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Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation

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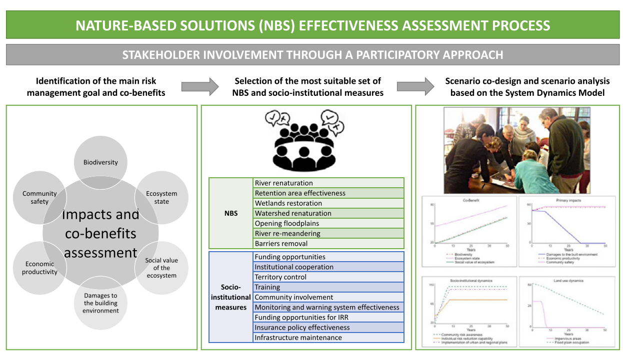
HIGHLIGHTS

- Nature-Based Solutions (NBS) reduce water-related risks and produce co-benefits.
- Valuing co-benefits is crucial to support NBS mainstreaming.
- Participatory activities allow effective stakeholder involvement in NBS co-design.
- System Dynamics Modelling (SDM) is used to perform NBS effectiveness assessment.
- SDM supports scenario analysis and comparison among different measures.

GRAPHICAL ABSTRACT



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ABSTRACT

There is an imperative worldwide need to identify effective approaches to deal with water-related risks, and mainly with increasingly frequent floods, as well as with severe droughts. Particularly, policy and decision-makers are trying to identify systemic strategies that, going beyond the mere risk reduction, should be capable to deal simultaneously with multiple challenges (such as climate resilience, health and well-being, quality of life), thus providing additional benefits. In this direction, the contribution of Nature Based Solutions (NBS) is relevant, although their wider implementation is still hampered by several barriers, such as the uncertainty and lack of information on their long-term behavior and the difficulty of quantitatively valuing their multidimensional impacts. The activities described in the present paper, carried out within the EU funded project NAIAD, mainly aim at developing a participatory System Dynamic Model capable to quantitatively assess the effectiveness of NBS to deal with flood risks, while producing a multiplicity of co-benefits. The adoption of a participatory approach supported both to increase the available knowledge and the awareness about the potential of NBS and hybrid measures (e.g. a combination of NBS and socio-institutional ones). Specific reference is made to one of the demos of the NAIAD project, namely the Glinščica river case study (Slovenia).

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1. Introduction

Natural disasters are becoming ever more extreme, increasing in frequency and intensity, and with significant impacts on communities, on the economy and on the built environment (UNISDR, 2015). Among all natural hazards, flooding represents the main concern of European emergency management authorities (EEA, 2016; Faivre et al., 2018). Flood damages are expected to increase dramatically over time, leading policy-makers toward the implementation of innovative risk management strategies and solutions (e.g. EEA, 2017; Keesstra et al., 2018).

In the last decades, the most common approach to reduce flood impacts has been related to the use of 'grey' solutions (e.g. dams, embankments, levees, etc.) (Muller et al., 2015), although they demonstrated several limitations (EEA, 2017). For instance, they are capital intensive, often responsible for damage or elimination of the biophysical processes necessary to sustain both people and ecosystems, and even associated to a misleading sense of security that might condition communities' behavior (Palmer et al., 2015). Nature-Based Solutions (NBS), namely "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" are instead being increasingly adopted. NBS (e.g. wetlands restoration, reforestation, watershed/river renaturation) have the capability to reduce disaster vulnerability, but also a potential for nature conservation, natural resources management and for supporting the mitigation of and adaption to the disturbances generated from climate extremes and urbanization (Dong et al., 2017; European Commission, 2016; Liu et al., 2015; Nesshöver et al., 2017). NBS bring together multidimensional benefits that integrate technical, economic, governance, regulatory and social innovation (European Commission, 2015; Raymond et al., 2017b).

There is an increasing number of evidences on the positive effects of NBS on risk reduction and climate change adaptation (Kabisch et al., 2016), especially if they are strategically planned and managed, and interconnected in a network of solutions (Albert et al., 2019; Palmer et al., 2015; Raymond et al., 2017b). However, several uncertainties still exist to a fully effective implementation of NBS, and there is a need to promote their introduction and mainstreaming using the available knowledge while further exploring how challenges and issues might be faced (Cohen-Shacham et al., 2016; Kabisch et al., 2016; Schanze, 2017; Thorne et al., 2015). Firstly, the process of understanding which approaches would be more effective in the long term and which immediately after implementation is challenging. This aspect reflects the need for a long-term data collection and observation of the impact of NBS also through the comparison of experiences. Secondly, a relevant knowledge gap concerns the design process and, particularly, the role of existing technical knowledge to support their integration alongside grey infrastructures. Thirdly, NBS implementation has been little investigated, specifically on legal instruments, tools and requirements for a successful implementation. There is, in summary, a need to identify promising practice strategies for planning, designing and implementing NBS and generating more knowledge on their cost-efficiency in comparison to conventional grey approaches (Kabisch et al., 2016).

Such elements of uncertainty are responsible for several barriers, for instance institutional, legal, managerial, political, monetary and social. Among the most relevant ones, a key role is played by social and institutional acceptance, responsible e.g. for the resistance to change, reluctance to invest, lack of resources and perceived lack of policy support (O'Donnell et al., 2017). In this direction, acknowledging and underlining the multi-functionality of NBS, valuing their capability to provide benefits to multiple stakeholders and to meet several strategic objectives, has become central. Identifying all the benefits that can be produced for different beneficiaries, could support the development of a shared understanding and a negotiated set of values, thus leading communities to be more inclined to support implementation (O'Donnell et al., 2017). However, since NBS implementation involves a multiplicity of stakeholders with their individual objectives, specific risk perception and problem understanding, suitable tools need to be used to support investigating the potential impacts, to facilitate a dialogue, aligning divergences and promoting the social acceptance (Santoro et al., 2019). Although these issues are relatively well understood, there is still a lack of targeted strategies to overcome them beyond generic suggestions (e.g. promoting education, awareness raising, and stakeholders' engagement).

