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Decision trees in cost–benefit analysis for flood risk management plans

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ABSTRACT

According to the European Directive 2007/60/CE, flood risk evaluation should include a cost–benefit analysis (CBA) on a long-term time horizon to evaluate the impact of mitigation measures. The standard CBA assumes to know in advance the events observed in the time horizon and *a priori* compares all mitigation measures by an economic metric. No change is supposed to be made to these measures throughout the time horizon. This modus operandi is not appropriate in the domain of flood risk management because several conditions are uncertain when the CBA is made (e.g., urban policies). This article faces these challenges by the integration of cost–benefit analysis and decision trees, to prescribe mitigation measures under uncertainty on the budget for mitigation actions because their funding can be modified after the conclusion of the CBA. The former integration is discussed in the real case of the lowland valley of the Coghinas River (Sardinia, Italy), for which the classical CBA compared five mitigation measures of infrastructural works. The integration into the decision tree also allows to evaluating mitigation measures with changes in infrastructural works and a lamination action. The outcomes advise to decreasing the maximum storage level and increase the peak lamination.

Key words: cost–benefit analysis, decision analysis under uncertainty, decision trees, flood mitigation measures

HIGHLIGHTS

- It integrates decision tree into a cost-benefit analysis to prescribe optimal decisions for the planning of flood risk mitigation.
- It investigates the introduction of uncertainty on budget availability by the probability of funding each configuration in the time horizon.
- It defines optimal decisions under uncertainty and provides the authorities with strategic information about the flood mitigation measures to be implemented.

1. INTRODUCTION

Climate change and expansion in urbanization increase the occurrences of flood events in anthropized areas. These critical events result in damages affecting people's safety, civil infrastructures, industries, crops, and the urban environment. Their growing impact on human life motivates the need to set up adequate flood mitigation plans prescribing mitigation measures (actions or configurations).

The Organizations of European Community Countries recently stressed the need to improve Flood Risk Management Plans to assess land vulnerabilities, define mitigation infrastructures, and face the adverse consequences of floods (European Commission 2007). Emergency and risk management plans should be proactive measures required for preparation, mitigation, and possible reconstruction when natural disasters occur (Price & Vojinovic 2008; Poljanšek *et al.* 2017).

The European Commission Flood Directive 2007/60 requires a preliminary assessment of damages to estimate the impact of floods (Albano *et al.* 2017). It states that '*flood risk management plans have to take into account relevant aspects such as costs and benefits*' and recommends local authorities and policy-makers to decide upon the implementation of flood mitigation strategies by a cost–benefit analysis (CBA) (Bos & Zwaneveld 2017; Molinari *et al.* 2021). Hence, costs and benefits should be both evaluated. Costs are mostly due to the construction, operations, management, and replacement of the mitigation solutions. Benefits can be evaluated as a reduction of expected damages, which are avoided by the realization of specific scenario mitigation works (Ramirez *et al.* 1988; Gissing & Blong 2004; Jongman *et al.* 2012; Kind *et al.* 2017).

A correct CBA involves a deep knowledge of the rules in river systems management and flood flow estimation, which require a careful hydrological analysis (Sulis *et al.* 2020). This analysis could be based on a 'return time' T_r (i.e., the average time elapsed between two flood events reaching or overtaking the assessed flood value). However, when non-stationary effects are considered, one can refer to the probability of an event being exceeded in each year.

Furthermore, CBA compares the damages in the current configuration (i.e., ante-operam-scenario) and after the conclusion of works (i.e., post-operam-scenario) (Pistrika *et al.* 2014; Napolitano *et al.* 2022). In the comparison, the water flow depth and velocity in flooded areas are key data, which can be obtained from hydraulic simulation models of flood flows. The '*European JRC Flood Damages Functions*' in Huizinga (2007, Huizinga *et al.* 2017) can be applied to define the links among flood inundation features and potential losses in extreme flood scenarios and return a monetary estimation of damages from land uses and water depths (Dutta *et al.* 2003; Scawthorn *et al.* 2006; Frongia *et al.* 2015; Amadio *et al.* 2016; Martínez-Gomariz *et al.* 2020).

In the CBA, costs, damages, and expected benefits should be classified. Damages can be divided into two main categories: tangible (i.e., physical damages due to contact with water and loss of production and income) and intangible (i.e., loss of life and trauma). Both damages are direct or indirect (Jongman *et al.* 2012). In this study, direct tangible and indirect tangible damages are supposed to be monetary estimations of damages and benefits, which are evaluated as the reduction of damages owing to the realization of structural mitigation works or proactive management solutions (i.e., warning plans or reservoir operation rules to laminate flood peaks) (Meyer *et al.* 2012; Pesaro *et al.* 2018). All in all, the CBA is used by decision-makers to appraise the desirability of a given decision policy of mitigation measures, as well as the year in which benefits start overcoming costs by actualization procedures (Mechler *et al.* 2014).

However, a standard CBA concerns a long-term time horizon under a deterministic setting. This means that one assumes to know which uncertain data will be observed in the overall horizon, and *a priori* defines the possible mitigation measures with respect to these data. This modus operandi does not completely match the requirements of flood risk management plans because they must be made under uncertainty on both the climatic environment and financing availability and must be adapted in the case of unexpected data realizations.

This article investigates the possibility to face the former drawbacks by decision trees (DTs), which are logical and systematic ways to address decision problems with a single criterion under uncertainty (Bertsimas & Freund 2004). The criterion is the same economic metric adopted for the CBA (Shreve & Kelman 2014). The integration of a CBA into a DT results in the additional analysis of all configurations with changes among mitigation measures. These changes are made by decisions taken during the time horizon, whereas the classical CBA does not allow any change in the mitigation measures, which are *a priori* defined at the beginning of the same horizon. All in all, the integration between CBAs and DTs makes CBAs proactive and able to stand unexpected realizations of uncertain parameters.

This article is organized as follows. In Section 2, some essential recalls of CBA are given. In Section 3, a brief introduction to DTs is provided. In Section 4, we introduce the real case study of the Coghinas Basin in the Sardinia region (Italy). Different mitigation configurations are investigated to optimize the net benefit value in the case of uncertain funding.

2. THE COST–BENEFIT ANALYSIS

CBA is a systematic approach for estimating the strengths and weaknesses of several alternatives (Woodward *et al.* 2014; Sulis *et al.* 2020). It aims to select the best alternative for achieving benefits while preserving savings (Nas 1996). This approach is widely used in economics and engineering to compare different projects or investments (Loucks & Van Beek 2017). In CBA, benefits and costs should be expressed in monetary terms and adjusted according to the time value of money. In this article, the comparison is made in terms of the net present value (NPV), but one could also adopt different metrics, such as the internal rate of return, the benefit–cost ratio, and the payback period.

In CBA, all streams of benefits and costs over time must be expressed on a common basis in terms of their present values, regardless of whether they are incurred at different times. The present value (PV) of future costs or benefit values represents today's value of a future stream of payments. The PV can be computed as follows:

$$\mathrm{PV} = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} \tag{1}$$

where R_t represents the net cash inflow/outflows in period t; r is the discount rate; and T is the length of the planning horizon.

The PV in (1) allows to put all costs and benefits in a common temporal step, using time and money values (cost/benefit) occurrence estimations. The NPV of benefits can be computed by the difference between the future expected streams of awaited benefits (B) and costs (C) as follows:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{2}$$

In a CBA, the NPV should be maximized. Clearly, one is interested in the flood mitigation policy maximizing the NPV.

2.1. NPV assessment in flood risk management

To properly analyse a flood risk management problem, a fixed time horizon should be considered to make a correct and effective economic comparison between cost and benefit values.

