Nature-based Simulation to Address Climate Change-Related Flooding. Preliminary Insights on a Small-Sized Italian City

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Abstract. Climate change impacts on cities are likely to require changes in urban adaptation planning. Despite the low degree of climate change manageability, the Nature-Based Solutions (NBS) are considered resilient measures that integrate the ecological dimension into spatial planning while playing a crucial role in addressing societal challenges and multiple benefits.

In urban planning, ecosystem models can be used to develop flood management strategies even if the limited experience with models and model output is a challenge for planners in thinking about addressing potential climate change impacts effectively. Consequently, this new challenge is based on the need for spatially explicit biophysical assessment related to NBS scenarios' implementation.

This study considers the urban flood vulnerability assessment and how these vulnerabilities can be reduced through NBS simulation scenarios in a small-sized Italian coastal city of the Liguria Region. To quantify the amount of runoff during extreme rainfall events while identifying the greatest critical areas, the Urban Flood Risk Mitigation model (InVEST) integrated into a GIS environment have been employed. Furthermore, the biophysical assessment of NBS implementation has been supported by highlighting the crucial role of biodiversity type.

Keywords: Climate change adaptation · Pluvial flood · Spatial modelling

1 Introduction

Cities are becoming increasingly vulnerable to weather extremes, especially by considering flash flooding events resulting from short-duration intensive rainfall [1, 2]. In the context of climate change, this scenario is exacerbated mainly in coastal urban areas, where compound flooding due to simultaneous storm surge, sea-level rise and increased runoff during extreme rains requires deepening local knowledge of the flood-prone regions [3, 4]. The supply of urban ecosystem services (ES) can help mitigate

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these climate change effects while improving human health and well-being in cities [5, 6]. The concept of Nature-Based Solutions (NBS) is considered as the new planning tool for ecologically sensitive urban development. Indeed, NBS include the main ideas of green and blue infrastructures and ecosystem services overcoming the boundaries of traditional approaches "predict and prevent" [7]. These innovative solutions comprise natural features characterized by multifunctionality and connectivity, thus providing multiple co-benefits (environmental, social and economic) [8].

According to DG Environment of the European Commission (2011) in "Towards Better Environmental Options in Flood Risk Management" such measures "*can be effective in protecting against flooding, as well as provide other benefits deriving from ecosystem services, such as for leisure activities and nature protection*"[1]. In this view, the NBS implementation and the simulation of biophysical impacts of NBS to reduce runoff volume can be considered good practice to quantify the benefits of these measures, mainly in terms of water regulation and flood control. Only evaluating simulation scenarios helps to adopt site-specific performance-based solutions, also differentiating more suitable vegetation type. This kind of approach has the potential for future urban strategies in the face of climate change.

For these reasons, this study aims to show the important role of ecosystem services implementation to support climate change adaptation planning. Adopting an integrated evaluation method is used to explore alternative nature-based scenarios on the study case of a small Ligurian city (Italy). The application of InVEST modelling combined with Geographic Information System (GIS) enhances estimating the spatial distribution of urban flood-related vulnerabilities while identifying where and how NBS can contribute to adapting the city. The novelty of this research is related to the application of integrated ES spatial modelling to provide results regarding flood risk mitigation through the NBS implementation. This paper is structured as follow: methodology presenting firstly, the functioning and data input of the Urban Flood Risk Mitigation model (InVEST) and the combination with GIS environment; secondly, describing the NBS scenarios and lastly, presenting the catchment area for the analysis; the results and discussions sections describe the output of implemented scenarios; conclusions shortly explaining the limit of this research and setting possible applications for future research.

2 Methodology

Such spatial integrated approach combines Geographic Information Systems (GIS) tools with InVEST modelling. Furthermore, this method is scenario-based since it is characterized by simulating three scenarios through adopting the Urban Food Risk Mitigation model. This enables us to examine simulation results to finally quantify and evaluate the NBS benefits regarding flooding regulation.