Starting from these premises, the present work proposes a participatory System Dynamics Modelling (SDM) approach, for the assessment of NBS effectiveness, with a specific focus on their capability to produce co-benefits (e.g. nature conservation, community well-being, etc.) besides supporting risk reduction (e.g. flood risk reduction). Specifically, the proposed model aims to: i) semi-quantitatively simulate the multi-dimensional impacts of NBS (in combination with socio-institutional measures); ii) analyze their effectiveness with respect to the main risk management goals and co-benefits identified by the involved stakeholders. This article argues that modelling the multi-dimensional NBS effectiveness might be the key to raise awareness and enhance the social and institutional acceptance of these measures. This work has been carried out within the EU funded project NAIAD, and specific reference is made to the Glinščica river case study (Ljubljana, Slovenia). The research activities aim to answer to some of the guiding questions still open on NBS (Schanze, 2017): i) how can the potential of NBS in terms of risk reduction and co-benefits production be investigated in an integrated way? ii) how can the design of NBS be supported taking into account the wide range of objectives and dimension involved? iii) how can NBS be combined and implemented, starting from a comprehensive impact assessment integrating risk reduction benefits and co-benefits? iv) how can the participatory design and implementation of NBS portfolios be supported, enhancing cultural and social acceptance and feasibility, thus overcoming existing barriers?

2. Frameworks and approaches for NBS effectiveness assessment

Despite the growing attention on NBS, a stronger evidence base is needed on their multiple benefits and co-benefits, and assessment frameworks are required to prove their multi-dimensional effectiveness. In fact, the process of measures selection is significantly complex, given the numerous options, criteria and combinations that can be identified (Alves et al., 2018). The existing assessment frameworks are only partially capable to drive this process, and still far from being able to support an integrated assessment and decision-making (Calliari et al., 2019).

Going further into details, most of such frameworks focus on the effectiveness analysis in terms of risk reduction. The main limitations are related to the lack of stakeholders' involvement (Calliari et al., 2019; Narayan et al., 2017), as well as to the limited capability to analyze the NBS potential for producing co-benefits and to describe the dynamism associated with their implementation (Kabisch et al., 2016; World Bank, 2017). The issue of co-benefits assessment is, instead, central in the EKLIPSE framework proposed by (Raymond et al., 2017a, 2017b), which starts from the identification of ten 'challenges' and of the expected impacts of NBS, characterized in terms of benefits and costs, together with related indicators. The authors explicitly underline the importance of using participatory approaches in co-benefits assessment, although the framework has still limited potential in driving decision-making (Calliari et al., 2019). Participatory Multi-Criteria Analysis was used to identify and analyze the multiple benefits of a NBS in an ex-post assessment, starting from the analysis of stakeholders' preferences (Liquete et al., 2016). A novel method was also proposed to support selection of both green and grey measures, including the definition of preferences over a broad range of co-benefits. The method, in its current form, is still limited in the possibility of performing the analysis with multiple measures and in including stakeholders (Alves et al., 2018). The assessment of co-benefits in different scenarios is also central in the framework proposed by Lanzas et al. (2019), although additional investigation is needed in the characterization of the potential conflicts and/or co-benefits between different objectives.

Most of the cited approaches are based on linear causal thinking, thus providing a limited representation of the multiplicity of interactions, dependencies and constraints in the diverse sub-systems in which NBS are set to operate (Calliari et al., 2019). Additionally, some of them provide a limited stakeholders' involvement, do not allow scenario analysis (useful to support comparative assessment of NBS effectiveness) and dynamic simulation (crucial to take into account the evolving environmental conditions in which NBS operate as well as the time needed to become fully effective). Considering such limits, the use of System Dynamics Modelling techniques (SDM) could help investigating the behavior of complex systems over time by converting the whole system into a set of variables interconnected also through feedback loops (Chen and Wei, 2014; Zomorodian et al., 2018). It may support the development of participatory and shared vision models, reducing the level of conflict among different agents, providing a clearer basis for decision-makers, and supporting a wider participation, understanding and awareness on specific issues (Zomorodian et al., 2018).

After its early applications mainly in industrial and urban dynamics (Forrester, 1990, 1987), SDM soon showed significant potential to support the analysis of environmental systems, which are highly complex and dynamic and comprise numerous interacting elements and interdependencies (Nabavi et al., 2017; Sahin et al., 2018). SDM consists of both qualitative/conceptual (e.g. Causal Loop Diagrams) and quantitative/numerical modelling methods (e.g. stocks and flows models) (Sterman, 2000). 'Participatory SDM' is a broad definition, that refers to any approach for engaging stakeholders in problem analysis, such as group model building and mediated modelling (Stave, 2010). It generally relates to the use of SDM to structure group analysis of a problem, whether through a conceptual or a fully operational model, and whether or not the model users are involved in model development. Stakeholders participate to some degree in different stages of the process, including problem definition, system description, identification of policy levers, model development and/or policy analysis (Voinov et al., 2016; Voinov and Bousquet, 2010).

Several recent applications highlighted the relevance and the potential of using participatory SDM in the integrated water resources planning and management (de Vito et al., 2019, 2017; Gastelum et al., 2018; Pagano et al., 2018; Wang et al., 2018) as well as in the 'water security' field (Chapman and Darby, 2016; Chen and Wei, 2014; Pagano et al., 2017; Phan et al., 2018). Dealing specifically with flood risk, participatory SDM has been used to support decision-making (Berariu et al., 2016) and community active involvement (Cassel and Hinsberger, 2017; Giordano et al., 2017). A few studies also used SDM to perform an integrated analysis of the impact of multiple measures, such as NBS, on flood risk and related environmental issues. Chu et al. (2010) adopted a SD based approach to analyze a multipurpose urban shallow artificial lake, simulating the impact of multiple different strategies. SDM also supported to identify stakeholders' mental models and to simulate a dynamic wetland environment (Chen et al., 2014). Such technique was also adopted for resilience assessment with focus on flood risk in case of typhoons, assessing the effect of the introduction of green infrastructure (roofs, infiltration storage facilities and porous pavement) (Song et al., 2018).

The adoption of participatory SDM techniques for the purposes of the present work has multiple elements of relevance. Firstly, it could support organizing the collective knowledge of stakeholders in a graphical structure that promotes learning as well as constructive and targeted discussions to conceptualize and understand problems (Rich et al., 2018; Vennix, 1996). Secondly, it supports active collaboration and the rigorous integration of different expertise and interdisciplinary skills, thus building greater trust in models (Zomorodian et al., 2018). Thirdly, it may contribute to show how the complex interconnections among system elements may lead to unexpected effects, thus helping to anticipate possible rebound effects or policy resistance (Meinherz and Videira, 2018; Pluchinotta et al., 2019a) as well as to identify suitable strategies to act on the systems (Lopes and Videira, 2017). Lastly, besides the model, the whole process itself promotes awareness and motivation of those taking part in decision- or policy-making processes, thus providing a platform for the joint-ownership of results (Pluchinotta et al., 2019b, 2018; Rich et al., 2018).