Each infrastructure configuration can be considered as a flood mitigation solution (Haddad *et al.* 2015). These configurations have different costs and benefits per year, which can be set up by hydraulic simulation. The benefits of reservoir management are the reduction of the flood rate due to lamination and land flooding during the lifetime of the infrastructure. More formally, benefits are computed by the initial estimation of the expected annual value of flood damages and the evaluation of their reductions. The expected annual value of damages can be computed by Equation (3):

$$E(D) = \int_0^1 D_{T_r} d(P_{T_r}) \tag{3}$$

where D_{T_r} represents the economic evaluation of flood damages of an expected flood flow with return period T_r and occurrence probability $P_{T_r} = (1/T_r)$.

The effectiveness of each alternative can be evaluated by the comparison between the mean annual value of flood damages in the actual configuration without intervention (denoted by Configuration (*0*)) and the damages in the case of a specific *i*th configuration (denoted by Configuration (*i*)).

In Figure 1, these damage functions are drawn for different values of the occurrence probability (or the related return periods T_r), as discussed by Frongia *et al.* (2015, 2018). The area between Configuration (*0*) and Configuration (*i*) represents the expected decrease in flood damages after the realization of the *i*th Configuration. The left part of these functions considers very exceptional flood events when $T_r > 200$ years.

Expected benefits in each configuration can be evaluated by (4). It computes the annual expected benefit for the *i*th configuration (B_i) as the difference between the expected damages in Configuration (0) (denoted by $E(D)_0$) and the expected damages in the *i*th configuration of mitigation works (denoted by $E(D)_i$):

$$B_i = E(D)_0 - E(D)_i \tag{4}$$

Then, one can derive the benefit $B_{i,t}$ of configuration i at time t.

Costs must account for construction, operation, maintenance, and replacement. When an upstream reservoir is devoted both to flood lamination and water regulation for users, additional costs must be considered. They mainly depend on the reservoir's operation rules, indeed the additional storage capacity devoted generated by the lamination could decrease water demand fulfilment for the users in the case of drought.

In addition, it is of interest to include penalties for funded configurations, which are not made owing to unexpected changes in mitigation policies. It is worth noting that these penalties are not adopted in a standard CBA because they can be observed only after the beginning of the time horizon. However, they can be taken into account if a new mitigation configuration is selected. In the notation, a parameter $\delta_{i,t}$ is introduced: it takes value 1 if configuration i is selected at time t, 0 otherwise. In a standard CBA, $\delta_{i,t}$ takes value 1 for configuration i only if t is the first period of the time horizon, 0 otherwise. Moreover, the following notation is adopted for costs:

- $C_{c\,i,t_c}$ is the construction cost of configuration *i*th actualized at the building year t_c.
- $C_{\mathrm{OMR}\,i,t}$ are operation, maintenance, and replacement costs in configuration *i*th at year t.
- $\mathrm{def}_{i,u,t}$ is the deficit cost for user *u*th in configuration *i*th of reservoir operating rules at year t.

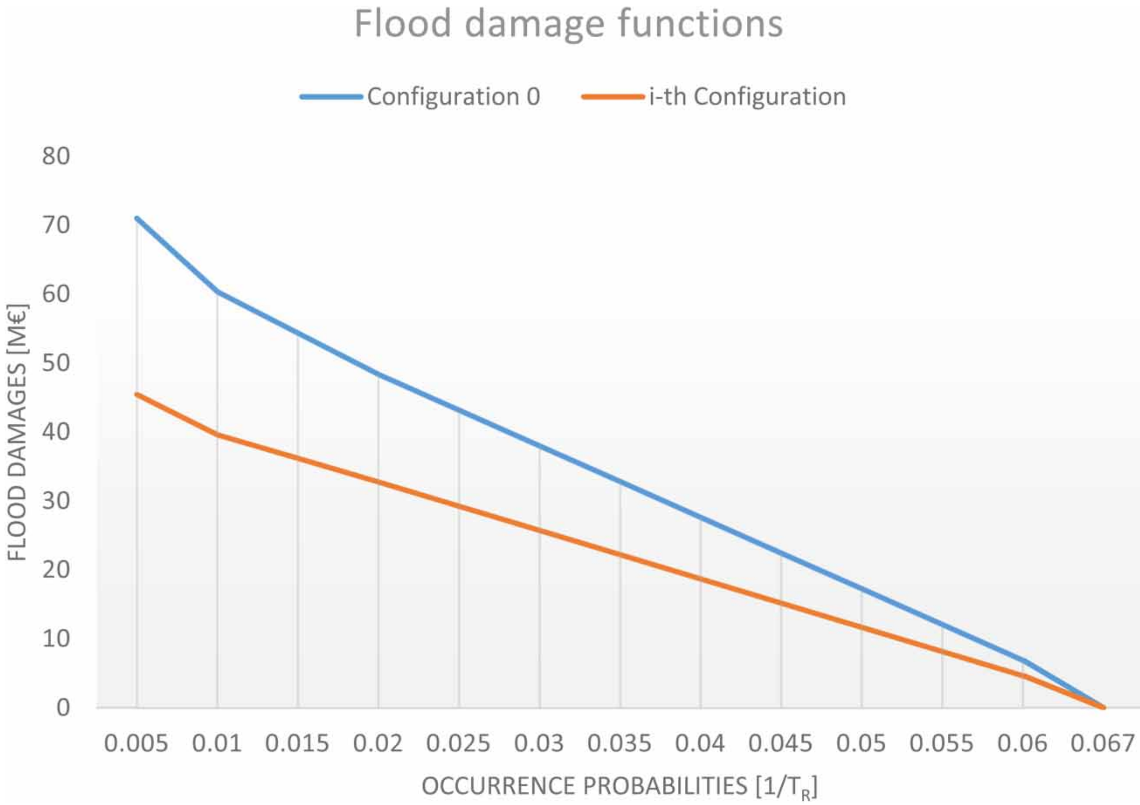

Figure 1 | Flood damage comparison: configuration (0) – configuration (i).

- $P_{\mathrm{NC}\,i,t_{\mathrm{NC}}}$ is the penalty (actualized at year t_{NC}) paid in the case of missing realization of configuration ith, even if the funds are available.

All costs and benefits are assessed, actualized, and cumulated along the time horizon of analysis. Since different configurations can be integrated into each possible system evolution throughout the planning horizon, one could compute the NPV as follows:

$$\sum_{i=1}^{I}\sum_{t=1}^{T} B_{i,t}\cdot\delta_{i,t} - \sum_{i=1}^{I} C_{c\,i,t_c}\cdot\delta_{i,t} - \sum_{i=1}^{I}\sum_{t=t_c+1}^{T} C_{\mathrm{OMR}\,i,t}\cdot\delta_{i,t} - \sum_{i=1}^{I}\sum_{u=1}^{U}\sum_{t=1}^{T}\mathrm{def}_{i,u,t}\cdot\delta_{i,t} - P_{\mathrm{NC}\,i,t_{\mathrm{NC}}}\cdot\delta_{i,t} \tag{5}$$

where I is the total number of configurations and T is the number of years in the planning horizon.

One computes NPV by (5) for all configurations and selects the configuration with maximum NPV.

3. BUILDING AND SOLVING A DT

DTs are analytical models to systematically define, structure, and analyse decision problems under uncertainty with a single criterion (Bertsimas & Freund 2004). Figure 2 lists the steps required for building a DT.

In step 1, one must list all decisions to be made and all uncertain events. For example, a possible decision in this problem is to adopt or ignore the reservoir operation rules. A possible uncertain event is the possible change in the budget: in this study, it could increase or remain unchanged.

In step 2, one selects the criterion to compare mitigation policies. In this article, the criterion is the NPV, which is computed according to Equation (5), clearly preferring a higher net benefit to a lower net benefit.

