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SPATIAL COST BENEFIT ANALYSIS IN FLOOD RISK MANAGEMENT: EVIDENCE FROM A CASE STUDY IN ITALY

Abstract
The number of natural catastrophes is increasing worldwide: among these, flood is one of the worst hazards causing thousands of losses of life and damages to property.
Flood risk mitigation was traditionally carried out by reducing the hazard through the construction of structural hydraulic defenses. Nowadays, the approach to flood risk mitigation is conceived as combination of structural and non-structural defenses, as recommended in UN/ISDR, (2005) and in the EU Flood Directive (60/2007): in the specific, the EU directive requires the ex-ante evaluation of costs and benefits from mitigation measures in risk management plans. In this light, the paper proposes the application of a Cost-Benefit Analysis (CBA) to a case study of the city of Olbia in Sardinia Region, example of Historic Urban Landscape (HUL) in Italy, in order to support the public administration in the choice of the most sustainable plan, reducing social and environmental risk and, at the same time, ensuring its feasibility from a financial and economic perspective.

Keywords: flood risk, cost-benefit analysis, risk management

Introduction
In recent years, the increased impact of floods has caused huge damage and thousands of deaths worldwide [1]. This impact is even higher in urban areas, especially if, as often occur in Italian contexts, their territorial dimension can be recognised as Historic Urban Landscape (HUL): it stems from the combination of material heritage, economic processes, social and cultural values and practices [2]. Consequently, the assessment and management of flood risk in urban areas have gained a central role in engineering researches and applications [3], [4].
Flood risk mitigation has been traditionally achieved by reducing the hazard trough the construction of structural hydraulic defences such as levees, retention basins, and diversion channels. Proper structural measures design requires the computation of the design flood event [5], often characterized by a return period between 100 and 200 years, according to Water Authorities regulation. This approach is no longer sustainable, especially in urbanized area, where the construction of flood defence works is often source of long-term conflicts and call for significant financial resources and larger spaces than the ones available. In order to face the increasing engineering, economic, and environmental constraints in building structural hydraulic defences, novel methods for flood risk mitigation have been defined by combining structural with non-structural measures, as recommended by the United Nation [6] and the European Commission [7], [8], [9], [10]. The need to ensure adequate financial provisions for flood risk mitigation investments requires to investigate different design approaches from the conventional ones [11]. In this context, the assessment of risk mitigation and management measures stands out as an important part of the risk management and hydrogeological planning process. In this regard, the Legislative Decree no. 49/10 (attachment 1), claims the need to estimate the costs and benefits of the interventions, in order to assess their financial and economic feasibility and the related funding lines. Moreover, the European Community, with regulation no. 1303/2013, makes compulsory to sustain the "major investment projects" for different strategic sectors, including the prevention of hydraulic risk, with a Cost-Benefit Analysis (CBA), in order to assess their co-funding (Cohesion Fund 2014-2020). As suggested by Italian and European regulations, CBA can be an effective tool for supporting public decisions in strategic sectors and, thus, its correct implementation becomes fundamental [12], [13], [14].
For these reasons, this study illustrates a Spatial CBA (SCBA) to support investment choices for flood risk mitigation, ensuring the evaluation of trade-offs between preventive maintenance actions and expected economic damage in a perspective of sustainable allocation of resources. The proposed model allows to define the optimal design return period based on the logic of financial sustainability, comparing investment costs of different measures and expected damages. The paper is organized as follow:

- In the first part the methodology of SCBA is presented with specific reference to the evaluation of different flood mitigation measures;
- In the second part the first results of the application of SCBA to the case of Olbia in Italy, an example of Historic Urban Landscape (HUL), that was heavily struck by a huge flood in 2013, are displayed.
- In the conclusion some reflections are proposed, and future research lines are drawn.