2.1 InVEST Model and GIS Integration

The Urban Flood Risk Mitigation (UFRM) model is a recent product (2019) of the software InVEST - 3.9.0 (Integrated Valuation of Ecosystem Services and Tradeoffs) part of

[1] https://ec.europa.eu/environment/water/flood_risk/better_options.html.

the Natural Capital Project[2]. This spatial model focuses on urban areas' ability to reduce runoff due to extreme rainfall and flash flooding events [9]. The UFRM model considers the potentiality of permeable green places to mainly reduce runoff while slowing surface flows and creating space for water (as in floodplains or basins). The model output represents the amount of retained runoff per pixels assuming mainly the flood-prone areas due to the interaction between the permeable-impermeable surface layers (related to the land use type) and the soil drainage (depending on the soil characteristics). This urban flood model uses the USDA (United States Department of Agriculture) Soil Conservation Service – "SCS runoff curve number" (SCS-CN) method to estimate runoff, which is based on the water balance equation of the rainfall. The SCS-CN method has been developed for runoff volume estimation and it knew widespread use by public agency, local governments, and professionals [9, 10]. The runoff retention index estimated per pixel (R_i) represent the ratio between the quantity of precipitation retained (P-Q) and the total precipitation (see Eq. 1)) over the study area:

$$R_i = 1 - \frac{Q_{p,i}}{P} \tag{1}$$

Required model inputs, a short description and the source are synthesized in Table 1.

Since the InVEST software works with spatial models, the elaboration of model inputs and outputs is conducted through the employment of GIS tools. The UFRM model solves the empirical representation of the hydrological aspects for estimating runoff production and retention ability in the study area [12]. By applying GIS-based approaches to elaborate model's output, the potential localization of the implementation areas (opportunity spaces) for selected NBS is identified [13]. Overall, the resulting spatial index from GIS provides a picture of the vulnerability pattern and the biophysical assessment [14]. Figure 1 shows the flow diagram of the integration among various methodological steps.

2.2 NBS Scenarios

Although quantitative reduction targets of flood risk or proposed methodologies for NBS implementation are missing in the Flood Directive, an estimation of the possible contribution of NBS to manage flood risk is provided by simulating the biophysical impact derived by the diffuse implementation of these measures. This method provides a quantitative reduction target while setting the NBS scenarios by selecting the vegetation necessary to reach it.

The NBS biophysical benefits assessment has been developed by simulating changes on the curve number values for hydrological soil groups in the sensitivity table of model input to increase the city's retention capacity. This assumption keeps constant all the other data input. The base scenario represents the present state, while NBS-1 and NBS-2 concern the future adaptation scenarios after NBSs implementation (see Fig. 2). The prioritization of the suitable areas for implementing NBS follows the vulnerability analysis provided by the base scenario. Particularly, the scenario NBS-1 is characterized by

[2] Available at https://naturalcapitalproject.stanford.edu/software/invest.

Table 1. UFRM model inputs

Data type	Description	Source (year)
Watershed vector	Hydrographic basins delineating the studied area	- Geoportal Liguria (2019)
Depth of rainfall	Total rain for a given single storm event typical of the region. Value of 70 mm for 3 h of rainfall duration	- ARPA Liguria - [2]
Land Cover raster	Integration of two data, respectively Land cover and Imperviousness maps, to obtain this raster categorized following USDA (United States Department of Agriculture) classes	- Geoportal Liguria (2019) - SINANET (2015)
Soil Hydrological Group (HSG) raster	HSG represents the saturated hydraulic conductivity of soils (Ksat mm/h). Employment of 'Landscape Units' and 'Profili and Trivellate' to build the final map	- Geoportal Liguria (2000)
Sensitivity table	This table represents the land use classes associated with each HSG	- [11]

implementing 'Green parking' in areas classified as 'urban district' following the Land cover map. Only those areas with 72% of impervious surfaces that highlighted low-level runoff retention capacity below 60% in the base scenario set scenes of NBS-1 measures. Li et al. (2018) demonstrated that permeable pavements could absorb stormwater improving overland flow regulation by approximately 67% [15]. The scenario NBS-2 concerns the implementation of 'Rain gardens' along the streets. This measure has the function to collect and store stormwater attenuating runoff while having esthetical functions (amenity value). The classes categorized as 'street, roads and railways' for the Land cover map, which have shown low retention capacity around 50–60% from the base scenario, have been chosen for the implementation.