3. Description of the case study

The activities described in the present paper were performed in one of the case studies of the NAIAD project, namely the Glinščica river case study. The Glinščica catchment is located in Slovenia, within the borders of the municipality of Ljubljana and has an area of approximately 17 km^2 (Fig. 1). The catchment headwaters are natural, mainly characterized by forest and, in some areas, by pastures; the downstream area, instead, is particularly suitable for both agricultural activities and for urbanization. Steep slopes in the headwaters give rise to a fast and powerful water flow that historically dissipated in the meanders starting at the foothills and extending throughout a forested floodplain before discharging into Gradaščica stream. However, due to the expansion of urban areas in the lowlands of the river basin, the hydrological regime of the river basin has changed dramatically with an increased proportion of impervious surfaces. The typically torrential behavior, along with the negative effects of uncontrolled urban development, groundwater level raise, and climate change result in regular flooding particularly in some districts of the city.

Several initiatives have been proposed during the last decade in order to comply with the requirements of the European Water Framework Directive (2000/60/EC) and Flood Directive (2007/60/EC). The occurrence of severe floods (mainly in 2010 and 2014) also contributed to stress the need to identify strategies to reduce risk level and the impacts of extreme events. Such initiatives were mainly oriented to restore Glinščica, fostering the environmental sustainability and bringing the system toward a more natural state, securing the vulnerable areas from flooding. The restoration of natural features has been integrated in the Municipality planning actions as one of the priorities in water management, in order also to support the conservation of the ecological status of water bodies. Glinščica is also one of the priorities for river restoration in the Slovenian Program of Fish Management.

Multiple stakeholders were involved in project activities and in participatory exercises as thoroughly described by (Santoro et al., 2019). Both institutional agents, with specific roles and prerogatives in decision-making processes at catchment scale (e.g. key ministries and municipal offices), and key agents within the community (e.g. civil initiatives) were included in the activities. Further details can be also found in Pengal et al. (2017).

4. Methodological approach

The present section summarizes the participatory process that has been carried out in the Glinščica case study (Section 4.1), then focusing specifically on the key output, i.e. the participatory SDM for NBS effectiveness assessment (Section 4.2).

4.1. Overview of the participatory process

The whole methodological process adopted is schematized in the following Fig. 2.

Briefly, within the 'qualitative modelling phase', described in detail in (Santoro et al., 2019): i) Fuzzy Cognitive Maps (FCM), are applied to elicit and structure stakeholders' risk perceptions, knowledge, and problem frames; ii) the Ambiguity Analysis is then carried out on individual FCMs in order to highlight similarities and differences among stakeholders' risk perceptions. This phase contributed to the definition of a collective FCM and the identification of key variables and

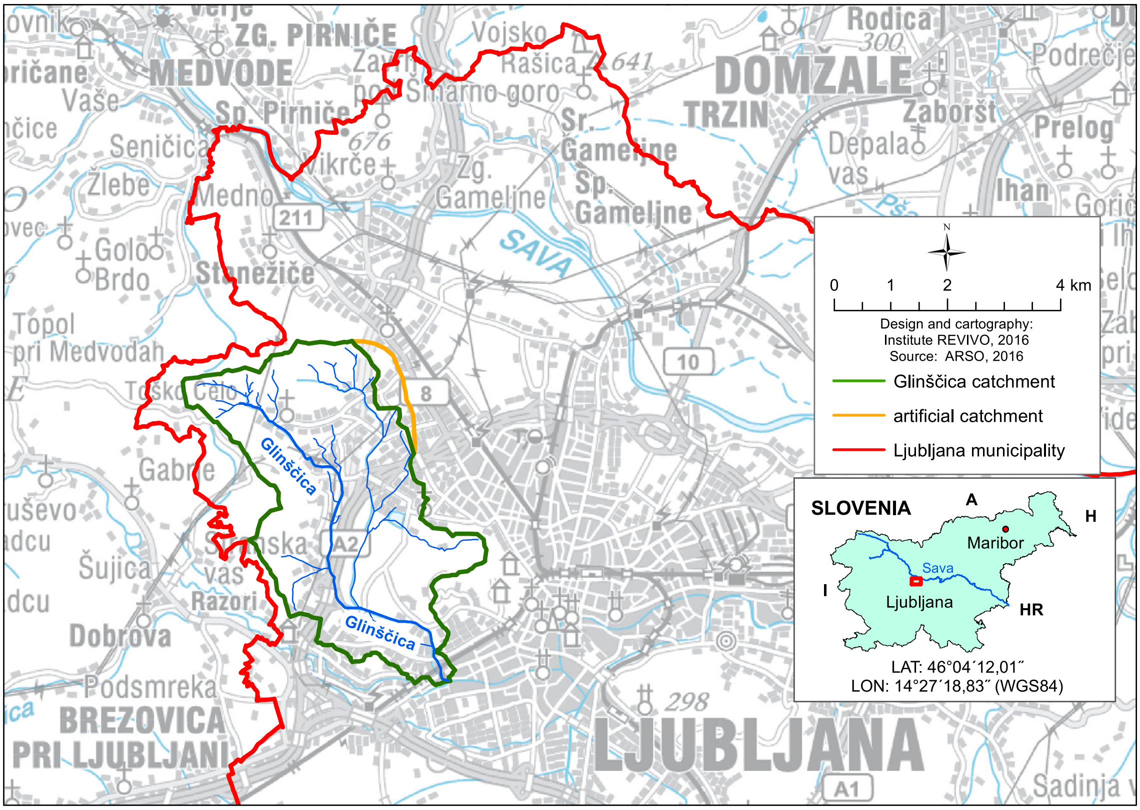

Fig. 1. Map with the location of the Glinščica river case study.

relationships to include in the SDM. The 'qualitative modelling phase' is closed with the 1st stakeholder workshop, having a twofold objective: i) to identify the most important risk management goals, and the most suitable and effective measure(s) to achieve these goals; ii) to support building an aggregated version of the FCM.

