing flood risks was conducted as part of a previous study by IDB (2017), using a probabilistic inundation hazard assessment for the study area. First, a set of stochastic rainfall scenarios were generated based on historical information. The scenarios generated represent historical variability historical variability and were used as input for hydrologic simulations in a rainfall-runoff model the Hydrologic Engineer Center - Hydrologic Modeling

[8] Heavy rain episodes have been particularly exacerbated during La Niña period of 2011-2012.

[9] The estimated maximum probable losses are associated with 0.08, 0.13, 0.87, 1.65, and 6.9 percent of total exposed value.

[10] The delineation of the flood risk zone is based on a comparison between simulated floods (using HEC-RAS) and observed floods for the years 2011-2012, when significant flooding occured. Further details can be found in IDB (2016).

System (HEC-HMS) version 3.5[11]. Hydrologic results were incorporated into a hydrodynamic model, Hydrologic Engineer Center - River Analysis System (HEC-RAS)[12], previously calibrated with historic inundation events in the Rocha River Basin. The simulated rainfall scenarios and corresponding inundation flood maps were used to derive probabilistic flood hazard maps of maximum inundation depths for different return periods.

Second, an exposure model was built in the study area comprising a total of 16 different building construction typologies[13] and different types of agricultural land use amounting to 2,200 hectares. The total values at risk for all the building types[14] and agricultural land[15] were estimated using secondary data available from a variety of sources[16]. Subsequently, vulnerability functions[17] for each type of building and agricultural land are used to estimate expected damages to each of the exposed components with respect to different inundation depths.

Next, damages were calculated for each stochastic rainfall scenario using the CAPRA platform for probabilistic risk assessment (CAPRA, 2018). Figure 3 provides an example of the geographic distribution of expected flood losses for a rainfall scenario associated with a 100-year return period. Finally, simulated damages for 1,800 stochastic rainfall scenarios were used to derive an exceedance-probability loss curve, which was used to calculate expected annual damages[18] (EAD, or 'flood risk'). The flood risk estimates mostly pertain to buildings and agricultural use and amounts to 679 US$ thousand per year. Other damage categories, such as indirect economic damages (e.g., business interruption), and direct damage to other assets (such as infrastructure) have been introduced by scaling up the risk simulations. The scaling factor for indirect damages has been estimated at 40% of total direct damage based on IDB (2016). This factor has been applied to the risk estimates, assuming a constant ratio between damage and risk. The rescaled flood risk amounts to 950 US$ thousand per year.

[11] https://www.hec.usace.army.mil/software/hec-hms/

[12] https://www.hec.usace.army.mil/software/hec-ras/

[13] A geodatabase was constructed using aerial photography, satellite images and field inspection visits. The main building construction characteristics included were constructed area, number of stories (that range from 1 to 5) and main construction material (masonry, wood, adobe and cement).

[14] Total values at risk for the buildings have been estimated per building type, using the average square feet per building type, and the mean cost per square foot

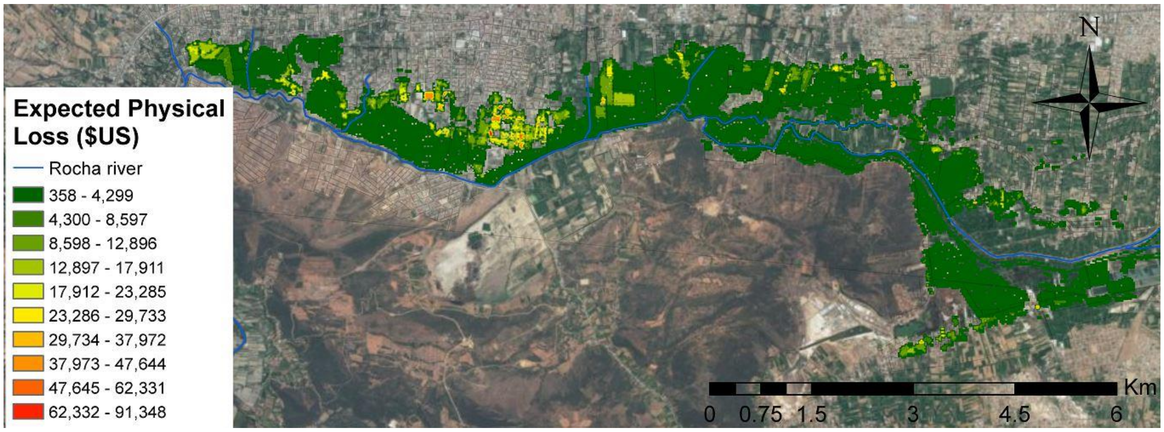
[15] The main types of agricultural land are used to cultivate soy and maize crops, as well as mixed crop systems. There are also two main cropping seasons.

[16] IDB (2016) contains a more comprehensive description of data sources and estimations.

[17] Vulnerability functions and flood damage functions are used inter-changeably in the document. A total of 9 vulnerability functions were used for buildings and 6 for agricultural crops.

[18] Following standard practice such as Beard (1997) and USACE (1996), EAD is calculated by plotting damages on the exceedance-probability loss curve and integrating the area below. EAD is also referred to as annual average losses in the disaster risk management literature.

Figure 3 Estimated flood risk for a 100-year return period event in the area of interest in the Rocha Basin.