Methodology: a Spatial Cost-Benefit analysis
The CBA was created as a technique for evaluating investments in the private sector and then spread to the field of public decision-making, as a tool to support the economic and financial feasibility analysis of a single project, a program or even an economic policy instrument [15]. It is an investment evaluation technique, based on the assumption that all the benefits and costs related to a project can be evaluated in monetary terms. It is based on the principle of the "intertemporal discount of values". The first applications in the assessment of flood risk mitigation and management plans and projects date back to the early 1960s, but it was only in the 1990s, with the introduction of Geographic Information Systems (GIS), that CBA becomes widely used in different international contexts, thanks to the ability of these new technologies to process and correlate spatial data on the dangerousness of expected events with the different components of urban and territorial contexts at risk [16], [17], [18], [19]. Many studies have been conducted in the recent years in the field of flood risk mitigation, both in the national and international context [20], [21], [22], [23], [24]. Most of them concerned the application of CBA as an ex post evaluation in order to assess the damages after the flood events and the costs of remediation.
The aim of this study is to apply SCBA, to risk management, as an ex ante evaluation tool, in order to define the optimal design return period based on the logic of financial sustainability, comparing investment costs of different measures and expected damages.
In this context, this methodology moves from the definition of risk, calculated according to the provisions of EU legislation (Directive 2007/60 and from that Italian Legislative Decree 49/2010) as a function of i) the frequency of occurrence of the flood, H, ii) the type of elements at risk (buildings and productive activities) present in flooding area, E; iii) their level of vulnerability, V, expressed by the equation:

$$R = H \times E \times V \quad (1)$$

Furthermore, with the aim of estimating costs and benefits from mitigation and risk management interventions, it integrates simulation models of hydraulic phenomena and monetary damage assessment models, in order to compare different intervention solutions based on financial and economic performance indicators, as Net Present Value (NPV) and Internal Rate of Return (IRR).

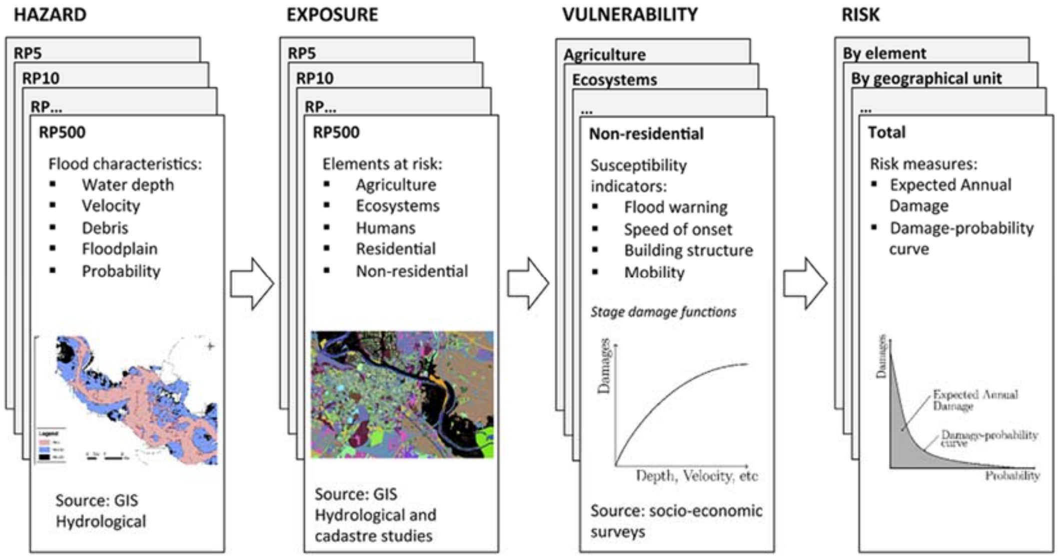

Fig. 1. Spatial Cost -Benefit analysis methodology.

In this sense, the proposed model represents an innovative tool to support the design decision process, integrating different aspects and considring all the stakeholders involved. This methodology is illustrated in Fig. 1.
As shown in Fig. 1, the SCBA is structured in different steps, related to the different components of the risk function. In particular:

- Step 1 (H) concerns the simulation of flood events for different return periods (1:25; 1:50; 1:100; 1:200; 1:500), in order to calculate for each event, the extent of the flooded area and the water height.
- Step 2 (E) concerns the classification of the elements at risk, by type and land use, and the estimation of the assets' value by the "depreciated reconstruction cost " method for each damaged item, by considering only direct physical damage caused by the event [25], [26]. Direct damage to the buildings is estimated considering water height function, the vulnerability of the building elements to the hydrostatic actions, and the average cost of reconstruction of each damaged building element [27].
- Step 3 (V) deals with a crucial aspect: the identification of the vulnerability function. The vulnerability function, or the assessment of percentage of loss, is defined through an engineering approach, based on the discretization of each component of the asset at risk. According to this approach, the damages are assessed with respect to a type of standardized elements, considered prototypes of types of collateral exposed elements. The equation to calculate the damage suffered by the generic building is:

$$ED_i(T) = PD_{str.} \times A \times C_{rec.} + PD_{cont.} \times A \times C_{rep.} \quad (2)$$