In step 3, one represents decisions as branches emanating from decision nodes and uncertain outcomes as branches emanating from event nodes. The links between these nodes must be consistent with the problem dynamics. For example, in flood

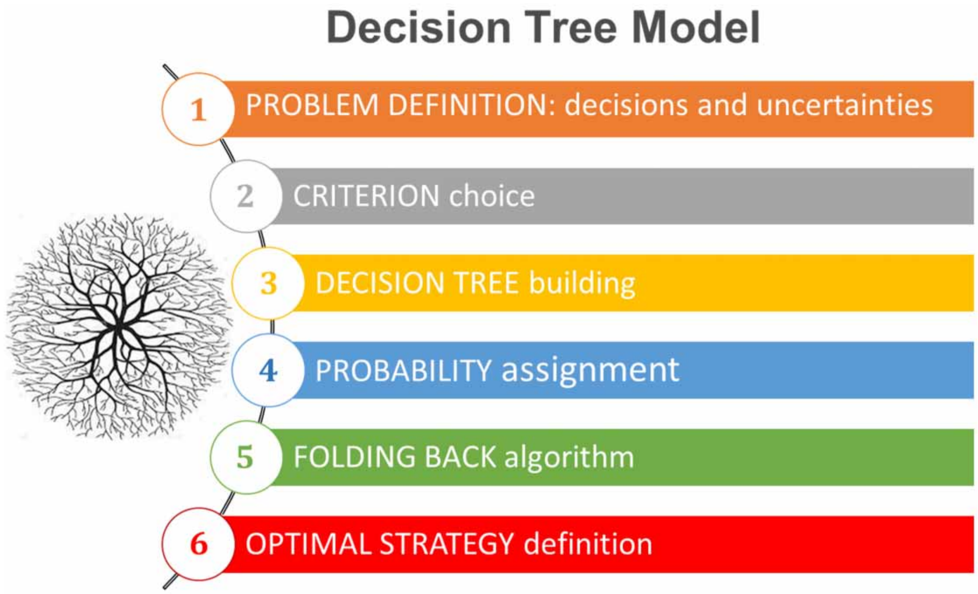

Figure 2 | Decision tree steps.

risk management, one could decide first if the reservoir rules must be adopted before observing if the budget for works is increased or unchanged. This can be shown in Figure 3, where time flows from left to right.

In step 4, one must set or determine the probabilities of each branch emanating from event nodes, to quantify the possibility to observe the associated random outcome. For example, in Figure 4, two event nodes are reported after the decisions as shown in Figure 3, and the probabilities of branches leaving from event nodes are supposed to be 0.5.

In step 5, one must compute the numerical value of the decision criterion in the final branches of the DT.

In step 6, one solves the DT by backward induction (or folding back algorithm). It starts from the final branches of the DT and moves toward the starting node. When an event node is visited, one computes the average value of the criterion from all possible outcomes. This means to convert the distribution of possible net benefits to a single numerical value using the average, which weights all possible outcomes by their probability. When a decision node is visited, one chooses the branch emanating from this node with the best value of the criterion. In the CBA, this means to cross off the branches emanating from a node with a worse value of the NPV of benefits. Note that in a decision node, the decision-maker selects which branch to opt for according to the selected criterion, whereas this is not possible at event nodes because one cannot decide which outcome will be observed.

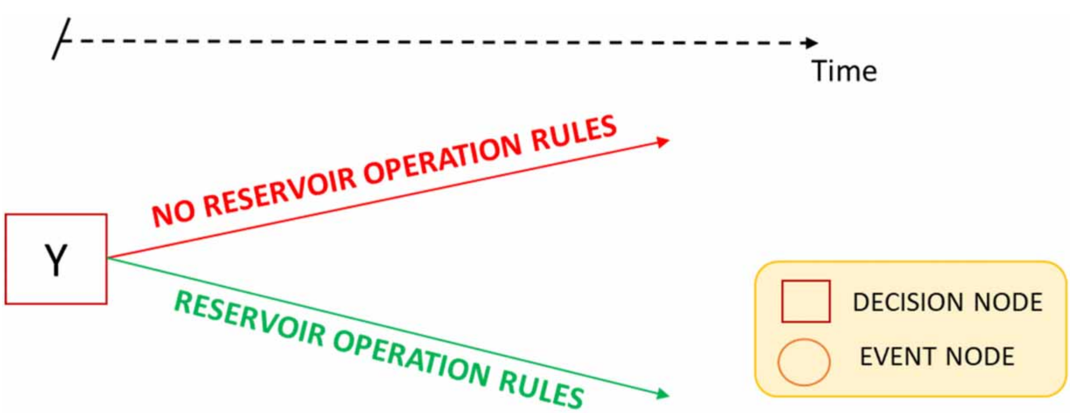

Figure 3 | A DT with two possible decisions at node Y.

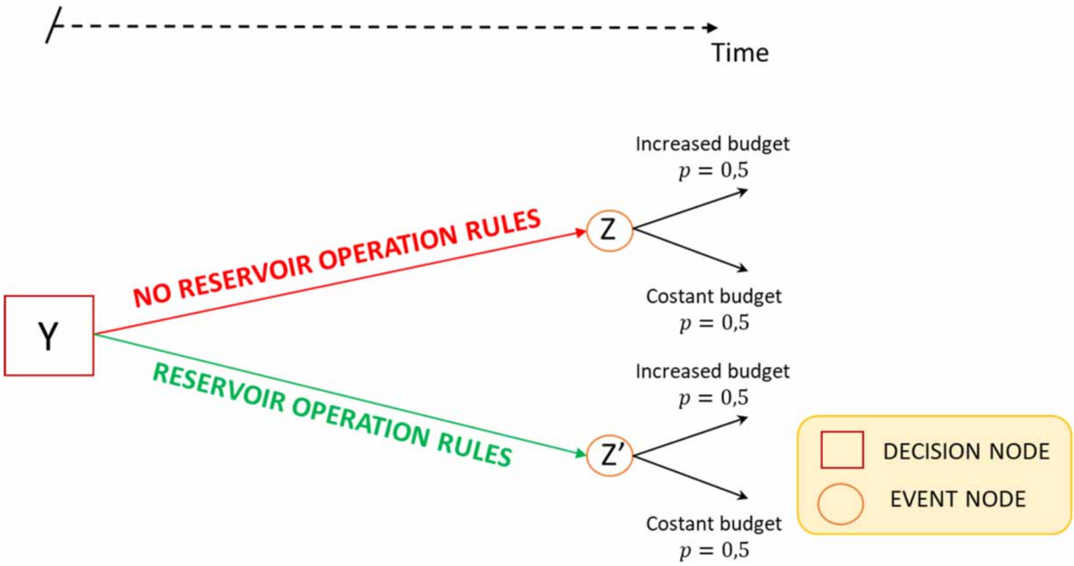

Figure 4 | A DT with two event nodes, each with two uncertain outcomes with equal probability.

The folding back algorithm stops when the initial node of the tree is visited. The solution of the DT can also be represented as the subset of edges selected in the path emanating from this node.

4. EXPERIMENTATION IN A CASE STUDY

The former procedure is applied to define the optimal assessment for flood risk mitigation in the real case of the Coghinas River lowland flood plain, located in the northern part of the Sardinia region (Italy).

Coghinas River is the third longest river in the region and has a drainage basin of 2,551 km^2. The river flows into the Mediterranean Sea crossing a lowland valley and has an upstream artificial reservoir with a capacity of 283 Mm^3. This reservoir is determined by the 58 m high Muzzone dam. The reservoir stores almost the totality of water resources needed to fulfil the water request in the territories of north Sardinia.

In Coghinas lowland floodplain valley are located some urban settlements: Viddalba, Santa Maria Coghinas, and Valledoria. Moreover, the Coghinas lowland valley has a strategic relevance for tourism and agriculture.

4.1. Flood risk mitigation measures for the Coghinas floodplain

According to the Regional Plan for Flood Mitigation (ARDIS 2014) in the future, this valley could be highly exposed to flood events generating significant damages to civil properties, crops, livestock, infrastructures, and the environment. Therefore, public authorities and policy-makers defined some strategic structural and proactive reservoir management policies to mitigate the consequences of possible flood occurrences.

4.1.1. Structural flood risk mitigation measures

To reduce the impact of flood damages, Sardinia Region defined some structural solutions such as critical bridge demolition, levees and drainage channel improvements, and new constructions. The possible actions for flood damage reduction in the Coghinas floodplain area are reported in Table 1, with their construction costs, according to the Regional Plan for Flood Mitigation (ARDIS 2014).