Source: IDB (2016)

2.3 Estimation of costs and benefits of flood risk mitigation options

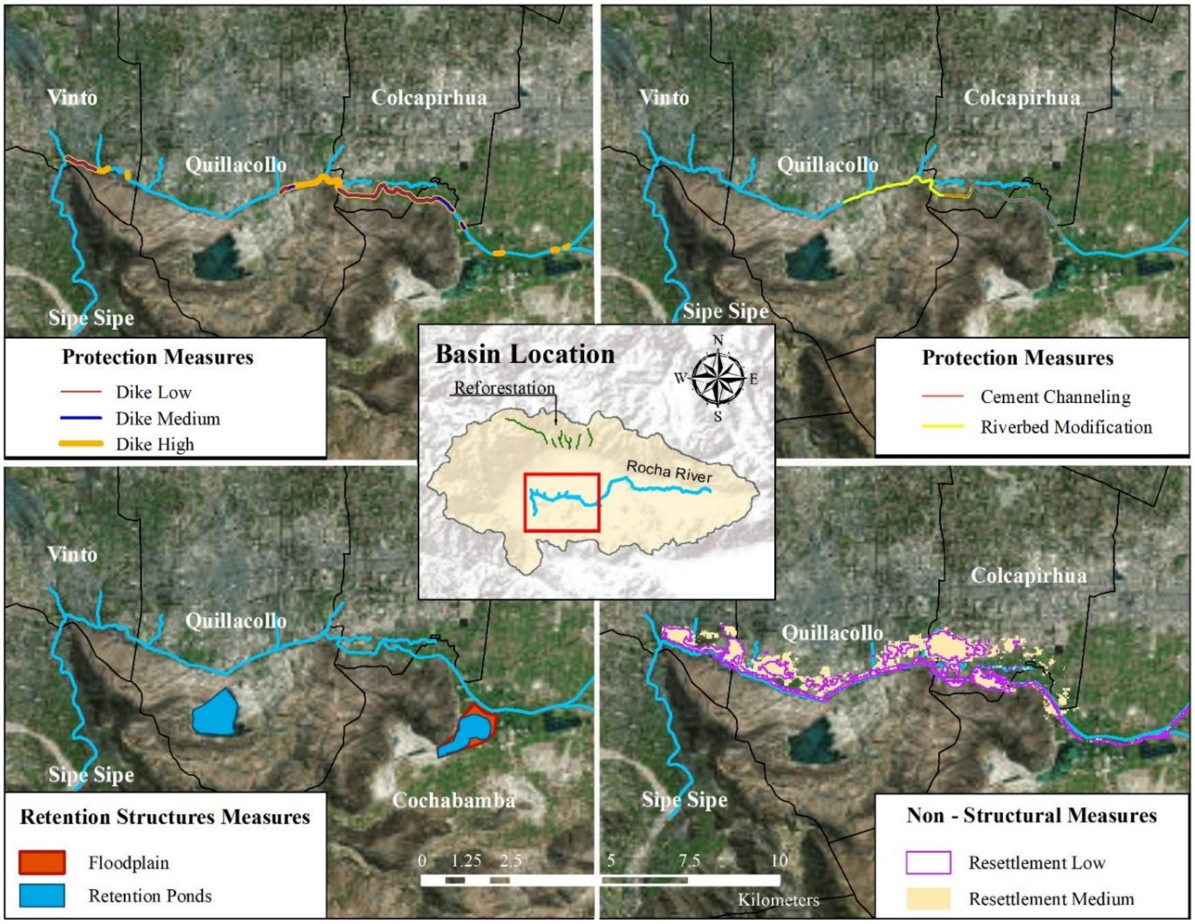
IDB (2019) contains detailed information on data and methods used in the identification and estimation of benefits and costs of mitigation options. This section presents a summary of the approach, the main insights from the results, and the main data to be used as input in the investment model.

Engineering analysis was conducted in the study area to identify a range of flood risk reduction options. Table 1 presents a summary of the main features of the measures, and figure 4 presents the location of the measures in the watershed. The identified options comprise mainly structural measures. Measures such as floodplain storage, retention ponds and reforestation aim at decreasing peak flows. Other measures such as riverbed modifications, cement channeling and dikes decrease peak stages for given flows. Finally, resettlement is also analyzed as a non-structural measure aimed at decreasing the susceptibility to flood damage. For measures such as dikes and resettlement, different levels of intervention were analyzed. These measures were labeled, for simplicity purposes, as low, medium and high. The benefits and costs of resettlement measures are presented in this section; however, these measures are not considered in the investment optimization analysis as they were not politically feasible.

Table 1 Summary of the main features for the identified mitigation measures.

Measure Name	**Summary of the main features**
Floodplain	Construction of a flood plain storage in the left riverbank connected to the Rocha River through floodgates. Total area of 108 hectares.
Retention ponds	Construction of two retention ponds in different areas of the watershed connected to the Rocha river through floodgates. Total area of 75 and 109 hectares, respectively.
Dike (low)	Construction of dike structures along a flood section of the river covering a total length of 4.35 km, with an average height of 5.14 meters.
Dike (medium)	Construction of dike structures along a flood section of the river covering a total length of 5.1 km, with an average height of 5.12 meters.
Dike (high)	Construction of dike structures along a flood section of the river covering a total length of 7.72km, with an average height of 5.14 meters.
Riverbed modification	Dredging of the riverbed along 4.1 km of flood section to decrease the slope and reduce flood impacts in the downstream areas.
Cement channeling	Application of cement to build a channel of 4.3 km in the Rocha river's flood section and homogenization of the slope to avoid backwaters in the section.
Reforestation	Reforestation of 665 hectares in the upstream areas of the watershed to control the flow in the main tributaries of the Rocha river.
Resettlement (low)	Resettlement of the population and economic activities corresponding to 194 buildings and an area of 197 hectares of agricultural land.
Resettlement (medium)	Resettlement of the population and economic activities corresponding to 552 buildings and an area of 365 hectares of agricultural land.

Figure 4 Types and location of the main flood mitigation measures



Economic benefits were estimated for the identified mitigation options as follows. For each option, the associated flood risk, measured as expected annual damage, was estimated using the framework presented in section 2.2. The estimated flood risk for each option is compared to the existing flood risk, or "business as usual" (BAU) scenario. Using these estimates, benefits associated with mitigation options are calculated as the reduction in flood risk with respect to the BAU scenario. It should be noted that the analysis does not account for possible loss of lives nor injuries. As such, our benefit calculation (avoided damage) represents a lower bound value. Including avoided value of statistical life (VoL) and health care spending would increase the benefit of the proposed measures.

The estimation of costs for each measure was based on engineering calculations. These consider indicative regional unit costs and material quantities estimation, based on preliminary structural drawings or standard replacement values for the local conditions at year 2017. Both investment and maintenance costs were considered in the calculation. Table 2 presents a summary of the benefits and costs of the main individual mitigation options.