The definition of these two NBS-scenarios has been developed under the 'Piano Nazionale di Adattamento al Cambiamento Climatico' (PNACC - 2017), which identifies 21 key actions among various sectors synthesized in four main fields: hydrogeological instability, coastal area management, biodiversity, and urban settlement [17]. Particularly, both NBS-scenarios definition follows the Cloud Burst action plan of the Local Resilience Strategy - Genova Lighthouse. Indeed, through the Urban Agenda Genova 2050, this action foresees the implementation of adaptation measures based on nature (as NBS) integrated with grey approaches to reduce runoff volume due to extreme rainfall events by mainly integrating greenways and converting impervious surfaces [18].

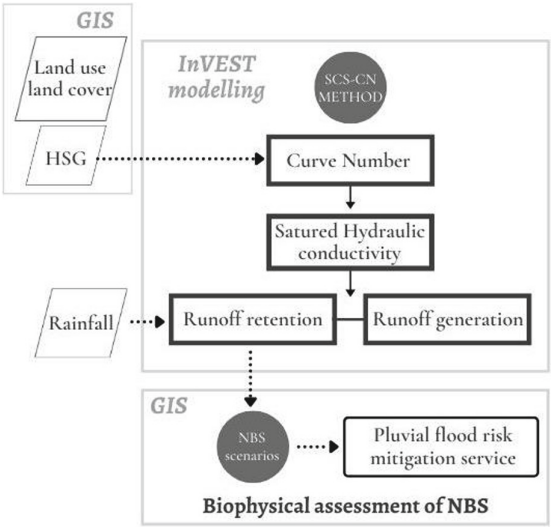

Fig. 1. Flow diagram of the integrated approach

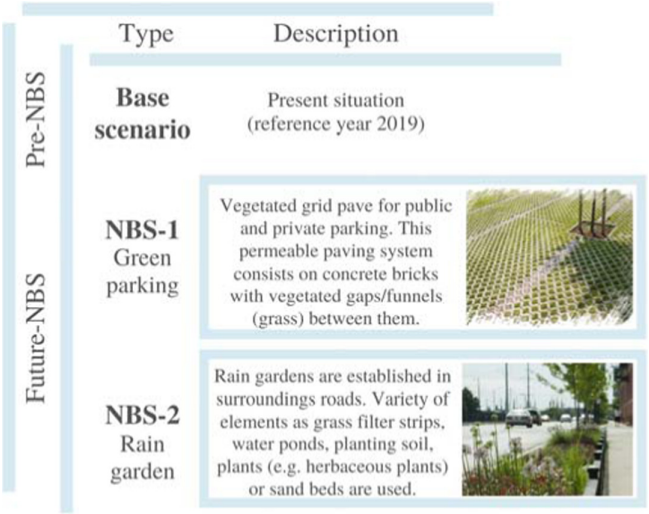

Fig. 2. NBS scenarios overview (authors' elaboration from [16]).

2.3 Study Area: City of Rapallo

The area of analysis is the city of Rapallo. Rapallo is a coastal city in the Metropolitan area of Genoa in the Liguria Region (Italy) (see Fig. 3). The municipality, located 25 square kilometres southeast of Genoa, is part of the Tigullio Gulf. With an extension area of about 34 square kilometres, the city of Rapallo covers one major natural watershed linked to the Boate torrent and other seven smaller basins. The watershed boundaries

have been used as a delimiting area to run the InVEST model. The town lies 3 m above sea level, mainly extending through a lowland between Boate and San Francesco torrents.

The Mediterranean climate characterizes this area through essentially rainier months during the winter season. However, from recent studies, extreme rainfall events frequently occurred in this Mediterranean region, causing intense flooding, especially in the eastern part (Levante) of Liguria[3].