The present paper is mainly focused on the 'quantitative modelling phase', and specifically on the process from the definition of an aggregated FCM to the SDM building. The process of aggregation is not straightforward, particularly considering the ambiguity and the differences in problem framing that emerged in the 'divergent thinking' phase. However, there are several methods that can be used to aggregate individual FCM (Solana-Gutiérrez et al., 2017). In this case, instead of performing an additive method, stakeholders were directly invited to construct an aggregated map (van Vliet et al., 2017). The process started, with the support of the analysts, merging similar variables (e.g. the same concept expressed using different words). Then, a

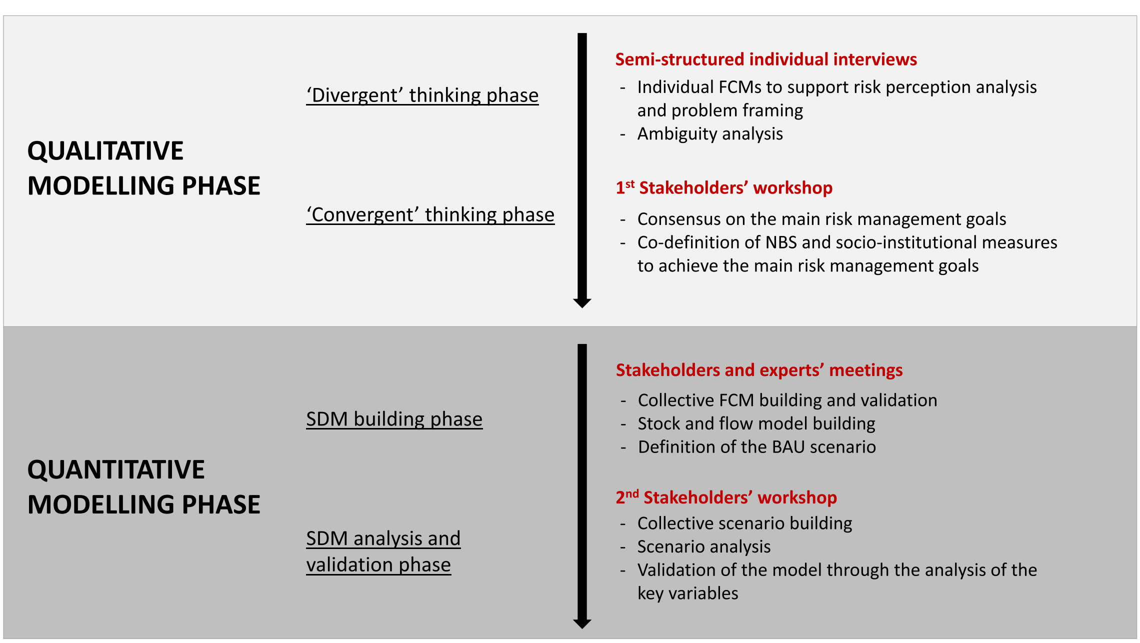

Fig. 2. Overview of the main phases of the process. The present article focuses specifically on the 'Quantitative modelling phase'.

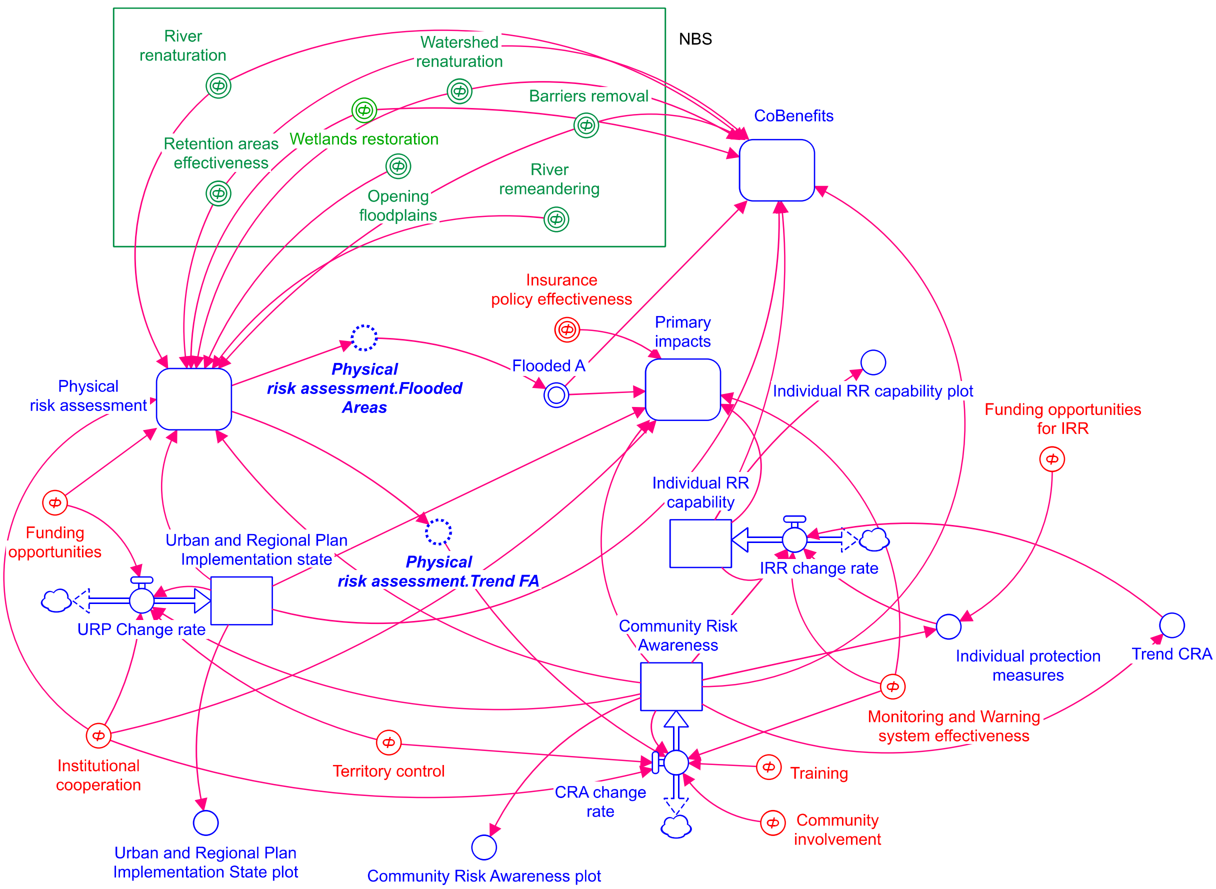

Fig. 3. Global stock and flow model for the Glinščica river case study.

discussion between the stakeholders was intended to draw the weighted connections among the variables. Stakeholders, also, had the opportunity to add specific variables and connections that were relevant according to their knowledge and specific expertise. Once the global structure was collectively built, it was further discussed, and potential inconsistencies analysed.