Where:

- EDi is the economic damage suffered by the generic building;
- T is the return period;
- $PD_{str.}$ is the damage suffered by the structure [%];
- $PD_{cont.}$ is the damage suffered by the content [%];
- A is the surface area of the building [m^2];
- $C_{rec.}$ is the cost of restoring the structure of the building [€/m^2];
- $C_{rep.}$ is the cost of replacing the contents of the building [€/m^2].

The total economic damage (ED(T)) suffered by the buildings as a result of a flooding event in the return period T was, however, defined as follows:

$$ED(T) = \sum_{i=1}^{N} ED_i(T) \quad (3)$$

Where:

- ED is the total economic damage for an event of assigned return period;
- ED_i is the economic damage suffered by the generic building;
- N is the number of buildings affected.
- Step 4 concerns the interpolation of all available data from the potential damages, estimated in different scenarios of hazard and their probability of occurrence. Once the damage liability curve was defined, the annual expected damage (EAD) was calculated; it shows the average of the flood damage for each of the flood scenarios considered in the hazard assessment and for the additional scenarios obtained by interpolating the damage liability curve.

Then, a series of mitigation measure will be identified in order to mitigate the EAD.
The mitigated damage (PAD - Prevented Annual Damage) from the various interventions, identified for a given flood scenario was defined through the following equation (4).

$$\mathrm{PAD} = \int_{1/\mathrm{T}}^{\infty} \mathrm{ED(x)} \quad (4)$$

While, the residual damage or damage not mitigated by the intervention (READ - REsidual Annual Damage) was calculated using the following formula (5).

$$\mathrm{READ} = \mathrm{EAD} - \mathrm{PAD} = \\ = \int_0^{\infty} \mathrm{ED(x)} - \int_{\frac{1}{\mathrm{T}}}^{\infty} \mathrm{ED(x)} = \int_0^{\frac{1}{\mathrm{T}}} \mathrm{ED(x)} \quad (5)$$

The total cost avoided by the mitigation intervention, therefore, will be precisely represented by the area underlying the EAD curve; thus, the intervention maximizing the difference between the investment and operating costs and the benefit for the community or the lack of damage can be chosen. In this sense, the economic performance indicators calculated throught a DCA analysis provide a measure of the current value of the project (NPV), and of the Internal Rate of Return (IRR), as the value of the social opportunity cost, that is the threshold value of risk acceptability. It is clear that the project with the highest NPV is preferable, and all projects whose IRR falls within a politically defined threshold rate are eligible for funding.

Results

The case study of Olbia in Sardinia, Italy
Olbia is located in the north-eastern part of Sardinia: to the east, it faces the homonymous gulf belonging to the Tyrrhenian Sea; to the west, it lies on a flat area of 376,1 km^2, delimited by a mountain range. This city of ancient foundation, dating back to the Roman age, in the last 30-40 years has developed in a chaotic way over an alluvial plain without considering the presence of creeks that, as usually occur in semiarid areas, are dry except than during heavy rainfall.
In particular, in recent decades, there has been an important economic development followed by a strong demographic increase. This has generated industrial and commercial growth, the creation of new infrastructures and the emergence of multiple tourist settlements. Olbia is in fact, for number of inhabitants (59.000 inhabitants, Istat 2020), the third largest municipality in Sardinia after Cagliari and Sassari and, consequently, one of the most important municipalities in the region and the main economic engine of the province.
In 2013 the area was affected by a meteorological event, named Cleopatra, characterized by extreme rainfall intensity (rain rate exceeded 120 mm/h in some localities), and amount (more than 450 mm of cumulated rainfall in 15 hours) that sets the maximum return period of precipitation well above 200 years.
The water level reached in the municipality of Olbia was 2 meters height, causing extensive damage to buildings (Fig. 2). After the flood event, an accurate census was conducted with the aim estimate ex post the total damage to the housing stock. The census reported an estimate damage for the buildings of approximately € 100 million.
The case of Olbia seemed, therefore, an interesting case study in order to test the methodology for the ex ante estimation of the damage in a real case study, allwing to compare data estimated ex post with those predicted by the model.