These structural mitigation actions can be clustered into five main project configurations.

As illustrated in Table 2, each project configuration includes different single works and aims to protect different areas along the Coghinas River (ARDIS 2014). Each project configuration gathers specific actions, which could be funded and built in different time steps, according to priorities and probabilities of funding that can be evaluated.

Configuration 0 represents the non-intervention option. Nevertheless, it concerns the demolition of two existing bridges, and these actions are considered the highest priority and are also included in all the other possible configurations (while action with work code 'O' is aimed at protecting Viddalba only). Configuration 1 and Configuration 2 aim to safeguard

Table 1 | Structural flood risk mitigation actions

Work code	Work description	C_c (M€)
A	New levee on the right bank to protect Viddalba town	2.38
B	Adjustment of the levee on the left bank (up to Santa Maria Coghinas)	2.59
C	New levee to protect Santa Maria Coghinas town	1.81
D	Hydraulic arrangement of the hydrographic network upstream of the levee which protects Santa Maria Coghinas town	0.33
E	Adjustment of all the levees on the left bank	15.67
F	Demolition of the old bridge along the provincial road n° 146 over the Coghinas river near Viddalba town	0.09
G	Demolition of the bridge along the provincial road n° 90 over the Coghinas river near Valledoria town	0.32
O	Demolition of the bridge over Badu Crabile river along the provincial road n° 35	0.19

Table 2 | Cluster of works related to each project configuration

Project configuration					
	Configuration 0	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Work code	F G	A O F G	B C D F G	A O B C D F G	A O F G E

the two towns of Viddalba and Santa Maria Coghinas, respectively. Configuration 3 aims to consider the protection of both these two towns. Configuration 4 is the most expensive in terms of costs, as it guarantees mitigation measures for the whole Coghinas lowland floodplain, also considering the territories of Viddalba.

The benefits of each configuration are estimated from the reduction of expected damages considering 12 categories of land use. They are listed in Table 3, which reports related values of maximum damage for surface units (Sulis *et al.* 2020). It is worth noting that the maximum flood damage cannot be always defined in a univocal way, such as for class with labels

Table 3 | Land-use classes and maximum damage values

Label	Land-use class	Max damage value (€/m^2)
1	Residential buildings	618
2	Commercial	511
3	Industry	440
4	Agriculture	0.63
5	Council roads	10
6	Provincial roads	20
7	Other roads	40
8	Infrastructural (areas with water supply network, electric grid and similar systems)	40
9	Dams, rivers, and similar areas	–
10	Environmental heritage areas	–
11	Historical and archaeological heritage areas	–
12	Area subjected of other intangible damages	–

9–12. Territories with labels 9–12 are considered restrictive for the construction of mitigation works and are not included in the CBA.

The definition of the damage function was made by a flood damage assessment according to the evaluation of water depth resulting from the hydraulic simulation models (Frongia *et al.* 2015; Sulis *et al.* 2020). To predict the expected mean annual value of flood damages, three values of return time-period are considered: $T_r = 50$, 100, and 200 years, and related flood peaks and hydrographs have been evaluated. In this study, the residential depth-damage curve was taken from the study by Frongia *et al.* (2015), while the JRC damage curves were adopted for other land uses.

4.1.2. Reservoir operation rules for the flood risk mitigation

In addition to new structural configurations, flood risk mitigation could be achieved, or even avoided, by planning in the upstream reservoir some proactive management rules workable for both uses of flow regulation and lamination. Two reservoir operation rules are here considered for the management of the Muzzone Dam:

- Keep the maximum storage level, i.e.: 164 m above sea level (m a.s.l.) as the available capacity for flow regulation.
- Decrease the maximum level to 162 m a.s.l. and increase the lamination volume of 35 million cubic meters, thus reducing the downstream flood peak.

The tree configurations can be clustered into the two main project configurations L0 and L1, which are reported in Table 4.

Configuration L0 is based on the reduction of storage capacity and the increase in flood lamination volume. Additional costs are considered to guarantee annual levees maintenance in the current configuration. Meanwhile, Configuration L1 implements the new set of structural works listed in Table 5, which can completely avoid residual damages.

Both these configurations L0 and L1, consider a new cost term in (**5**), which is computed as the cost of deficit occurrences in water demand fulfilment. As reported in the lines of Table 6, the deficit in water demand fulfilment can be categorized into two classes: planned and unplanned. Planned deficits can be forecasted in advance for users, while unplanned deficits arise in the case of hydrological scenarios of unexpected water scarcity, thus affecting and harming users. To consider this possibility, for each kind of water use, an initial percentage (15% for irrigation use, 2% for civil, 5% for industrial) of the unsatisfied demand (deficit) is computed as a planned deficit, while remaining surpluses of shortages are considered as unplanned deficits.

Table 4 | Cluster of works related to each project configuration – reservoir operation rules

Project configuration		
	Configuration L0	**Configuration L1**
Work code	0	0
		1
		2
		3
		4
		5

Table 5 | Structural flood risk mitigation actions – reservoir operation rules

Work code	Work description	C_C (M€)
0	Annual levees maintenance	0.16
1	New levee on the right bank to protect Viddalba town	0.2
2	Levee adjustment on left bank	6.04
3	New levee section overflowable construction on the right bank	1.95
4	Security adjustment of all the levee on the left bank	1.41
5	Dune and bank protection operation	0.74

Table 6 | Annual deficit (100 years) – reservoir operation rules

	Cost (€/m^3)			Storage level (m a.s.l.)	
Deficit	**Irrigation**	**Civil**	**Industrial**	**164 (Mm^3)**	**162 (Mm^3)**
Planned	0.06	0.25	2.56	113	119
Unplanned	0.6	2.5	256	132	138
Total	–	–		245	257

The annual total amounts and their costs are evaluated using regional studies to define the water rates for units of volume applied to different kinds of use. Deficit costs are evaluated through a multiplicative coefficient applied to water rates (RAS 2006).

The impact of this operation rule is assessed by evaluating the differences between the deficit in these two storage configurations. Table 7 summarizes the deficit evaluation over 100 years obtained using the WARGI DSS simulation tool (Sechi & Zuddas 2000; Sulis & Sechi 2013). WARGI-SIM is the simulation module developed by the Water Research Group at the University of Cagliari (Sulis & Sechi 2013). It provides a network representation of water systems and determines water flows based on operative rules, technological constraints, preferences, and priorities.

Table 7 shows that the total amount of evaluated deficit is nearly equally divided between planned and unplanned. However, the impact of unplanned shortages is much more relevant with respect to planned shortages. The total annual amount of the related costs should be actualized and cumulated year by year along the whole planning horizon.

After the analysis of Tables 2 and 4, a classical CBA was made to select the optimal flood mitigation measure for the Coghinas floodplain in a time horizon of 100 years (ARDIS 2014).

Table 8 reports the main outcomes of the standard CBA on structural mitigation measures only: the first year with positive NPV and the NPV itself.

Clearly, Configuration 2 was selected as opposed to each structural project configuration. However, this decision assumed a priori knowledge of budget availability throughout the planning horizon and ignored the opportunity to upgrade Configuration 2 if the budget increases in the time horizon. Moreover, the standard CBA did not consider any lamination action. The integration of CBA into DTs overcomes these limits and returns a more reliable planning strategy.