SDM can be interpreted as an evolution of FCM. Its structure can be developed as a set of mathematical expressions governing the system, incorporated via flow diagrams and finally transformed using a simulation environment (Teegavarapu and Simonovic, 2014). This step is crucial to fully translate the verbal descriptions of individual problem understanding into a working simulation model of the system, supporting the mathematical computation of the outputs. FCM's variables and causal relationships were identified and translated into the common SDM sets: stocks (quantities subjected to accumulation, either physical or not), flows (rates of changes, either increasing or depleting stocks), converters (intermediary variables that can help describing the processes of the model), connectors (interrelationships among various elements in the model which can reflect cause-and-effect rules). On the basis of the identified variables, and their causal dependencies, hypotheses were formulated on the mathematical functions and parameters (Meinherz and Videira, 2018), integrating multiple sources of information, mainly expert consultation, scientific/grey literature and field surveys. Lastly, the SDM was validated, firstly with sensitivity runs to check the consistency of model structure and equations, and subsequently with a conceptual validation with stakeholders. All the stakeholders involved in model building were asked to support model validation, each one referring to the specific sub-set of variables on which he/she felt more qualified or entitled to contribute. This step was performed using both individual activities and participatory exercises (during the 2nd workshop).

This workshop aimed also to develop different risk management scenarios. The first session introduced and discussed a glossary, some examples of successful implementation of NBS across Europe and few indicators, their role and how they can be generated - specific reference was made to the EKLIPSE framework. The second session focused on the co-design of three scenarios for improved risk management using both the NBS and the socio-institutional (S-I) measures. Following a general presentation of the SDM, stakeholders were asked to collectively select a combination of measures for each scenario (at least 1 NBS measure and at most 5 S-I measures altogether). The scenarios were simulated, and the results collectively discussed considering the variation of the main variables of the SDM (specifically benefits/co-benefits) in comparison to the BAU scenario.

4.2. SDM description

The model was built using Stella® Architect software, which has a user-friendly interface and offers several features that make the model highly useful in participatory activities. Firstly, it allows to easily and intuitively set the input conditions for the simulation, supporting also a real-time visualization of the results and of the changes originated by the variations in the state of the input variables. Secondly, it supports a comparative analysis of scenarios and includes several tools for model analysis (e.g. sensitivity analysis). Lastly, although the phase of model building requires the support of the analyst, the final model can be shared online and easily used for an asynchronous interaction with the stakeholders.

The key assumptions of the model are summarized in the following:

– The duration of the simulation is 50 years. This allows to take into account that many NBS or S—I measures require a long-time span to become fully effective, providing a gradual contribution to risk reduction.

- The time step of the simulation is 1 year. From a physical point of view, the analysis is performed starting from hydrological information, and analyzing the impacts of a 100-years return period flood event.
- The states of these variables and the equations behind the model have been defined integrating the expert knowledge collected through the participatory activities.
- The main variables (stocks) are all expressed in dimensionless terms, ranging from 0 to 1 (or 100 in % terms). The model does not aim, at this stage, to provide a quantitative effectiveness assessment of the effect of NBS and S—I measures use, but rather at suggesting a semi-quantitative comparative analysis.
- Specific dynamics can be isolated and arranged in sub-models, which support an easier representation and visualization, without losing the characteristics of the global structure. Besides a global model representing the main socio-institutional dynamics, there are three specific sub-models for physical risk assessment, primary impacts and co-benefits assessment.

The global stock and flow model for the Glinščica is proposed in Fig. 3. The present section provides a general description of model features and of its key elements, while the whole list of equations behind the model are included in the Supplementary Material.

Referring to Fig. 3, the variables identifying the selected NBS are in green. Such variables range from 0 to 1, representing a variable level of implementation from very low (0, i.e. not applied) to very high (1, i.e. applied, fully functioning and effective). Similarly, the variables in red represent 'socio-institutional' (S—I) measures, and they range from 0 to 1, according to their level of implementation. For the sake of simplicity, only two different states were used to activate/deactivate such variables, i.e. 0.1 and 0.9. The following Table 1 includes all the measures (both NBS and S—I) that have been selected during the 1st stakeholders' workshop.

The global model includes the main S—I dynamics and the key stocks are:

- 'Urban and Regional Plan Implementation state' representing the level of implementation of planning regulations at both urban and regional level. This variable depends mainly on the institutional capability to cooperate and provide funding to enhance the control of the territory. It has several impacts, which are included in the physical assessment sub-model (mainly on the evolution of impervious areas and floodplain occupation level), on the impact assessment sub-model (it affects community safety, building damage level and business productivity) and on the co-benefits assessment sub-model (both in terms of biodiversity enhancement and change of the social value of ecosystems).
- 'Community risk awareness' denoting the level of awareness of people with respect to water related risks. It can be improved through specific strategies (e.g. the community involvement activities) and varies according to the memory of recent events (trend of the 'Flooded Areas'). This variable has also significant effects on the physical assessment sub-model ('Floodplain occupation' depends significantly on the 'Community risk awareness') and on the primary impacts ('Community safety').
- 'Individual risk reduction capability' describing the effects of skills, tools and opportunities that concur to define the individual capability to deal with risks. It directly affects all the main impacts ('Community safety', 'Built environment damage level' and 'Business productivity') and some relevant co-benefits, such as the ecosystem state and its social value.

In the following, the individual sub-models are described in full details.

The 'Physical risk assessment' sub-model (Fig. 4) provides a simplified risk assessment, combining the effects of surface runoff and groundwater level raise. The model aims to estimate the extent of the 'Flooded Areas' under a constant rainfall event (100 years return period) and variable environmental conditions (e.g. changes in the land use and floodplain occupation). The 'Flooded Areas' are expressed in terms of ratio with respect to the current situation (i.e. a value of 2 means that the flooded areas are double than in the current state). The effect of natural/climatic conditions is taken into account through a specific subset of parameters, i.e. 'rainfall intensity' and 'average recharge rate' that are constant during a simulation (and fixed according to the current situation). The human influence is described referring to both groundwater ('GW withdrawals') and runoff dynamics ('impervious area' and 'floodplain occupation'). Going further into details, the 'impervious area' evolves mainly according to the 'watershed renaturation' processes and the 'urban and regional plan implementation state'. Similarly, the 'floodplain occupation' depends on both NBS ('opening floodplains' and 'wetlands restoration') and S—I variables ('community

Table 1
Overview of the measures (both NBS and S—I) identified (see also Santoro et al. (2019)).