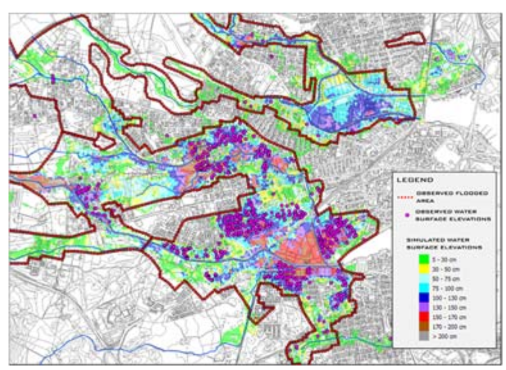

Fig. 2. Extent of flooded area in the Olbia city centre hit by the 2013 event as surveyed by technical office of the Municipality, water depth simulated with the mathematical model, and locations of buildings where maximum water surface elevation was measured.

The application of a Spatial Cost-Benefit analysis

The methodology described in session 2 was applied to the case study of Olbia, with the aim to evaluate the economic performance indicators of a mix of structural and non-structural mitigation measures for the flood-damaged area.

A GIS system was developed to assess the flood risk in different scenarios and the damages in the two scenarios before and after the implementation of the mitigation measure. The analysis carried out are for each step of the methodology are represented as an example in Figs. 3, 4.

Once the parameters determining flood risk were defined, the damage corresponding to each of the flood scenarios examined above was estimated. In order to obtain the damage estimation, it was first necessary to import and superimpose in the QGIS software the hazard layer with the exposure layer.

In this way, each building was assigned the water height values corresponding to each of the different scenarios. These values were calculated by mediating the water heights contained in the discretization cells of the hazard maps that intersect the area of building itself.

Knowing the different intended uses of the buildings and the relative water heights, it was possible to calculate the damage suffered by the individual building by applying the (2). The total economic damage suffered by the buildings as a result of a flooding event in the return period T was, however, defined applying (3).

Tab. 1 shows the total economic damage calculated according to the procedure.

As shown by Tab. 1, the damages have been calculated in reference to the building (structures, installation, fixuters) and to the content of the building [28].

The first was estimated using a parametric reconstruction cost approach, while the damages to the content where estimated through the cost of replacing content: it has been calculated by multiplying the average restoration cost of residential building structures by the Content to Structure Value Ratio (CSVR), that defines the value of the content according to the value of the structure [29]. The value chosen for CSVR is the same as the one proposed by other authors who state that the value of the content of a residential building is half the value of its structure.

With regard to the costs of replacing the contents of other types of buildings, the study referred to the one used for residential buildings, multiplied by the values of a parameter P, obtained either by expert judgment [30].

The damage, thus calculated, was interpolated into the frequency domain through a logarithmic function and the corresponding damage-probability curve was obtained (Fig. 5).

Through interpolation, damage estimatations were also obtained for other flood scenarios (T=25, 20, 5, 2, 1 years).

After defined the damages corresponding to each of the scenarios, the different types of structural interventions for flood risk mitigation and related costs have been identified (Tab. 2) according to the Sardinia Basin Authority.