Table 7 | Deficit evaluation over a planning horizon of 100 years

	Deficit (Mm^3)			Total deficit	
Deficit	**Irrigation**	**Civil**	**Industrial**	**Mm^3**	**M€**
Planned	5.8	0.2	0	6	0.4
Unplanned	5.86	0.14	0	6	3.5
Total	11.66	0.34	0	12	3.9

Table 8 | Standard CBA outcomes

Project configuration	First year with positive NPV	NPV (M€)
Configuration 0	Never	−4.24
Configuration 1	Never	−7.05
Configuration 2	7th	13.34
Configuration 3	13th	10.02
Configuration 4	40th	1.43

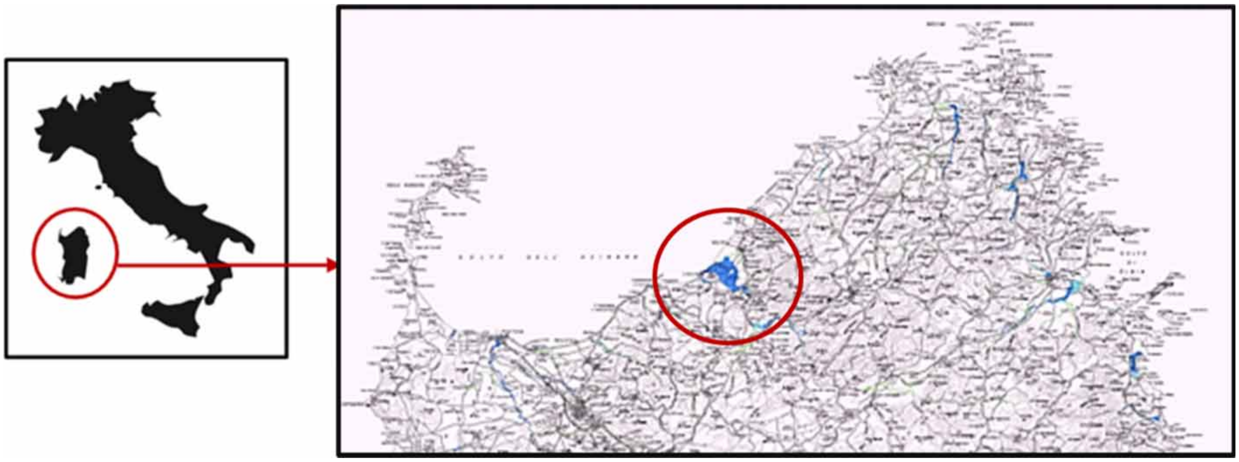

Figure 5 | Sardinia island and the Coghinas River Basin location.

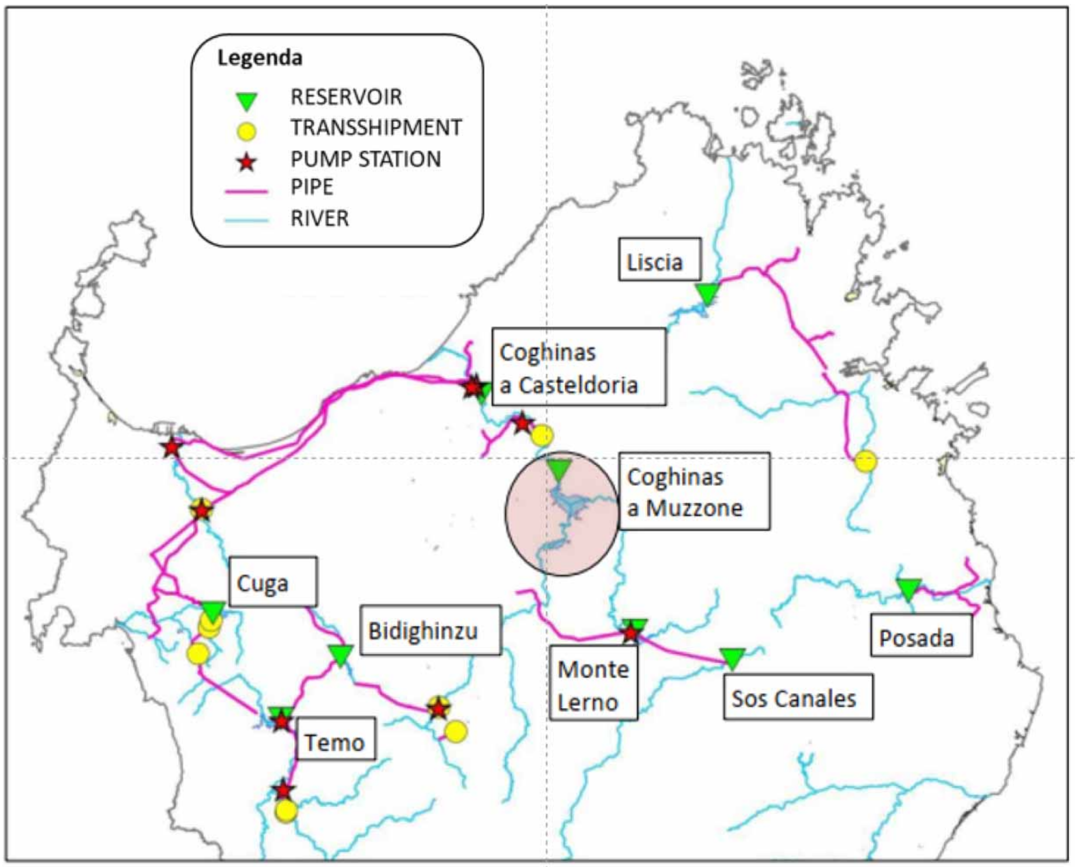

Figure 6 | North Sardinia water supply system.

4.2. CBA and DTs in the Coghinas floodplain

At the beginning of the planning horizon, the budget is supposed to be sufficient to implement all possible configurations listed in Table 2, as in a standard CBA. Nevertheless, funding availability could be uncertain in the future. A new update about the budget is supposed to be observed in the 10th and 20th years:

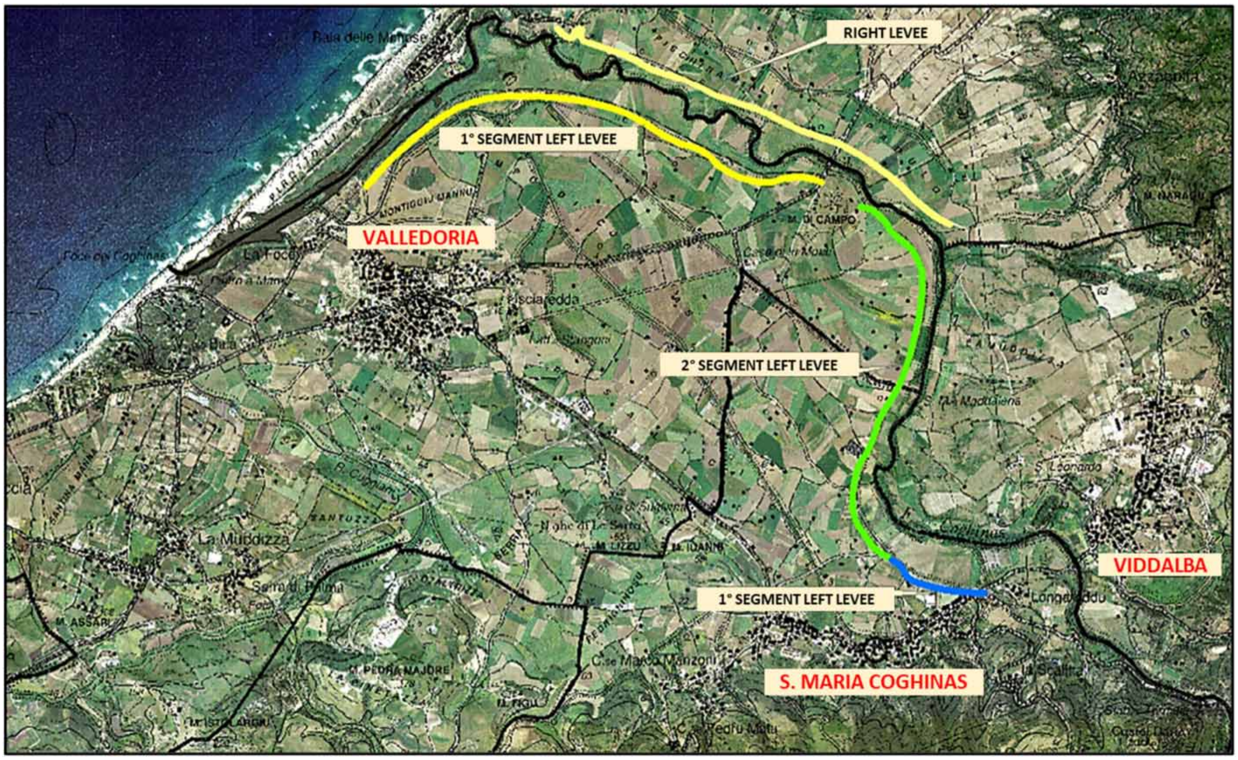

Figure 7 | Coghinas lowland floodplain with original levees configuration.