Class	Name	Description
NBS	River renaturation	Actions that limit the human impacts and pressures on the river restoring natural conditions (e.g. riverside forests and natural embankments)
	Retention area effectiveness	Effectiveness of detention basins (either dry or wet) designed and designated for the temporary or permanent retention of water volumes.
	Wetlands restoration	Many wetlands have the capacity to temporarily store water during high runoff events. Furthermore they contribute to restore ecological integrity.
	Watershed renaturation	Actions that contribute to restore the natural conditions in the watershed (e.g. reforestation)
	Opening floodplains	Increase in the connectivity between the river and the floodplains, which contribute to the peak discharge reduction.
	River re-meandering	Renaturalization of the river geometry, with related reduction of water speed and erosion, and improvement of ecological status
	Barriers removal	Removal of longitudinal and transversal structures
Socio-institutional	Funding opportunities	Economic resources and investments to support urban planning and maintenance
	Institutional cooperation	Frequency and effectiveness of cooperation and communication between institutional agents involved in risk management activities
	Territory control	Monitoring of the state of the area (e.g. to contrast illegal behavior)
	Training	Training activities contributing to increase the community risk awareness
	Community involvement	Activities focused on the active involvement and participation of the community
	Monitoring and warning system effectiveness	Existence and operation of tools and systems supporting during the flooding event
	Funding opportunities for IRR	Economic resources and investments to support Individual Risk Reduction capabilities
	Insurance policy effectiveness	Effectiveness of insurance tools to support limiting the impacts of hazards
	Infrastructure maintenance	Activities oriented to improve the functionality and the operation of sewage systems

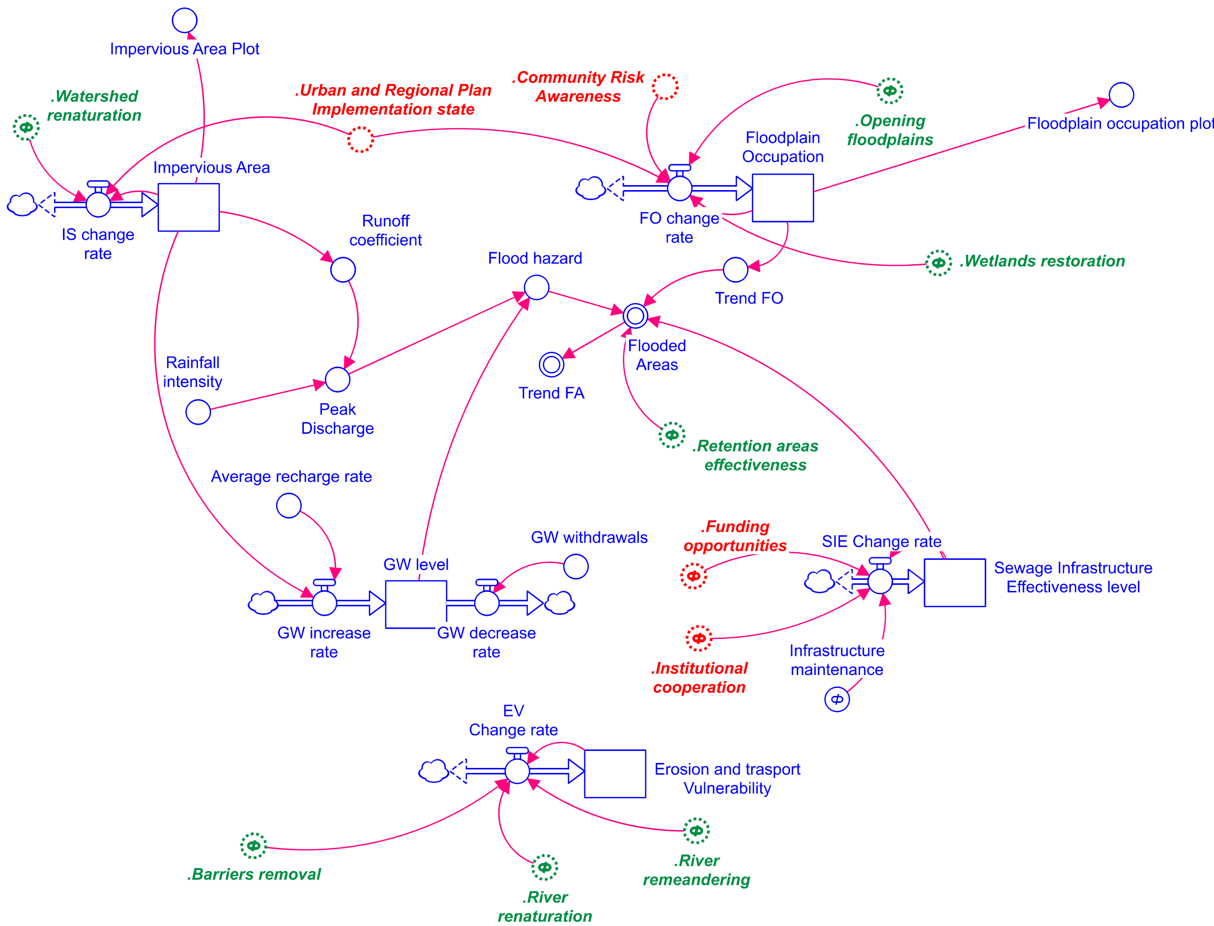

Fig. 4. Physical risk assessment sub-model.

risk awareness'). The 'Flooded Areas' are also conditioned by the operation of sewage infrastructures, whose effectiveness and functionality has a significant effect on the potential impacts of floods. Additionally, the GW level might increase the flood hazard, in case the water table goes beyond a threshold value and thus the surface soil saturates. Moreover, the sub-model provides also a simplified analysis of the 'Erosion and solid transport vulnerability', which is considered a relevant issue according to the stakeholders' risk perception and problem understanding.

The 'Primary Impacts' assessment sub-model (Fig. 5) is focused on the analysis of the effect of the selected measures on the main impacts associated to floods. Three main effects of are taken into account, according to the outcomes of stakeholders' involvement activities, namely: a) 'Community safety' (safety and well-being of population), b) 'Built environment damage level' (ratio of buildings and infrastructures that can be affected by the flood), c) 'Business productivity' (potential impact of the flood on the economic activities in the affected area). All the cited impacts concur to the definition of a global level of economic losses. The magnitude of impacts is directly dependent on the extent of the flooded areas, and can be significantly limited introducing suitable NBS and S—I measures.

The 'Co-benefits' assessment sub-model (Fig. 6) aims to investigate the additional effects that specific risk management measures might have on social, environmental, economic and ecological issues. More specifically, both NBS and S—I measures might have a positive impact on the 'Ecosystem state' (improving the quality of the environment), on the 'Biodiversity', on the 'Agricultural productivity' (the process of watershed renaturation and reduction of urban areas might increase the area available for agricultural activities) and on the 'Social value of ecosystem' (e.g. helping social interaction, education, health and well-being). Clearly, different measures have a different effect on co-benefits production. This sub-model is highly relevant since it allows underlining the value added of NBS and S—I measures, which is the production of positive impacts that go beyond the mere reduction of primary impacts and risk levels.