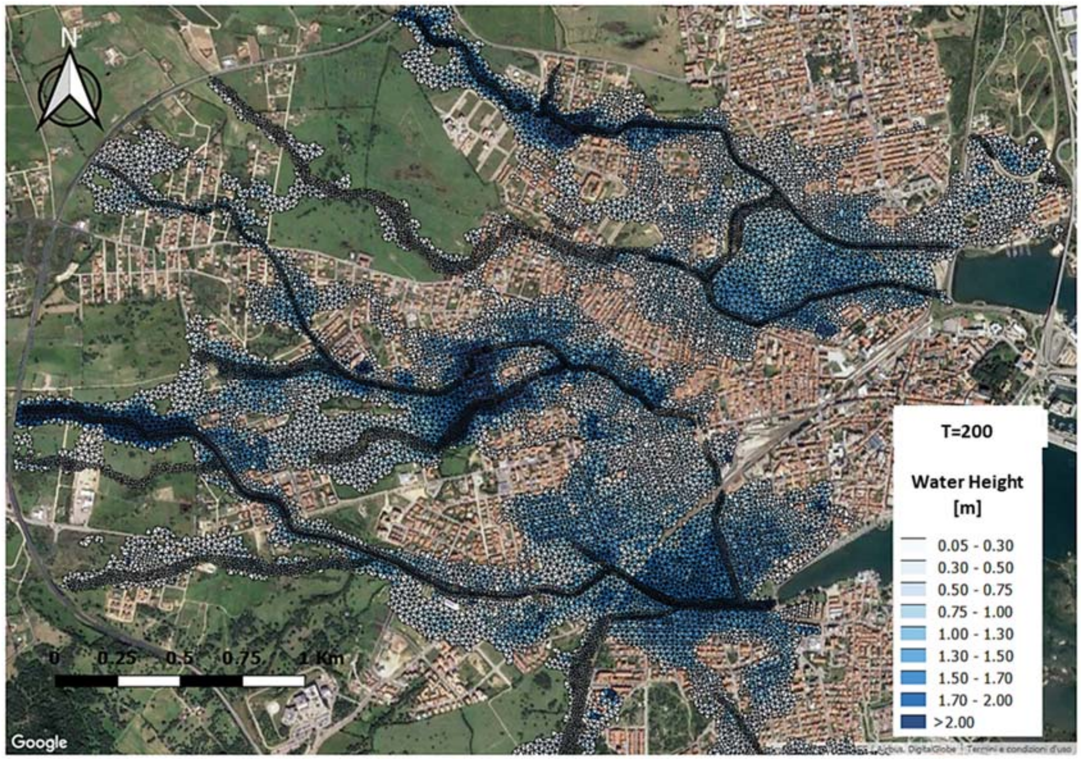

Fig. 3. Hazard layer: flood map related to a 200-year return period flooding scenario. The same maps have been developed for different year return period (50-100-500).

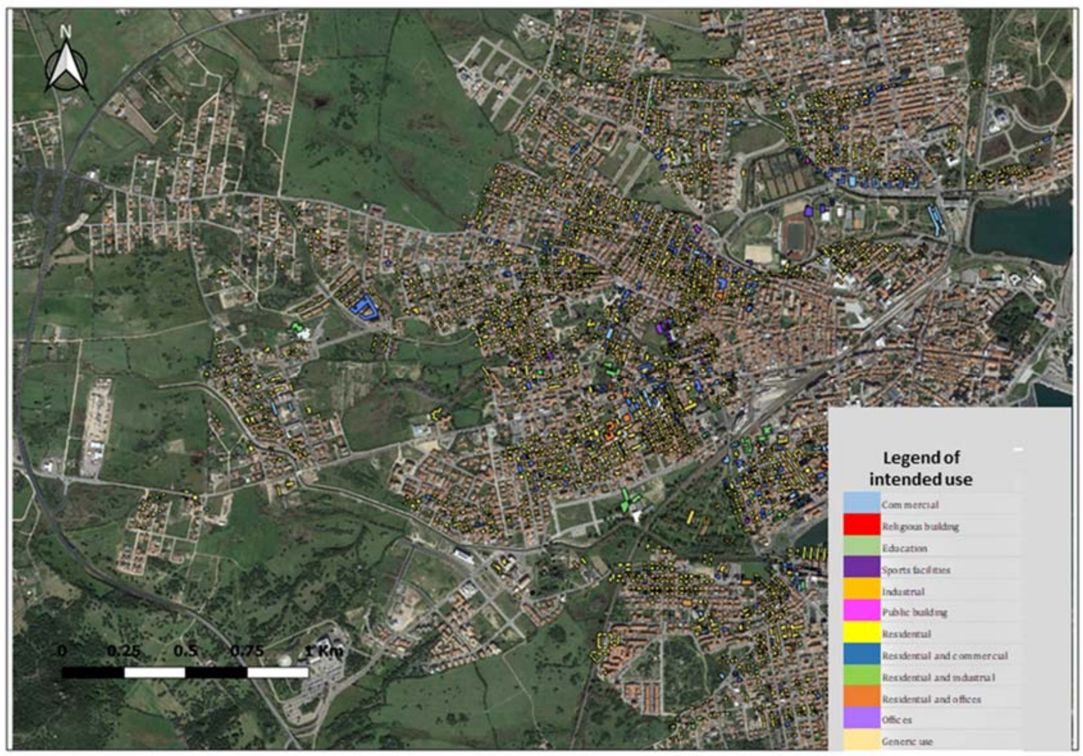

Fig. 4. Exposure layer: typology of building exposed.