- It could increase (higher budget) with a probability of 0.5 and allow to upgrade to a more expensive configuration or keep the current one.
- It could have no change (constant budget) with a probability of 0.5 and allow to keep the current configuration only.

First, one must decide if reservoir operation rules must be followed. Therefore, the overall DT can be split into two main parts, one for each branch in Figure 8.

In the following sections, we build two subtrees generated after the former branches. Clearly, we will opt for the subtree with the maximum net benefit value, to decide if the reservoir rules must be adopted.

4.2.1. DT – maximum storage level for flow regulation

In this section, we describe the decision subtree after the branch denoted by 'NO RESERVOIR OPERATION RULES' in Figure 8. This subtree is reported in Figure 9.

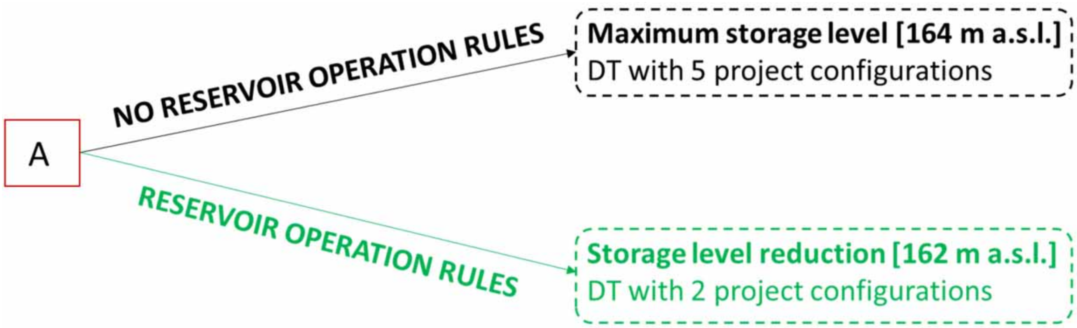

Figure 8 | The initial part of the DT.

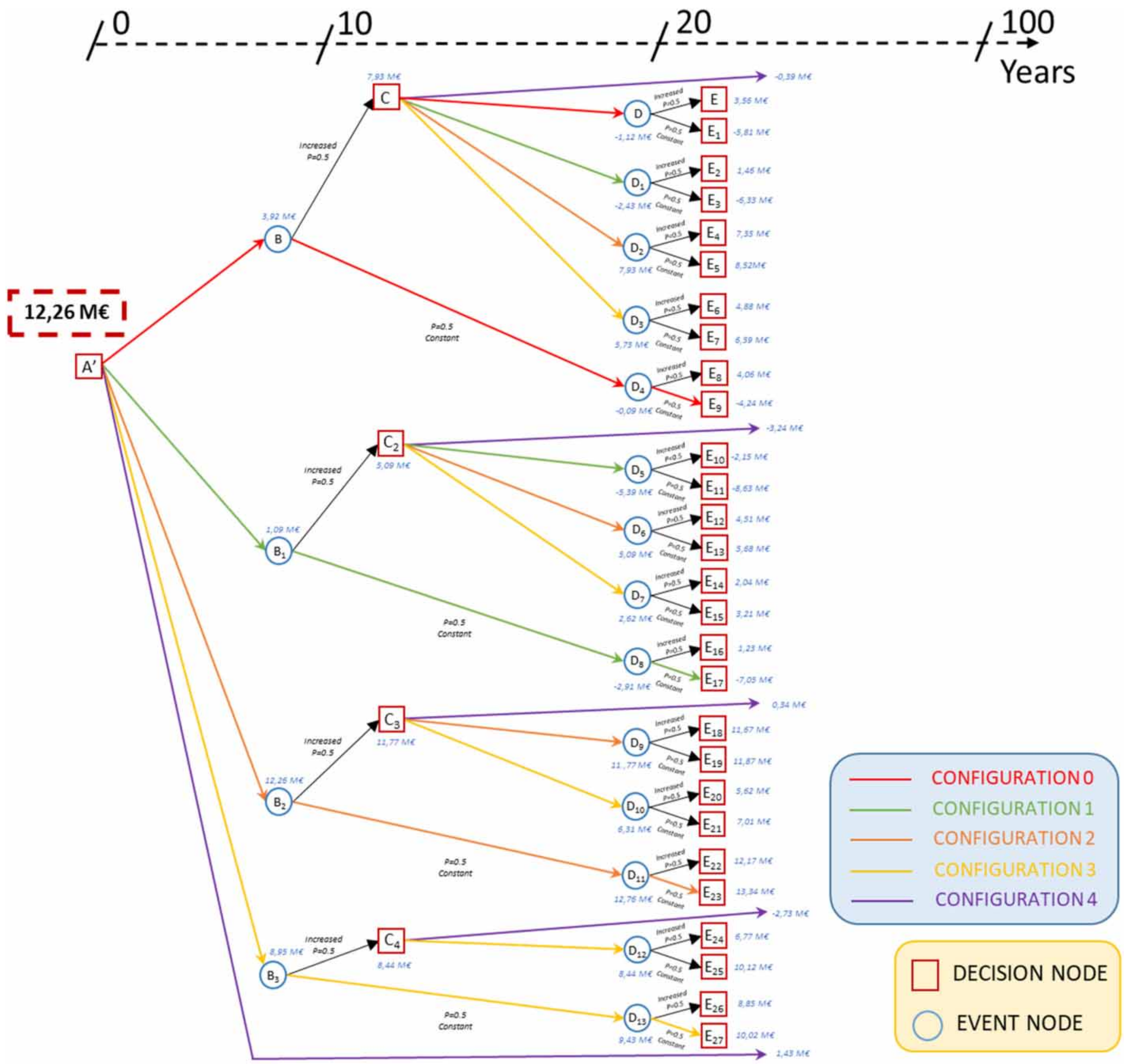

Figure 9 | The subtree of structural configurations.

In Figure 9, the initial decision is modelled by a decision node, which is drawn by a small box with the label A′ at year $t = 0$. Each possible decision at node A′ is a configuration in Table 2 and is represented by a branch emanating from node A′: the branch in red shows the selection of Configuration 0, the branch in green shows Configuration 1, the branch in orange shows Configuration 2, the branch in yellow shows Configuration 3, and the branch in purple shows Configuration 4.

If Configuration 0 is selected, one must face the uncertainty of whether the budget will increase or be constant at year $t = 10$. Since it may be constant with probability 0.5 or increase with probability 0.5, this uncertain event is modelled by an event node, which is represented by a small cycle with label B at year $t = 10$. Each possible outcome of this event is represented by a branch emanating from B. More precisely, if the budget does not change, one joins node D_4 from node B; if the budget increases, one joins node C from B.

If a constant budget is observed at node B, the only possible decision at year $t = 10$ is to keep Configuration 0. This decision is represented by a red arc emanating from node B and joining node D_4. However, the budget could also change 10 years later (i.e., 20 years after the beginning of the planning horizon). It may be constant with a probability of 0.5 or higher with a probability of 0.5. In the first case, one joins node E_9 from event node D_4 and can only decide to keep Configuration 0. The value of the criterion at year 100 in paths A′, B, D_4, E_9 is −4.24 M€. If a budget increase is observed after node D_4, one moves to decision node E_8. Here, one can opt for all five possible configurations with different net benefit values associated with each branch. For the sake of clarity, Figure 10 zooms in these configurations at year $t = 20$.