5. Results

The stock and flow model described in the previous section has a quantitative basis, since every flow is associated to a differential equation. The model produces, as a result, both graphs and tables representing the evolution of the state of target variables with time, once the value of the input variables is defined collectively by the stakeholders during the workshop. It is worth reminding that the model is based on the stakeholders' understanding of the problem, and thus represents the expected evolution of system conditions. It can be used with a twofold objective: i) for the assessment of the long-term impacts of current system conditions (Business-As-Usual, BAU); ii) for a scenario analysis, useful to analyze the potential effect of the introduction of specific measures on both flood risk reduction and co-benefits production. The use of the SDM model for both purposes is detailed in the following.

5.1. Business-As-Usual Scenario

The following Fig. 7 shows the main results of the model according to the Business-As-Usual (BAU) scenario, i.e. assuming that all the variables keep the current state. In general, system conditions are expected to get rapidly worse in the future if nothing changes in the system.

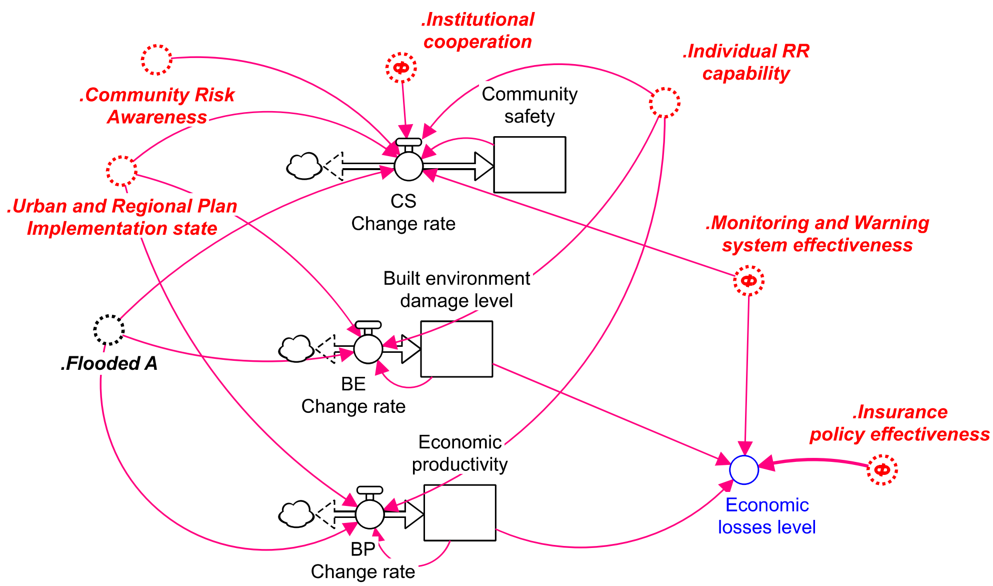

Fig. 5. Primary impacts assessment sub-model.

The results of the BAU scenario show that:

- The impacts of extreme events are likely to get even worse in the near future, mainly due to an increased exposure of the assets and an increased vulnerability of the area. A limited control of the area and a low community awareness may concur to exacerbate the effects of floods. This will have also an increasingly negative impact on 'Community safety' and on 'Economic productivity'.
- A significant decrease of the key ecological and environmental aspects is likely to occur. Particularly, both the 'Biodiversity' and the 'Social value of the ecosystem' (which already starts from a very low state) could be significantly reduced, since currently grey infrastructures are definitely preferred, there is limited attention to the control/planning/protection of the territory and a limited individual and collective awareness.
- The expected evolution of the system in the near future is due both to an increased vulnerability of the area (due to the increase of impervious areas and floodplain occupation) and to a weak socio-institutional framework, characterized by a decreasing individual/collective awareness and by a progressively lower capability to support the implementation of urban planning.

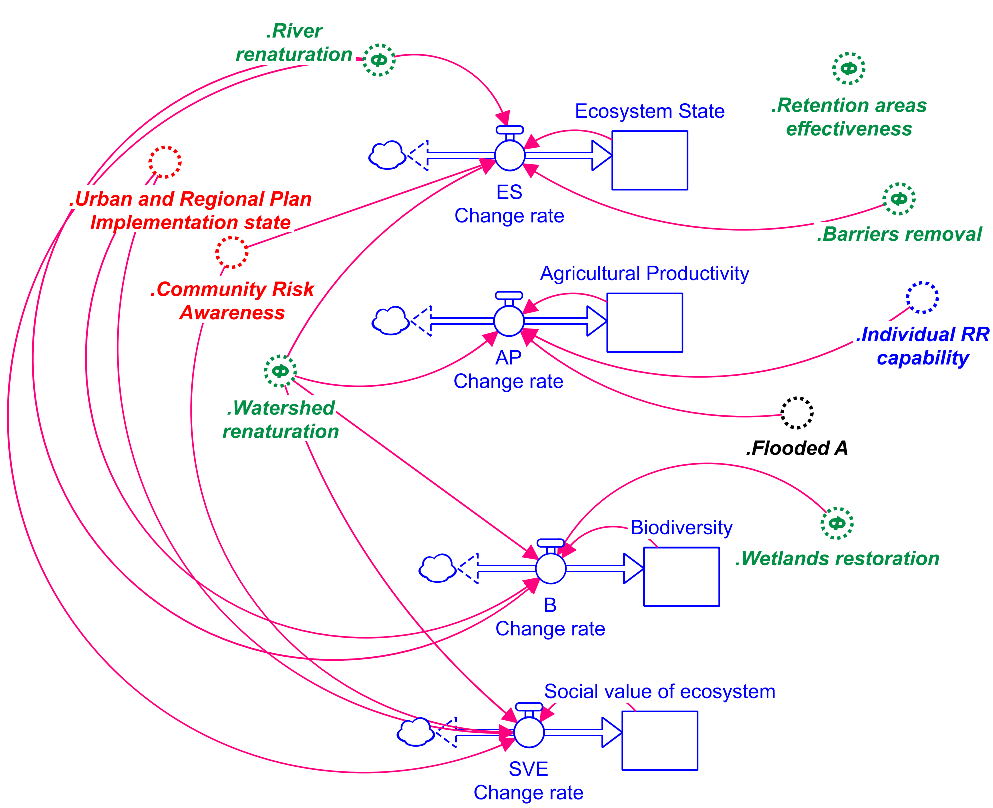

Fig. 6. Co-benefits assessment sub-model.