T	Damage				
	Building (residential)	Content (residential)	Building (nonresidential)	Content (nonresidential)	Tot.
50	85.036.168	45.844.675	9.717.545	14.467.449	155.065.837
100	93.907.027	50.718.411	10.947.240	16.992.124	172.564.803
200	102.334.845	55.734.271	12.129.529	19.346.743	189.545.388
500	108.762.914	59.636.448	12.705.018	20.242.084	201.346.465

Tab. 1. The economic damage calculated for different flood scenarios.

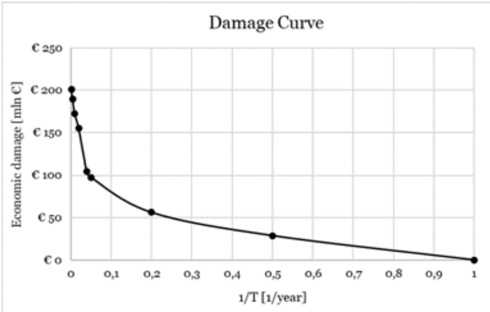

Fig. 5. The damage-probability curve.

T	1/T	Typology of intervention	Intervention costs [€]
1	1	No structural measure	0,0
2	0,5	No structural measure	0,0
5	0,2	Ordinary maintenance of watercourses	100.000
20	0,05	Enlargement of canals and reconstruction of bridges	5.040.000
25	0,04	Construction of retention basins	22.540.000

Tab. 2. Typology of intervention and related costs.

The measures indicated in Tab. 2 are intended to be incremental. Therefore, for example, in order to mitigate the damage resulting from a 500-year flood event, all the measures identified for the previous flood scenarios must be implemented.
Damage caused by events with a return period of 5 years can be mitigated through ordinary maintenance of the watercourses crossing the city. Events with a return period of 20 years can instead be managed through the reconstruction of those bridges that are an obstacle to the correct flow of water and through the widening of the canals. Retention basins are required to cope with events with a 25-year return period while, for events with T=50 years, spillway channels are also required.
In order to mitigate events with return periods of 100, 200 and 500 years, all structural measures previously identified, but re-designed on the basis of flow rate values specific to each of them, are required. A warning system was also envisaged as a non-structural measure.
Having identified the different types of interventions for the various flood scenarios considered, the corresponding damage reductions have been calculated. The mitigated damage (PAD - Prevented Annual Damage) from the various interventions identified for a given flood scenario was defined through (4) and (5).
In Tab03 the PAD and READ calculated are reported. The economic performance indicators NPV and IRR has been calculated throught a DCF analysis. The discount rate used for the application of the CBA has been diversified as follows:

- Discount rate of 2.6%, equal to the value of the 30-year government bond interest rate within the time horizon considered;
- Discount rate of 1.5% applied in the 30th year to take account of the continuity of both costs and benefits, that each intervention will generate in the years following the time horizon under consideration (perpetuity).

T	1/T	PAD Structural measure [€/year]	PAD FEWS [€/year]	READ [€/year]	PAD Total [€/year]
1	1	0,0	16.929.229	11.225.151	16.929.229
2	0,5	750.000	16.478.253	10.926.126	17.228.253
5	0,2	12.300.000	9.533.239	6.321.141	21.833.239
20	0,05	21.675.000	3.896.051	2.583.329	25.571.051
25	0,04	22.360.000	3.484.161	2.310.219	25.844.161
50	0,02	24.560.000	2.161.301	1.433.079	26.721.301
100	0,01	26.260.000	1.139.091	755.289	27.399.091
200	0,005	27.147.500	605.437	401.443	27.752.937
500	0,002	27.705.500	269.912	178.968	27.975.411

Tab. 3. PAD and READ estimated in each scenario.