Table 2 Summary of benefits and costs of main mitigation measures.

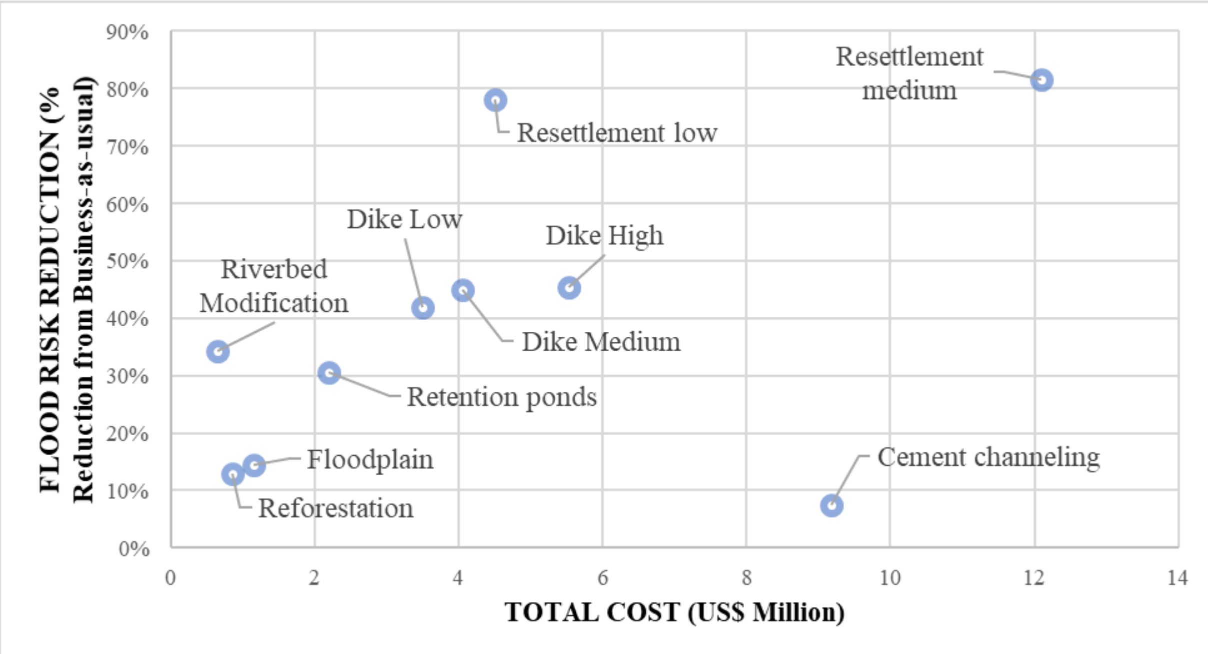
Measure Group	Measure Name	Expected Annual Damage (US$ 000)	Total Investment Costs (US$ 000)	Expected Annual Benefits* (US$ 000)
Structural	Floodplain storage	580.4	1,157.1	98.9
	Retention ponds	471.5	2,189.6	207.8
	Dike (low)	394.2	3,501.3	285.2
	Dike (medium)	373.9	4,047.4	305.5
	Dike (high)	370.6	5,538.8	308.7
	Riverbed modification	445.8	655.8	233.5
	Cement channeling	628.9	9,174.7	50.4
	Reforestation	591.4	864.5	87.9
Non-structural	Resettlement (low)	149.7	4,500.1	529.6
	Resettlement (medium)	125.9	12,092.6	553.4

* Calculated as the difference with respect to EAD in the BAU scenario (US$ 679 thousand)

Figure 5 plots the estimated benefits and costs for each of the measures. The y-axis represents the benefits, measured as percentage reduction of expected annual damage with respect to the business as usual scenario. The x-axis represents total costs, which can also be thought of as investment level. Several insights arise from careful examination of the figure. Fist, as expected, there is a positive relationship among the investment level and degree of flood risk reduction[19]. Resettlement is the most effective measure, although one of the costliest and politically difficult to implement. Both for resettlement and dike measures, the increases in investment costs clearly outweigh the increases in benefits when moving from a lower to a higher intervention level. Floodplain storage and reforestation measures provide partial risk reduction at a lower cost.

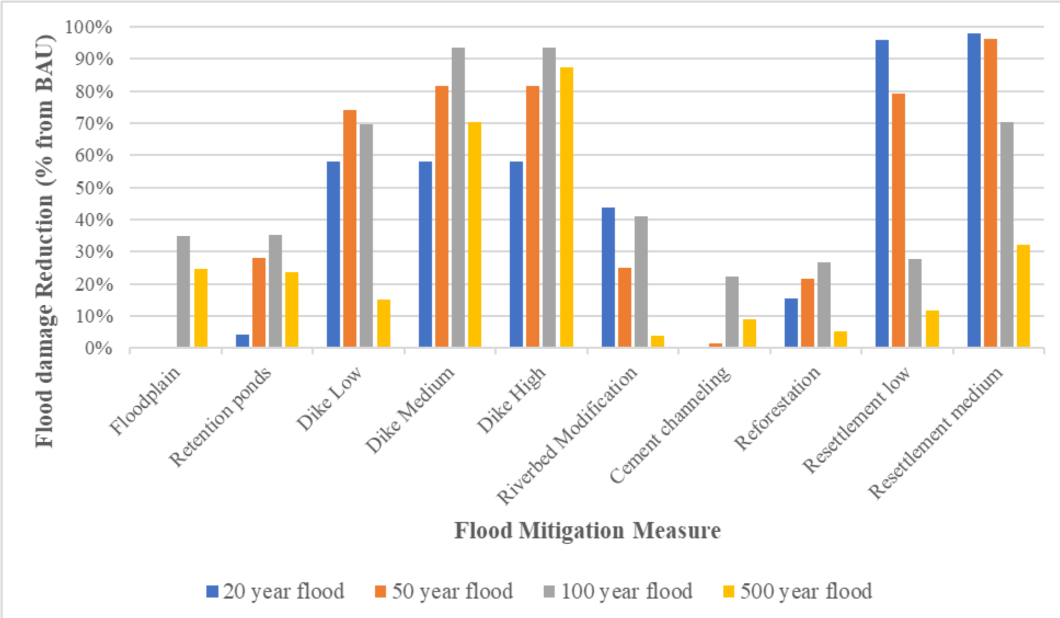
[19] The only outlier is cement channeling, which is too expensive for the benefit associated, although it may bring other relevant environmental benefits not quantified in the study.