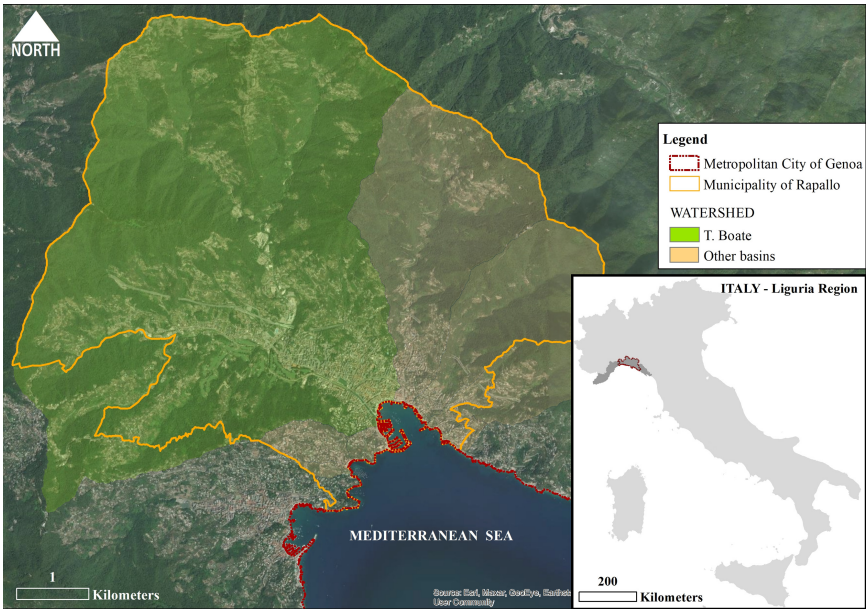

Fig. 3. The study area (authors' elaboration)

3 Results and Discussion

This section provides a critical analysis of the InVEST model's output for the study area by discussing the two NBS-scenarios implementations.

The hydrological curve number values in this study area vary between 30 to 98 across various pixels (excluding water bodies with curve numbers equal to 0). The dimension of pixels used for this analysis is of 5 m. The average values for the watersheds considered are between 61.26 and 86.79. This means that the studied catchment area presents a moderate degree of runoff production. As the urban landscape is more based on concrete surfaces, the runoff generation increases reflected through higher curve number values. Flood mitigation capacity by NBSs-scenarios is provided in terms of runoff retention index and quantified in runoff retention and runoff generated volume (see Table 2).

[3] https://www.arpal.liguria.it/homepage/meteo/analisi-climatologiche/atlante-climatico-della-liguria.html.

The total cumulative runoff volume calculated by the InVEST model in the study area for a design storm of 3 h duration having 70 mm of intensity is around 21.33 m^3. This amount corresponds to the runoff estimated for the base scenario, which showed a runoff retention index equal to 69.52%. The runoff retention index represents the relative measure of runoff volume retained in respect to the precipitation volume and ranges from 0 (low retention) to 1 (high retention).

Table 2. Summary of biophysical impacts' simulation

Scenarios	Runoff retention index %	Cumulative runoff retention volume m^3	Cumulative runoff volume m^3
Base	69.52%	1.22 m^3	21.33 m3
NBS-1	71.44%	1.25 m^3	19.99 m^3
NBS-2	69.76%	1.22 m^3	21.15 m^3

The NBS-1 scenario showed an average value of runoff retention index equivalent to 71.44%, with the cumulative amount of runoff volume approximately 20 m^3. Therefore, through a diffuse implementation of 'green parking' for a portion equal to 10% of the urban district, the mean value of the retention capacity for Rapallo municipality is most performing of approximately close to 3%.

By implementing NBS-2, which is characterized by 'rain gardens' for 8.8% of the street zones, the resulting runoff volume is very little lower (21.15 m^3) regarding the base scenario (21.33 m^3). Indeed, the runoff retention capacity increased only by 0.035%.

Overall, the average values of retention capacity for two NBS-scenarios varied between 0.6976 and 0.7144, indicating that 69–71% of the precipitation amount is retained in the catchment area of Rapallo (3348.16 ha as total surface area calculated on all census areas for Rapallo municipality).