The results considering only structural measure are reported in Figs. 6, 7. While the results introducing the warning system[1] are reported in Figs 8, 9.
The analysis of the results returns these considerations:

- The interventions designed to mitigate flood scenarios with return periods of 1,2 and 5 years have disadvantageous performance ratios both in terms of NPV and IRR;
- interventions identified for the mitigation of flood scenarios with return periods of more than 5 years are advantageous compared to all performance indices;
- the preferred advantageous intervention is the one allowing to mitigate the damage corresponding to a flood scenario characterized by T=20 years;
- the integration of alert systems with structural measures allows to improve, for each structural intervention considered, the SCBA performance indicesm regardless of the degree of preparedness of the population and the alert time.

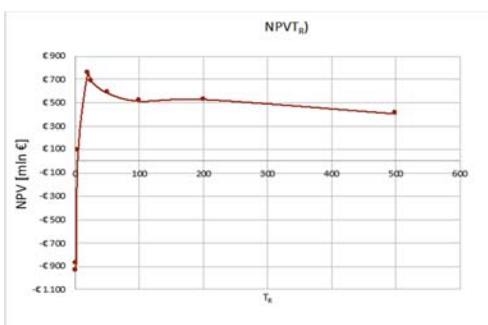

Fig. 6. The Net Present Value (NPV) calculated considering only structural measure.

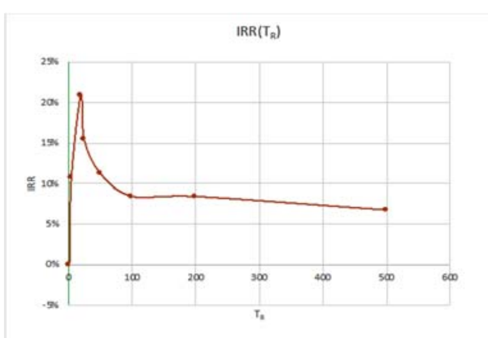

Fig. 7. The Internal Rate of Return (IRR) calculated considering only structural measure

Conclusion

The article shows a procedure for the application of the SCBA to the assessment of flood risk mitigation and management projects, as required by sector specific legislation. The proposed methodology is based on the logic of scenarios and is developed in a GIS environment, in order to spatialize economic magnitudes, i.e. the expected damage with respect to different hydraulic hazard scenarios. The first results obtained show that the only chance to limit cost to an affordable amount, is to lower the return period of the design discharge of the defense structure, increasing the residual risk or the hazard of the flood. The ongoing transformation in land use and the recent climate trends lead to adopt a change of paradigm in the approach to natural hazards, moving from the only defensive passive actions to integrated sustainable management of the risk, which means coping with floods in a preparedness territory with a high level of resilience.
Furthermore, the first applications of the methodology have pointed out some operational issues, related to the difficulty of collecting geo-referenced territorial data, i.e. the height of the buildings: this kind of issue could be solved through the cooperation with public entities, as the Territory Agency. Another relevant issue to be faced concerns the estimation of indirect and intangible damages, given the uncertainty deriving from a large-scale ex-ante evaluation of the Total Economic Value; this is extremely important when dealing with such a complex territorial system, as HUL is: further research developments should therefore be oriented in these directions, in order to implement a tool to support choices, easily applicable to the various cases on the territory.

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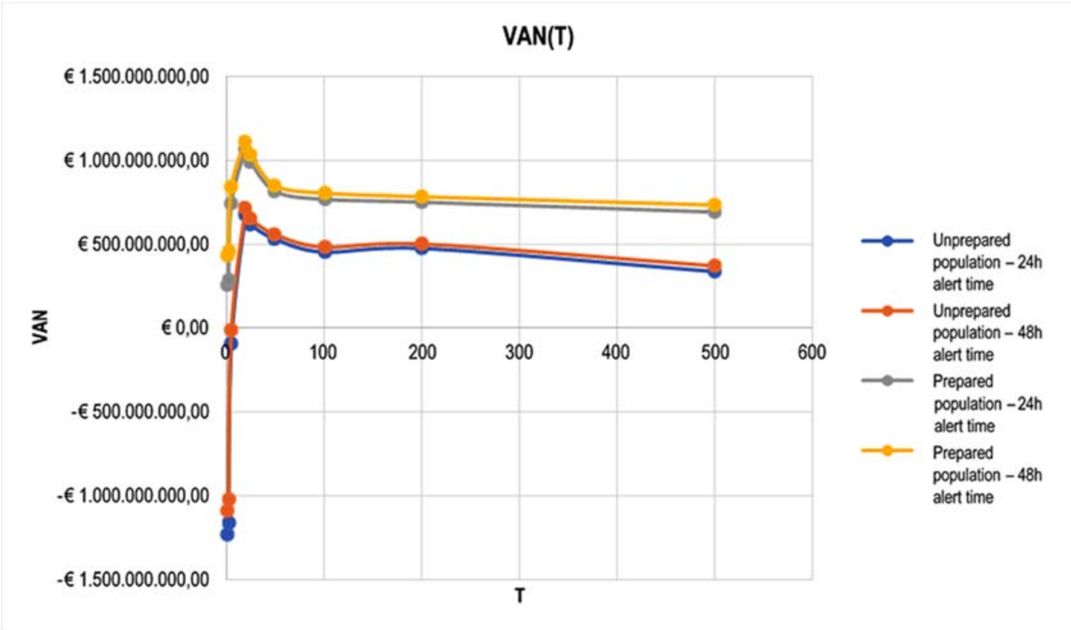