Figure 5 Flood risk reduction and costs of selected measures



The methodological approach used for the estimation of benefits allows to further understand the performance of each mitigation option for floods of different magnitude. Figure 6 presents the damage reduction of each measure with respect to floods of different return periods (20, 50, 100 and 500 years). Protection measures such as dikes are the most effective in reducing damage for extreme floods (500-year), whereas alternative measures such as resettlements perform best for more frequent and less damaging floods. Measures like floodplain, retention ponds, reforestation and riverbed modification are partially effective in reducing damages across different types of floods, but less so for 500-year floods.

Figure 6 Risk reduction effectiveness by return period for individual mitigation measures

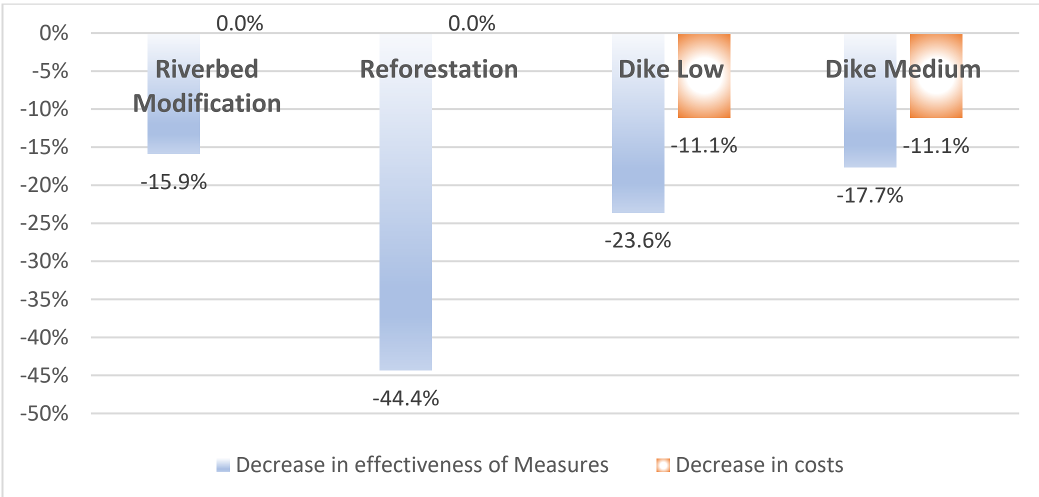


Finally, the modelling framework is used to analyze the costs and benefits of combining individual mitigation measures. Possible combinations are determined according to technical feasibility, based on engineering knowledge and judgement about the characteristics of the study area. This analysis represents a major contribution to the literature since most of the previous work does not consider the combined effects of more than one measure at a time. The logic behind this analysis is to estimate the possible decreasing returns[20] to damage mitigation, and economies of scale[21] when more than one measure is implemented in the watershed. More than 20 combinations of measures were analyzed, constituting new possibilities of investment strategies[22]. All estimations for the possible combinations are incorporated into the investment model. Figure 7 presents results from this analysis conducted for a specific case. Effectiveness, defined as the percentage decrease of expected annual damages with respect to business as usual, and total costs are compared for all the mitigation measures that can be combined with the construction of a floodplain storage. Results suggest that that floodplain storage reduces the effectiveness of dikes by 23% and 17% (for low and medium level of intervention, respectively) as extreme water levels are reduced in the main river channel. Cost savings can also be achieved when implementing both measures together (11%) as part of the materials and machinery can be reused from the construction of one measure to the other. In the case of riverbed modification and reforestation, no cost savings are realized

[20] Decreasing returns implies that risk reduction of combined measures is lower than total risk reduction of the individual measures when considered independently.
[21] Economies of scale implies that the cost of implementing combined measures is lower than the total cost of implementing individual measures independently.
[22] The existing measures together with their possible combinations allow us to characterize an investment function for flood risk reduction based on engineering analysis.

when implemented together with floodplain. However, effectiveness in risk reduction is reduced by 16% and 44% respectively.

Figure 7 Effects of combining floodplain storage with other risk reduction measures



3. Model Formulation

In this section, we define the structure of the investment model that will be used to determine the optimal combination of flood mitigation measures in a planning horizon. Decisions are based on a cost-benefit analysis, where the objective is to minimize total discounted costs, consisting of the costs of implementing flood mitigation measures and expected flood losses, subject to a budget constraint. The basic decisions to determine are which type of measure, what size or upgrade, what combination of measures, and when measures should be implemented. Two main tradeoffs exist in the investment decisions. The first one revolves around choosing between greater investment in flood mitigation measures, i.e. greater investment costs, or withstanding greater expected flood losses. The second one has to do with investing earlier in flood risk reduction or accepting expected flood losses for a longer time.

While several studies have suggested the nonlinearity of costs and expected annual damage reduction with respect to investment choices (Zwaneveld et al., 2018), our approach addresses this issue through the discretization of investment options. Options are characterized by two different types of flood mitigation measures, measures of one specific size, and measures that can be implemented in different sizes. The model uses two different sets to define each of the measures. Specific-size measures are part of set *I*, which, in the case study, contains five measures (retention ponds, channel improvement, natural flood storage, riverbed modification, and reforestation). Scalable measures in the model represent dikes. These can be built in three different sizes which are represented in the set *K (low, medium, high)*. Resettlement measures are withdrawn from the investment space given that they are not politically feasible to implement in this case. The flood

return periods used in the calculation of damages can be discretized in the set *J*, which represent (5, 20, 50, 100 and 500-year return period). To complete the definition of the model's discretization, time periods in the planning horizon are represented by the set *T* and defined in terms of years.