If a budget increase is observed at node B (year $t = 10$), one moves to decision node C, where one can choose all five possible configurations. More precisely, one can switch directly to Configuration 4, up to the end of the planning horizon, because the downgrade to a lower configuration is not allowed. In this case, the final value of the NPV is −0.39 M€.

If Configurations 0, 1, 2, or 3 are selected at node C, one needs to face budget uncertainty at year $t = 20$. It may be 'constant' with a probability of 0.5 or 'higher' with a probability of 0.5. This uncertainty is represented by event nodes D, D_1, D_2, and D_3. After these nodes, there are two possible decision nodes: if there is a 'constant' budget, one moves up to the end of the planning horizon just with the current configuration; else, if the budget is 'higher', one can choose the best configuration.

It is worth noting that the DT in Figure 9 also includes all configurations of the classical CBA in Table 8:

- Path A′, B, D_4, E_9 is Configuration 0 in the classical CBA (NPV = −4.24 M€)
- Path A′, B_1, D_8, E_{17} is Configuration 1 in the classical CBA (NPV = −7.05 M€);
- Path A′, B_2, D_{11}, E_{23} is Configuration 2 in the classical CBA (NPV = 13.34 M€);
- Path A′, B_3, D_{13}, E_{27} is Configuration 3 in the classical CBA (NPV = 10.02 M€);
- The purple leaving from A′ is Configuration 4 (NPV = 1.43 M€).

The additional scenarios in the DT present decision nodes at time $t = 10$ or $t = 20$, i.e., decisions modifying the initial mitigation strategy.

The optimal sequence of configurations can be determined by the folding back algorithm. One must start from the final branches and choose that branch emanating from the decision node with the best value of the criterion (for the sake of clarity, one can write this value above the node and cross off the branches with lower values of the criterion).

For example, in Figure 10, at decision node E_8 Configuration 2 is selected and the other configurations are disregarded. For each event node, we compute the average of the criterion over each branch weighted by its probability (for the sake of clarity, we write this number above the event node). For example, at decision node D_4, we compute the average between 4.06 M€ and −4.24 M€: −4.24 * 0.5 + 4.06 * 0.5 = -0.09 M€. This algorithm is iterated until all nodes of the DT are visited.

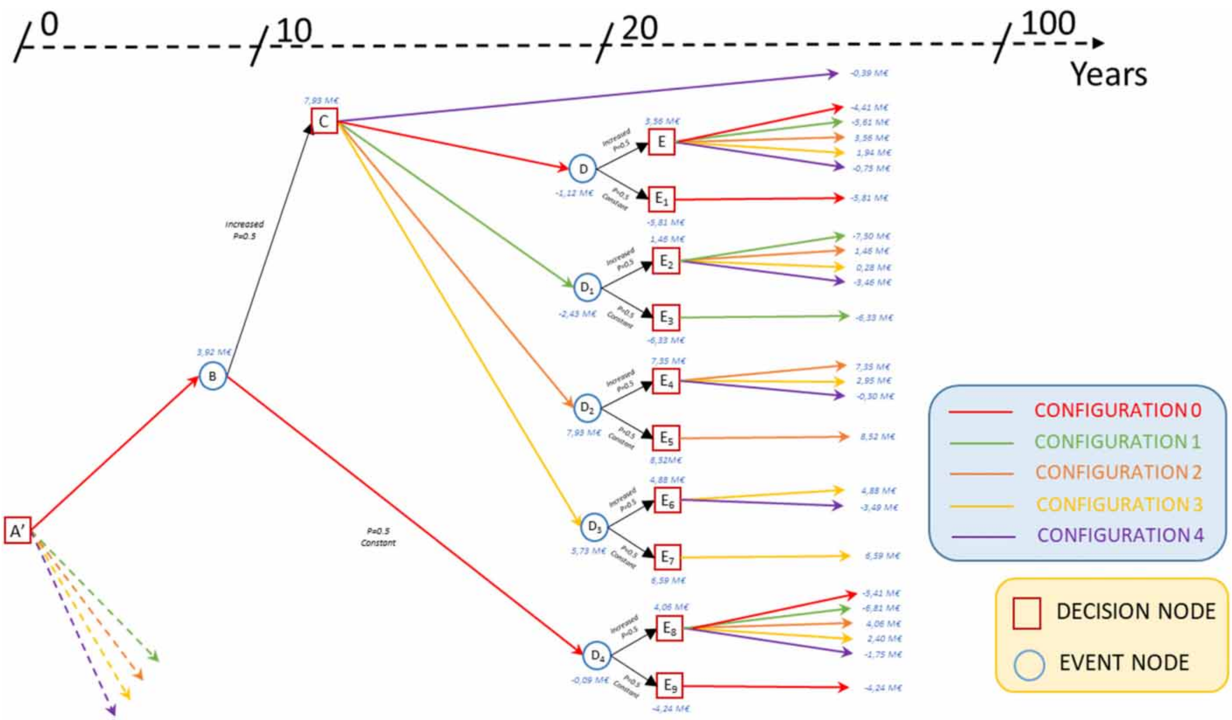

Figure 10 | Zooming on the branch A-B of DT.

The solution of this DT is reported in Figure 11. According to the solution, one should select Configuration 2 at the beginning of the planning horizon (i.e., move along the branch from A′ to B_2). Then, if a higher budget is available after 10 years (in the branch from B_2 to C_3), select Configuration 2. This selection must be repeated at year $t = 20$ regardless of the variation in the budget. If the budget is constant, keep Configuration 2 for 10 more years (move along the branch from B_2 to D_{11}). If the budget becomes higher (in the branch from D_{11} to E_{22}), keep Configuration 2, else (in the branch from D_{11} to E_{23}) select again Configuration 2. The overall value of this decision strategy is the value of the criterion computed in the initial node A′.

4.2.2. DT – storage level reduction for flow regulation and increase in lamination

In this section, we describe the decision subtree after the branch denoted by 'RESERVOIR OPERATION RULES' in Figure 9. This subtree is reported in Figure 12. Two possible configurations L0 and L1 can be selected, as detailed in Table 4. They are both characterized by the reduction of regulation capacity and maximum storage level at 162 m a.s.l.

The decision subtree starts from node A″ at the time $t = 0$ and splits up into two possible paths: Configuration L0 in golden colour and Configuration L1 in blue. If Configuration L1 is selected, one moves directly to the end of the time horizon at year $t = 100$ with a final value of the net benefit equal to 54.43 M€. If Configuration L0 is selected, one moves along the golden

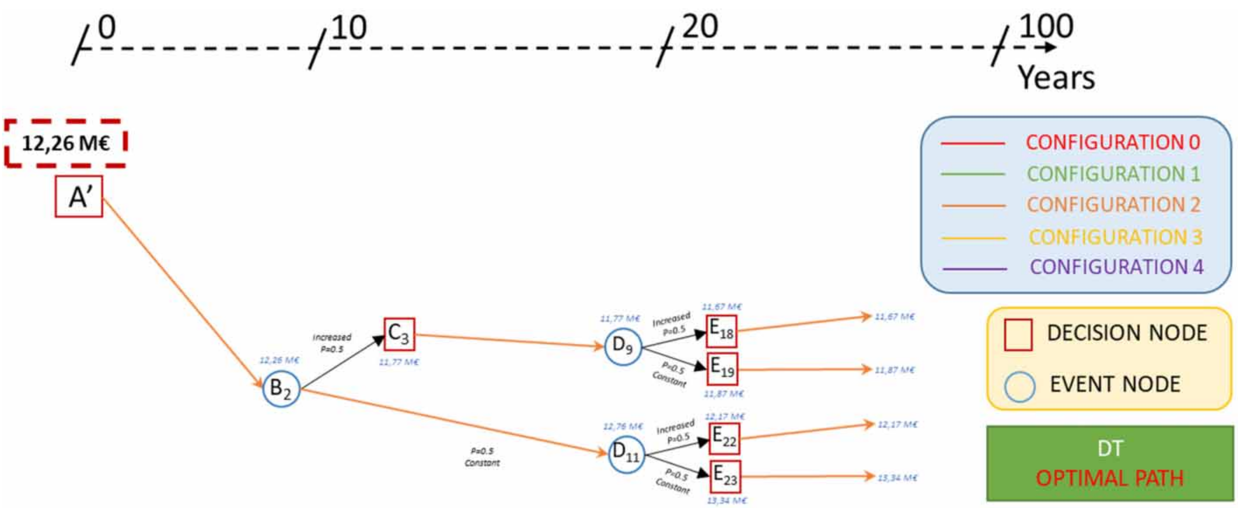

Figure 11 | Optimal paths on the DT with structural configurations.