Fig. 8. The Net Present Value (NPV) calculated considering structural measure and worning system.

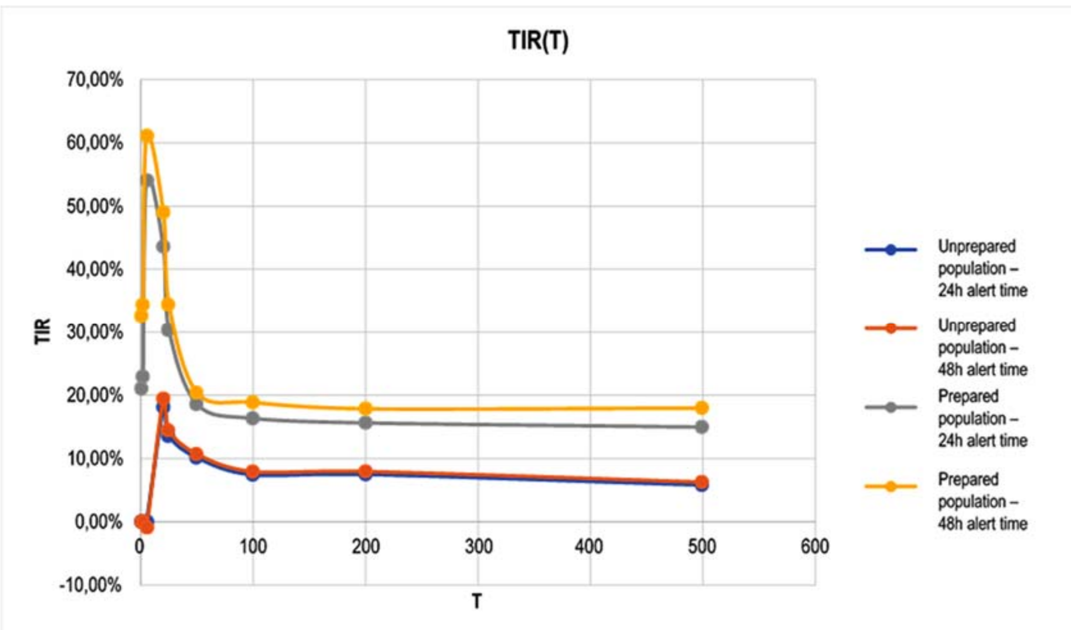

Fig. 9. The Internal Rate of Return (IRR) calculated considering structural measure and worning system.

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NOTES

1. In the case of Olbia, it was decided to assess the extent to which rapid alert systems (FEWS) are able to reduce residual damage not mitigated by the structural measures previously introduced. For these estimates, it was decided to refer to the reports proposed by Handmer and Smith (1990) which assess the effectiveness of early warning systems in relation to both the time of alert and the degree of preparedness of the community living in the territory. Since the alert systems are considered effective when they allow to issue alerts to the population in a period of time not less than 24 hours after the occurrence of a flooding event, it was decided to evaluate their performance in the following situations:
   - Unprepared population, 24h alert time;
   - Unprepared population, 48h alert time;
   - Prepared population, 24h alert time;
   - Prepared population, 48h alert time.