The model is formulated with enough flexibility to incorporate additional input parameters such as types and sizes of flood mitigation measures, with the corresponding costs and expected damage losses. The decision variables of the model are:

- *X(t, i)* which is a binary decision variable on the implementation of each of the five measures *(i)* at any specific time period *(t)*. Once a measure is implemented in any period, it will stay active until the end of the planning horizon. It can also be the case that more than one measure is implemented throughout the planning period.

- *L(t, k)* is a binary decision variable on the implementation of a dike of specific size *(k)* at any specific time period *(t)*. Only one level of protection can be implemented in a given time period; however, this variable incorporates the possibility to upgrade the dikes from low to medium to high level of protection.

The input parameters and main functions used in the model specification are as follows:

- *cX(t, i)* represents the investment and maintenance cost of each of the five flood mitigation measures.

- $cL(t, k_1, k_2)$ represents the investment and maintenance cost of implementing dikes. The structure of this cost function incorporates the possible paths for implementation of dikes. For instance, the cost of building a dike of a specific type will be discounted in the cases where it actually represents an upgrade ($k_2>k_1$) from an existing dike size.

- $\omega\ (t, X_i, L_k)$ is a cost adjustment parameter for cases when the implementation of more than one measure results in cost-savings due to economies of scale, it is based on engineering estimates.

- p_j is the probability of flood losses for return period *j*.

- Dam_{BAUj} is the flood loss for a return period *j*, when no measure is implemented

- $Dam\ (t, j, X_i, L_k)$ is the flood loss function for a return period *j*, in time period *t*, given the implementation of flood mitigation measures (*i* and *k* possibilities). This function accounts for the possibility of implementing more than one measure. When a combination of measures is implemented, non-additive flood damage reduction is contemplated to reflect decreasing returns to investment, these adjustments are based on flood damage simulations.

- *r* is the rate used to discount the flood losses and cost streams of different time periods

- B_t is the available budget for investment in time period *t*

All costs and damage parameters are calculated in net present value of a certain year, no inflation is considered in the model. It is assumed that the decision to implement any measure implies incurring a cost in year t, while flood damage reduction occurs in year $t+1$. The proposed optimization model is formulated as follows:

$$min \sum_{t \in T} (1+r)^{-t} \left[C_t(X_{it}, L_{kt}) + \left(D_t(X_{it}, L_{kt}) \right) \right] \tag{1}$$

Subject to:

$$C_t(X_{it}, L_{kt}) = \left(\sum_i cX_{it} * X_{it} + \sum_k cL_{kt} * L_{kt} \right) * \omega_t(X_{it}, L_{kt}) \tag{2}$$

$$D_t(X_{it}, L_{kt}) = \sum_j p_j * \left(\sum_i \sum_k Dam_{BAUj} - Dam_{jt}(X_{it}, L_{kt}) \right) \tag{3}$$

$$C_t(X_{it}, L_{kt}) \leq B_t \quad \forall t \tag{4}$$

$$B_t - C_t(X_{it}, L_{kt}) = B_{t+1} \tag{5}$$

$$\sum_k L_{k,t} \leq 1 \quad \forall t \tag{6}$$

$$X_{i,t} \in \{0,1\} \quad \forall t \, \forall i \tag{7}$$

$$L_{k,t} \in \{0,1\} \quad \forall t \, \forall k \tag{8}$$

The objective function in equation 1 minimizes the net present value (first term) of total cost (first term in brackets) and the total expected flood damage reduction (second term in brackets) over a planning period of *T* years. Equations 2 and 3 contain the cost and flood damage reduction functions resulting from the decisions of implementing flood mitigation options. Note that in the case that no measure is implemented, the cost function will be equal to 0 and the damage reduction function will be equal to the expected flood damage that currently occurs in the floodplain. Equation 4 is the budget constraint which ensures that, in any period *t*, investment is less than or equal to the available budget. Equation 5 determines the budget accumulation dynamics between time periods. Equation 6 constrains the implementation of one type of dike at any given period. Equations 7 and 8 are the decision variables to implement the available flood mitigation measures. Additional constraints are added to perform bookkeeping of the measures implemented through the planning period. The constraints on the possible combinations of measures are also added to reflect the existing physical characteristics of the basin.

An alternative formulation of the damage function will be used to explore the possibility of growing flood damages over time. Flood damages can grow due to several reasons such as economic development in the floodplain, population growth, or increased flooding probability due to climate change. Equation 3 is therefore modified to incorporate a growth trend. Equation 9 is the modified version. It contains the parameter ψ, which is the yearly percentage increase in damages. While, this is the simplest possible specification, it will allow to analyze how optimal investment decisions vary to accommodate alternative damage growth scenarios.

$$D_t(X_{it}, L_{kt}) = (1+\psi)^t * \sum_j p_j * \left(\sum_i \sum_k Dam_{BAUj} - Dam_{jt}(X_{it}, L_{kt}) \right) \quad (9)$$

Lastly, an alternative specification of the objective function is developed to explore the implications of accounting for the cost of risk taking. The original specification uses an average value of flood damages, without considering the dispersion of possible flood damages. A decision maker may, hence, be concerned with reducing damages from extreme floods as well as average damage. We modify the objective function (equation 1) through the reformulation of the damage reduction function. As equation 10 shows, average damage reduction is now pooled with damage reduction for a 500-year return period flood using weights (α). This specification will allow us to analyze how optimal investment decisions vary when more importance is given to mitigating the impacts from large flood damage events, i.e., larger α.

$$min \sum_{t \in T} (1+r)^{-t} \left[C_t(X_{it}, L_{kt}) + \left((1-\alpha) * D_t(X_{it}, L_{kt}) + (\alpha) * D_{t:j=500}(X_{it}, L_{kt}) \right) \right] \quad (10)$$

$$0 \leq \alpha \leq 1 \quad (11)$$

4. Optimization Model Analyses and Results

The optimization model presented in Section 3 is used to obtain optimal investment strategies for flood risk reduction. The model is formulated as a dynamic mixed integer-linear program (MILP) and has 1,729 single variables, of which 1,590 are discrete variables. This model is implemented in GAMS software version 24.9 and uses CPLEX 12.7 to solve the models through a branch and cut procedure.