Figure 4 illustrates the runoff retention index spatially distributed using the mean retention value for each pixel for base scenario (a), NBS-1 (b) and NBS-2 (c) simulations. This way helps to visualize the entity of waterflow event by identifying where and how should be increased the mitigation capacity from higher values of retention represented by a blue colour on the map to a lower value of retention, red in the map. NBS intervention areas' frames show the location of the NBS-scenarios implementation in Fig. 4(b) and (c).

4 Conclusion and Future Perspectives

This study represents the preliminary results of an ongoing research for that study area. The analysis is a first attempt to test and estimate the biophysical effects of NBS implementation on pluvial-related floods mitigation. The employment of the recent InVEST model, Urban Flood Risk Mitigation, and spatially mapping of elaborated outputs

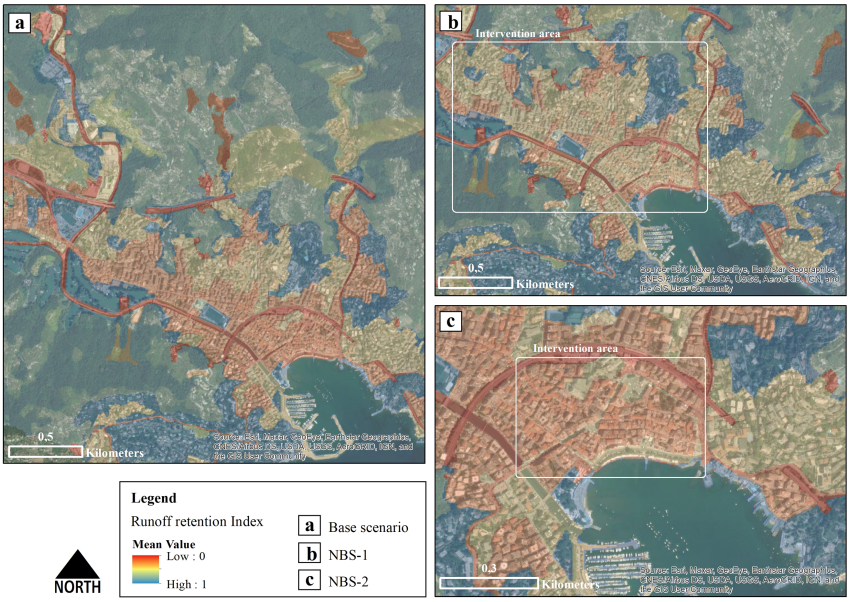

Fig. 4. Runoff retention capacity per pixel for the Base scenario, NBS-1 and NBS-2 (authors' elaboration)

through GIS environment in a small Italian coastal city highlights how performance-based adaptation planning could aid the decision-making process. The ES modelling output has been used to evaluate the biophysical values of runoff through measurable impacts at the urban level. This InVEST model for estimating urban flood risk is designed to suit hydrological aspects for easy implementation in adaptation policy research. Indeed, the SCS-CN method used by the model is a widely accepted empirical approach with limited data requirement. In addition, the GIS-based modelling enables to obtain detailed maps on pluvial flood vulnerability distribution while understanding where NBS can better contribute to adaptation. Nevertheless, the spatial variability and duration of the rainfall event are not integrated in the model. Further improvement by including this information into the analysis should be developed.

The results show that a diffuse implementation of NBS can improve the city's retention capacity. Still, the typology of measure and the chosen vegetation plays a crucial role for best performing. Indeed, changes in soil, climate and hydrological conditions call for defining how different ecosystems' restoration methods, including various landscapes, planning procedures and vegetation types, best fitted to local environments [10].

To manage the simulation NBS-scenarios implementation consistently, a deepening on threshold values to be employed by modifying curve numbers for hydrological soil groups will be conducted. This paper results could represent a starting point for future developments refining, for example, the NBS-scenarios building by selecting specific vegetation types for high-performance rate under changing climate conditions [19]. Indeed, this study is a contribution to assessing NBS effectiveness to reduce pluvial flood for Rapallo Municipality. Results could be improved by integrating a cost-benefit

analysis of NBS implementation, considering the economic savings from flood damage reduction and other non-monetary benefits.

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