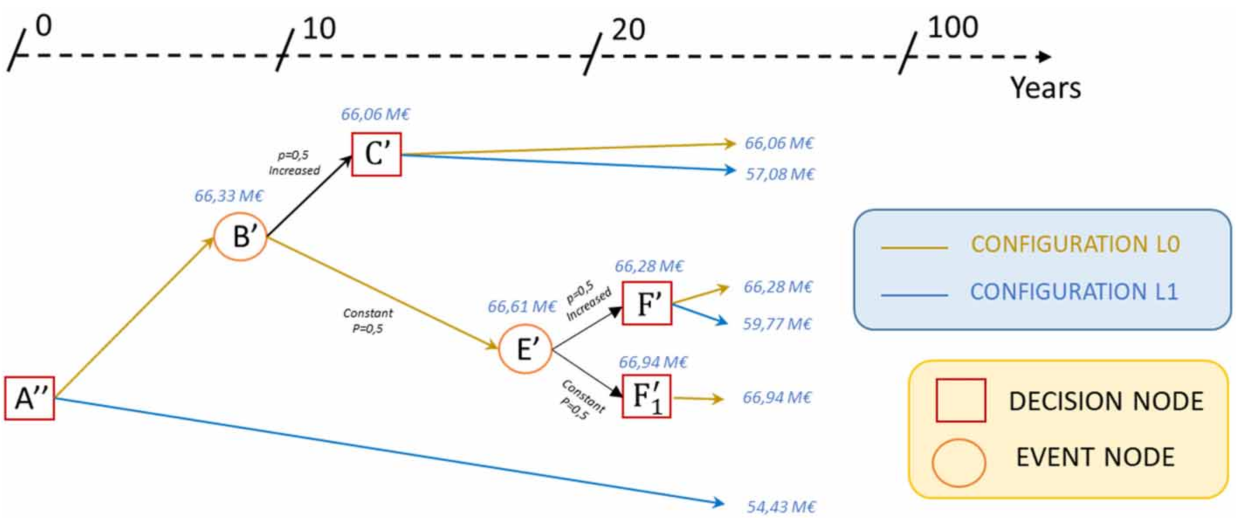

Figure 12 | The subtree with storage level reduction.

branch to the event node B′. In case of a higher budget, one moves to node C′, where the maximum benefit is 66.06 M€ if configuration L0 is kept.

If a constant budget is observed, the only possible decision at year $t = 10$ is to keep Configuration L0. After 20 years, the uncertain budget is described by node E′. One moves to node F_1' in case of low budget and node F′ in case of high budget.

The optimal path in the case of storage level reduction is reported Figure 13. The optimal value of the expected net benefit is 66.33 M€.

Since 66.33 ≫ 12.26, it is clearly recommended to decrease the maximum storage level for flow regulation and increase the peak lamination instead of making infrastructural works in case of the maximum storage level.

5. CONCLUSION

This article investigated the integration of a DT into a CBA to prescribe optimal decisions for the planning of flood risk mitigation.

The analysis starts from a classical CBA for optimizing the net value of expected benefits, which was chosen as the decision criterion. However, this CBA is made under the unrealistic assumption of knowing which uncertain parameter will be observed in a long-term planning horizon.

This drawback can be removed by the introduction of DTs in the CBA. More precisely, the article investigated the introduction of uncertainty on budget availability by the probability of funding each configuration in the time horizon. The optimization criterion of the proposed DT was the maximization of expected net benefit and accounts for construction costs, operation, maintenance, and replacement costs. Moreover, this article introduced deficit penalties in the case of operation rules changing water availability for users, as well as additional penalties when constructions are not made, even if funds could be available.

The proposed methodology was tested on a real case study of the Coghinas River floodplain, which is in the north of Sardinia (Italy). Mitigation actions were clustered into different configurations by merging different works along the river in a fixed horizon of 100 years.

The optimal solution was determined by folding back the DT, which maximizes the expected value of the selected criterion (in this case the NPV). The proposed methodology shows that net benefits due to operation rules are much higher than those related to structural solutions. This outcome depends on the higher amount of expected benefit per year due to the substantial reduction of expected flood damages, in the case of a reasonable reduction in the fulfilment of users' water demands.

Although the integration of CBAs and DTs can be supportive for regional authorities to optimally decide on flood risk mitigation works by measurable financial metrics, some limitations still exist in the use of CBA. On the one hand, European norms, requiring the use of monetary metrics, are very common in practice. On the other hand, CBA requires all costs

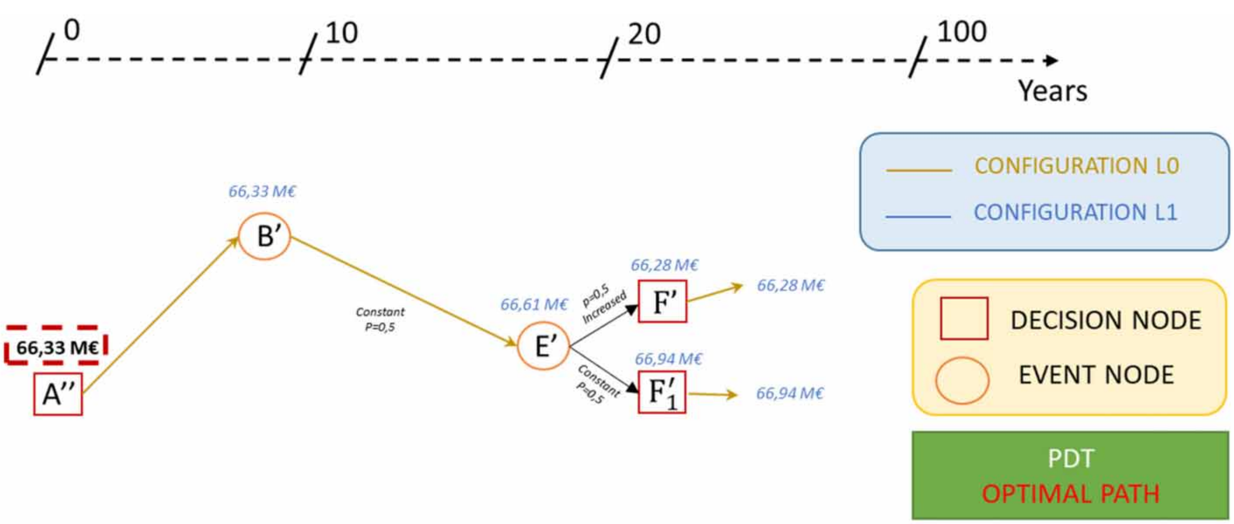

Figure 13 | Optimal paths on the DT with storage level reduction.

and benefits to be quantified in monetary terms, which is not always possible. However, this is not a limitation for the use of DTs, which can be built by any metric chosen by the decision-maker. Moreover, the integration of the CBA into a DT leads to risk-neutral decisions, but they can be properly corrected by decision-makers selecting suboptimal branches at decision nodes.

A promising research avenue is the integration of utility analysis into the DTs, to account for unmeasurable costs and consequences of the decision (e.g., directed intangible damages). Indeed, DTs leave freedom on the choice to be optimized. Moreover, future research developments may address decision-making under uncertainty on water level variations in the reservoirs due to climate change.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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