Data on costs[23] and benefits for each measure and combination of measures represent the main input[24] for the model. For the optimization exercise, the resettlement measures are withdrawn from the investment space given that they are not politically feasible to implement in this case. Additional parameters are defined to establish a base case scenario. The planning horizon of the analysis is 30 years, and time period length used is one year. The discount rate used is 5 percent

[23] Maintenance costs are set at 5% of investment costs.
[24] See section 2.3 for further information.

and annual budget availability is set at US$ 1 million[25]. Finally, expected annual flood damages under a business as usual scenario amount to US$ 679 thousand. Using these data, the optimization model presented in equations 1 through 9 is used to determine how investment in risk reduction varies with flood damages in the planning period. Additional analysis is performed to understand how budget availability and the discount rate affect optimal investment. Finally, a new model specification is used to understand how optimal investment varies when more importance is given to damages from extreme floods.

4.1 Investment strategy and flood damages

We investigate how the investment strategy for risk reduction varies depending on flood damages. The approach used compares a baseline scenario, where annual expected flood damages are stationary, to scenarios of increasing damages over time. Damages can increase due to climate change, population growth or socioeconomic development. No attempt is made at predicting the contribution of each driver to the growth in damages, but rather analyze the implications of increasing flood risk. Table 3 summarizes the results of the optimization analysis for the baseline case, i.e. no growth in damages, and three scenarios corresponding to 5, 10 and 15 percent annual growth in expected damages.

The economically justified investment in flood risk reduction depends, to a large extent, on the amount of total expected flood damages and the potential damage reduction that can be achieved. Optimal investment increases less than proportionally to the rate of growth in damages. A 0, 5, 10, 15 percent growth in damages is associated with a 1, 3, 7 and 7.5 million USD investment level respectively. A similar result applies to the percentage damage reduction over BAU[26] where 26, 33, 44 and 47 percent reductions were calculated respectively.

The types and sequencing of measures implemented under an optimal investment strategy differ considerably by growth scenario. In the baseline case, it is economically optimal to implement the riverbed modification measure as soon as possible, i.e. in the first year. This result is also consistent with the fact that the measure has the highest benefit-cost ratio of all individual measures. Under a 5 percent damage growth scenario, additional measures become justified economically. Retention ponds are built in year 13 in addition to the modification of the riverbed. Finally, the optimal combination and sequencing of measures varies under a 10 and 15 percent damage growth scenarios. Investment strategies include the implementation of smaller size dikes early in the planning horizon. Dikes are upgraded into medium size and retention ponds are constructed further along the planning period. The timing for the implementation of these additional measures is directly related to the magnitude of damage growth. A 15 percent damage growth scenario implies

[25] The choice of parameters is overall indicative, some of the assumptions are aligned to existing data. The real interest rate in Bolivia was 4.8% in 2018 (World Bank, 2018). The annual available budget was chosen to be close total annual expected direct and indirect damages of US$ 0.950 million.

[26] The NPV of flood damages under the business as usual case corresponds to US$ 16.27 million.

that the upgrade of dikes and construction of ponds becomes economically optimal four years earlier than under a 10 percent growth scenario.

Table 3 Optimal investment, total damage, damage reduction, and measures implemented for alternative damage growth scenarios

Annual Damage Growth	**NPV Investment (US$ million)**	**NPV Expected Annual Flood Damages (US$ million)**	**% Damage Reduction over BAU (NPV)**	**Measures Implemented (timing)**
0 percent (baseline)	1.15	12.01	26.2%	Riverbed modification (year 1)
5 percent	3.06	20.02	33.8%	Riverbed modification (year 1) Retention ponds (year 13)
10 percent	7.00	35.75	44.4%	Dike low (year 4) Upgrade to dike medium (year 14) Retention ponds (year 14)
15 percent	7.53	80.00	47.2%	Dike low (year 4) Upgrade to dike medium (year 10) Retention ponds (year 10)

Figures 8 presents the annual undiscounted investment and maintenance costs across the planning horizon of optimal investment strategies for each damage growth scenario. The major costs of the strategies pertain to the investment costs, which occur when mitigation measures are constructed. The remaining costs are attributable to maintenance costs of the implemented measures. Figure 9 presents the undiscounted expected annual flood damages associated with the optimal investment strategies for each damage growth scenario. For illustration purposes, the figure shows only the first half of the planning horizon. As can be seen, the timing for the reduction in expected annual damages corresponds to the timing on the implementation of the flood mitigation measures.

Figure 8 Annual Costs of investment strategies by damage growth scenario

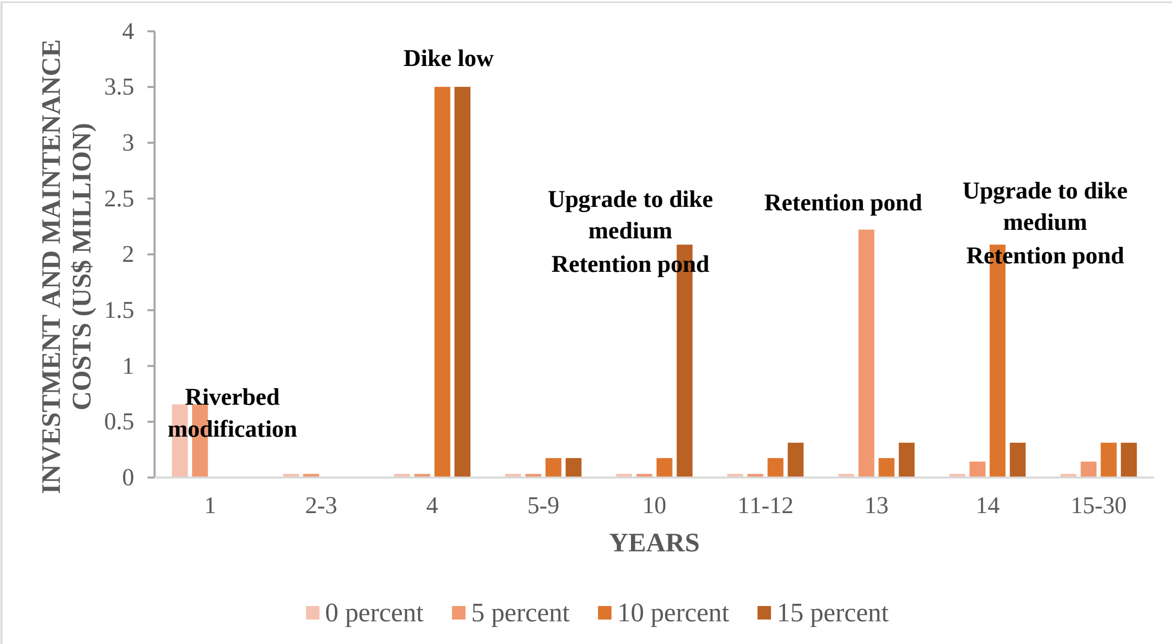
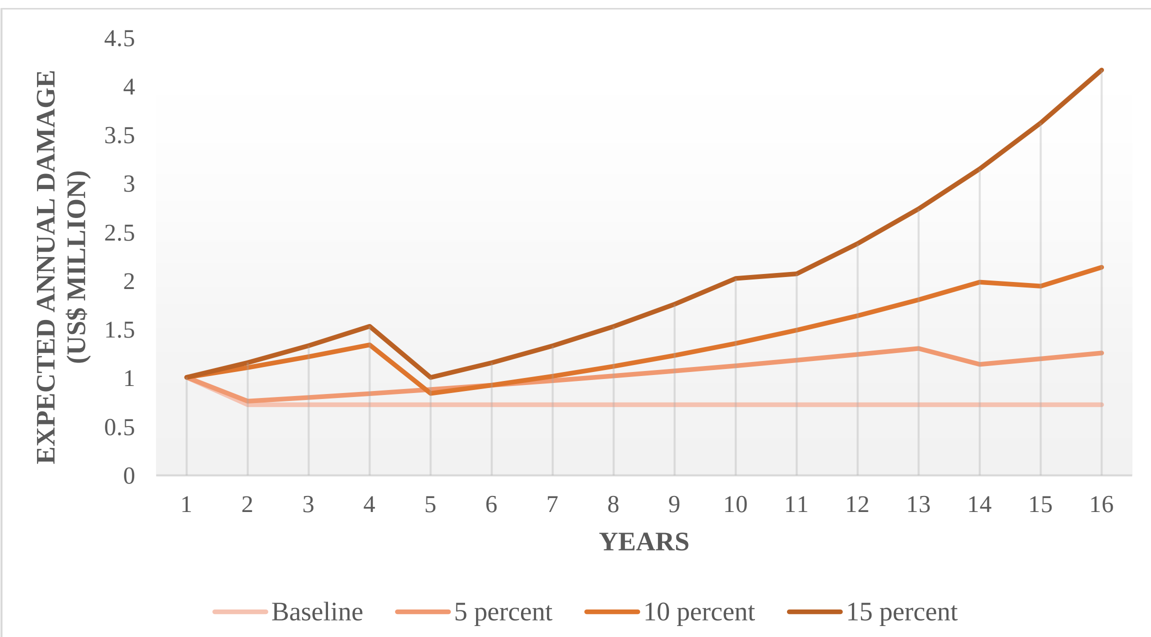


Figure 9 Optimal Expected Annual Damage by damage growth scenario, years 1 to 16



4.2 Discount Rate, budget availability and investment decisions

Additional analysis is conducted to understand how the investment strategy for risk reduction varies depending on the choice of discount rate and the availability of budget. A baseline scenario of 15 percent damage growth, 5 percent discount rate, and 1 million USD of annual budget availability is compared to alternative values of the aforementioned parameters.

Table 4 shows how investment strategies differ depending on the discount rates. Optimal investment in flood risk reduction is inversely related to discount rates. A higher discount rate results in lower investment in flood mitigation. The types and sequencing of measures are also affected. On one hand, investments are postponed when higher discount rates are adopted. A careful examination of the optimal investment strategy associated with 0, 5 and 10 percent discount rates reveals that the decision to upgrade the dike and build retention ponds is postponed from year 6 to years 10 and 13 respectively. On another hand, very large discount rates such as 20 percent, result in the implementation of lower cost mitigation measures such as the modification of the riverbed. These results stem from the fact that larger discount rates reduce the importance of future expected flood damages when evaluated in present value. As a consequence, the optimal strategy implies lower investment, and the implementation of less costly measures. Larger discount rates have therefore inter-generational implications as future generations will be subject to greater flood damages.

Table 4 Optimal investment, total damage, damage reduction, and measures implemented for alternative discount rates

Discount rate	**NPV Investment (US$ million)**	**NPV Expected Annual Flood Damages (US$ million)**	**% Damage Reduction over BAU (NPV)**	**Measures Implemented (timing)**
5 percent (baseline)	7.53	80.00	47.2%	Dike low (year 4) Upgrade to dike medium (year 10) Retention ponds (year 10)
0 percent	13.25	225.42	48.6%	Dike low (year 4) Upgrade to dike medium (year 6) Retention ponds (year 6)
12 percent	4.22	25.91	43.1%	Dike low (year 4) Upgrade to dike medium (year 13) Retention ponds (year 13)
20 percent	1.26	11.85	32.1%	Riverbed modification (year 1) Retention ponds (year 11)

The optimization analysis is also conducted to understand how budget availability affects the optimal investment decision. Equation 4 of the optimization model establishes that annual budget

availability serves to ration projects that can be built in any given year. Equation 5 of the model further specifies that budget resources can be accumulated overtime to afford costlier projects. Table 5 shows the results for scenarios of 1 (baseline), 2 and 4 million USD of annual budget. Overall, the optimization model runs show that the budget constraint permits implementing all the projects over the 30-year planning period. However, tighter annual budget availability slows the rate of measure implementation in the initial periods[27]. As more budget is available in earlier years, the implementation of small dikes is undertaken earlier in the planning period.

Table 5 Optimal investment, total damage, damage reduction, and measures implemented for alternative budget availability

Annual Budget (US$)	**NPV Investment (US$ million)**	**NPV Expected Annual Flood Damages (US$ million)**	**% Damage Reduction over BAU (NPV)**	**Measures Implemented (timing)**
1 million (baseline)	7.53	80.00	47.2%	Dike low (year 4) Upgrade to dike medium (year 10) Retention ponds (year 10)
2 million	8.15	78.92	47.9%	Dike low (year 2) Upgrade to dike medium (year 10) Retention ponds (year 10)
4 million	8.48	78.44	48.2%	Dike low (year 1) Upgrade to dike medium (year 10) Retention Ponds (year 10)

4.3 Investment and extreme floods.

Finally, we analyze optimal investment strategies for the mitigation of both average and extreme flood damages. The optimization model presented in section 3 was run replacing equation 1 with equations 10. This model specification explores how optimal investment varies depending on the importance assigned to reducing damages from extreme floods that have a 500-year return period. This approach is equivalent to factoring-in preferences towards risk. The importance of extreme flood damages in the optimization model is incorporated through a weight factor that ranges between 0 and 1. A weight factor of 0 means that standard model is run. Decision-making will focus on reducing average losses without regarding low probability extreme losses. A factor of 1 means that the model chooses investments to minimize the losses associated with the extreme floods only. In this case, the decision maker would have low tolerance for flood risks and will try

[27] The assumption about the possibility of budget carryover implies that the budget will allow the implementation of more expensive measures in later periods.

to minimize losses in a worst-case scenario, i.e., the 500-year return period flood. Any value in between is a combination of both.

Table 6 presents the optimization results for different values of the weight factor. The analysis uses a baseline of no damage growth, 5 percent discount rate, 1 US$ million annual budget availability, and a weight factor of 0. Results show that optimal investment in flood risk reduction increases as greater importance is given to extreme floods. Investment increases from 1.15 to 3 and 8.17 US$ million for weight factors of 0, 0.5 and 1, respectively. While investment in flood mitigation increases and results in both lower average and extreme flood damages, damage reduction is significantly different for each type of damage. This result suggests possible tradeoffs between reducing expected annual flood damages and extreme flood damages. Finally, the types of measures are different depending on the importance of reducing extreme damages. As these become more important in the optimization model, dike construction is preferred over riverbed modifications.

Table 6 Summary of results for alternative weighting of extreme flood losses

Weight Factor for 500-year floods	**NPV Investment (US$ million)**	**NPV Expected Annual Flood Damages (US$ million)**	**NPV 500-year flood damages (US$ million)**	**Measures Implemented (timing)**
0 (baseline	1.15	11.9	28.5	Riverbed modification (year 1)
0.5	3.07	11.3	22.95	Riverbed modification (year 1) Floodplain (year 2)
1	8.17	10.21	22.17	Dike low (year 4) Upgrade to dike medium (year 6) Retention ponds (year 6)

5. Conclusions

Investment in flood risk reduction requires both a comprehensive appraisal of flood mitigation alternatives, and a consistent approach to determine the economically desirable mix of measures. Optimization methods can provide insights into investment planning for flood risk reduction. This paper presented an optimization model developed to select the type, size and schedule of flood risk mitigation measures over a planning horizon. The model is formulated as a dynamic mixed integer linear program and applied to a river basin where severe floods have occurred historically.

The application of the optimization model to the Rocha River basin in Bolivia demonstrates its potential as a decision support tool. A variety of individual risk reduction measures and their possible combinations are used as inputs for the model to determine the optimal investment level as well as the combination and sequencing of measures in the basin. Initial analysis is conducted

for different scenarios of flood damage growth, investment financing constraints, and decision-makers' preferences towards extreme and future losses. The major conclusions of the case study application can be summarized as follows. Investment in flood risk reduction is economically justified based on the flood damage characteristics of the basin. The optimal investment level and combination of measures depends, to a large extent, on the amount of total expected flood damages and the potential damage reduction that can be achieved by mitigation measures. Possible future damage growth makes the implementation of additional measures economically attractive. The timing for the implementation of these additional measures is positively related to the magnitude of damage growth. On another hand, optimal investment level is inversely related to the discount rate, and budget availability can slow the rate of measure implementation in the initial periods. Finally, optimal investment level is higher when both average and extreme flood damages are considered in the decision framework.

The proposed approach to analyze investment in flood risk reduction can be expanded in several ways. The deterministic and perfect foresight analysis approach can be modified to incorporate uncertainty about future conditions. Through this extension, the performance of investment plans can be assessed with respect to different scenarios, shedding light on the robustness of investments (Matrosov et al., 2013; Herman et al., 2014). On another hand, additional criteria beyond minimizing total expected costs can be included as part of the investment decision framework. For example, a multi-objective optimization framework can consider the loss of life in addition to total expected costs (Woodward et al., 2014). While these extensions can provide valuable information on additional performance criteria of an investment plan, the number and combinations of measures that can simultaneously be analyzed is limited due to computational constraints.

In conclusion, the purpose of the example application presented herein was not to obtain a definitive solution, i.e. a specific optimal investment strategy for flood risk reduction, but utilizing the available data to demonstrate the potential of a framework to inform comprehensive investment planning in a floodplain. The model relies on the external evaluation of flood mitigation measures, their benefits and costs. Given the low levels of discretization of the alternative measures, it will not guarantee a global optimum. However, the possibility of comparing optimal investment strategies under different objectives and conditions offers invaluable insights for decision makers. Additional technical, financial, social and environmental objectives and constraints can be incorporated as needed. As further work is conducted on the evaluation of alternatives for flood mitigation, improved assessments about investment strategies can be performed. Furthermore, the model can be applied to any floodplain with available information, constituting a practical decision support tool to inform investment planning for decision-makers.

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