5.2. Scenario analysis

Starting from the analysis of the BAU condition, the SDM model was used to support the discussion among stakeholders concerning the selection of suitable combinations of NBS and S—I measures. Potential alternative scenarios were identified and discussed during the stakeholders' workshop using participatory exercises, as already discussed in the Section 4. Specifically, stakeholders were firstly required to create some scenarios selecting 5 different actions (both NBS and S—I), among which the ones identified in the following as Scenario 1 and Scenario 2 were identified as highly relevant. Secondly, the stakeholders were asked to identify an 'optimal' scenario (Scenario 3), without any constrain on the number of measures.

Firstly, Scenario 1, identified as 'Bureaucratic' was built activating 1 NBS and 4 S-I measures, namely: Opening floodplains (NBS), Territory control (S—I), Community involvement (S—I), Monitoring and warning system effectiveness (S—I), Insurance policy effectiveness (S—I). This scenario is characterized by the production of relevant socio-institutional benefits, due to the implementation of the selected strategies (Fig. 8). Specifically, an increasing community involvement produces an improvement of risk awareness, with a cascading positive impact on the implementation of the urban and regional plan as well. Moreover, the associated positive impacts in the land use dynamics – i.e. reduction of flood plain occupation and of the impervious areas – could decrease the building damages and stabilize both community safety and economic productivity. Finally, the social value of ecosystem and the biodiversity are positively affected. However, it should be noted that this scenario has a long-term effectiveness and there might be a positive effect to solve future challenges, but without a significant impact on the current situation.

Secondly, Scenario 2, identified as 'Renaturation' scenario is based, instead, on the activation of 3 NBS and 2 S-I measures, namely: retention areas effectiveness (NBS), river renaturation (NBS), wetlands restoration (NBS), infrastructure maintenance (S—I), funding opportunities for IRR (S—I). Indeed, participants felt that the introduction of more NBS would significantly contribute to improve flood safety, restoring at the same time the degraded stream conditions, increasing the recreational value of the area and ensuring higher biodiversity.

The results of Scenario 2 (Fig. 9) show the effectiveness of the selected strategy in producing the expected benefits and additional co-benefits. Concerning the primary impacts, the combination of NBS and S—I solutions produces limited improvements on the damages to the built environment and on community safety with respect to the BAU scenario. The most positive impact regards the state of the ecosystems and the level of biodiversity. Besides, an increase of the individual risk management capability is highlighted.

Lastly, Scenario 3 was developed with no constraints on the number of measures. The participants to the workshop thus decided to start from the results of Scenario 2, including additional S—I measures helpful to achieve the target benefits and co-benefits in the long term, and to make the implementation of NBS more effective. The additional S—I measures activated in the Scenario 3 are: territory control, community involvement, institutional cooperation, training, funding opportunities for IRR, insurance policy effectiveness, Infrastructure maintenance, monitoring and warning system effectiveness.

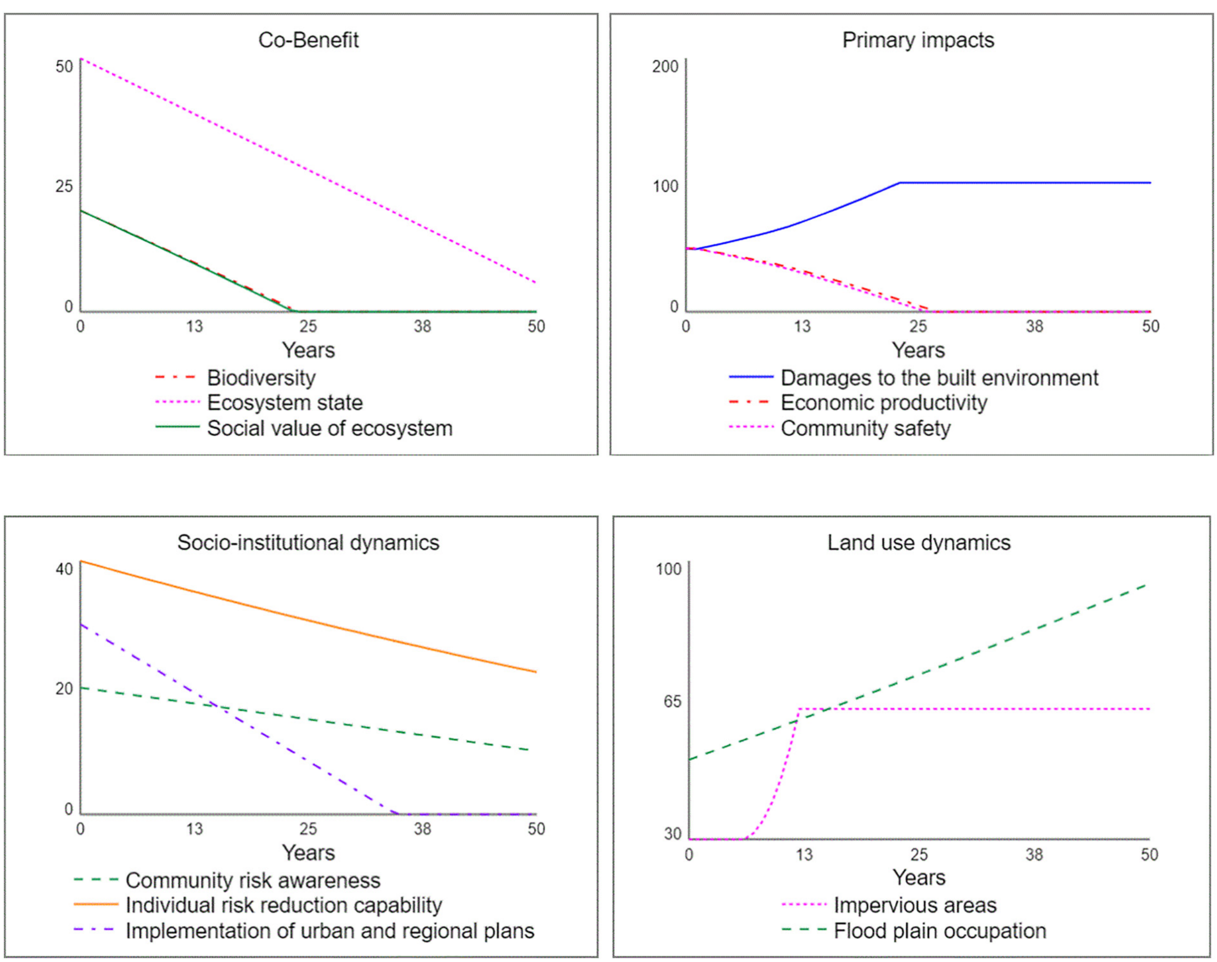

Fig. 7. SDM results for the BAU scenario.

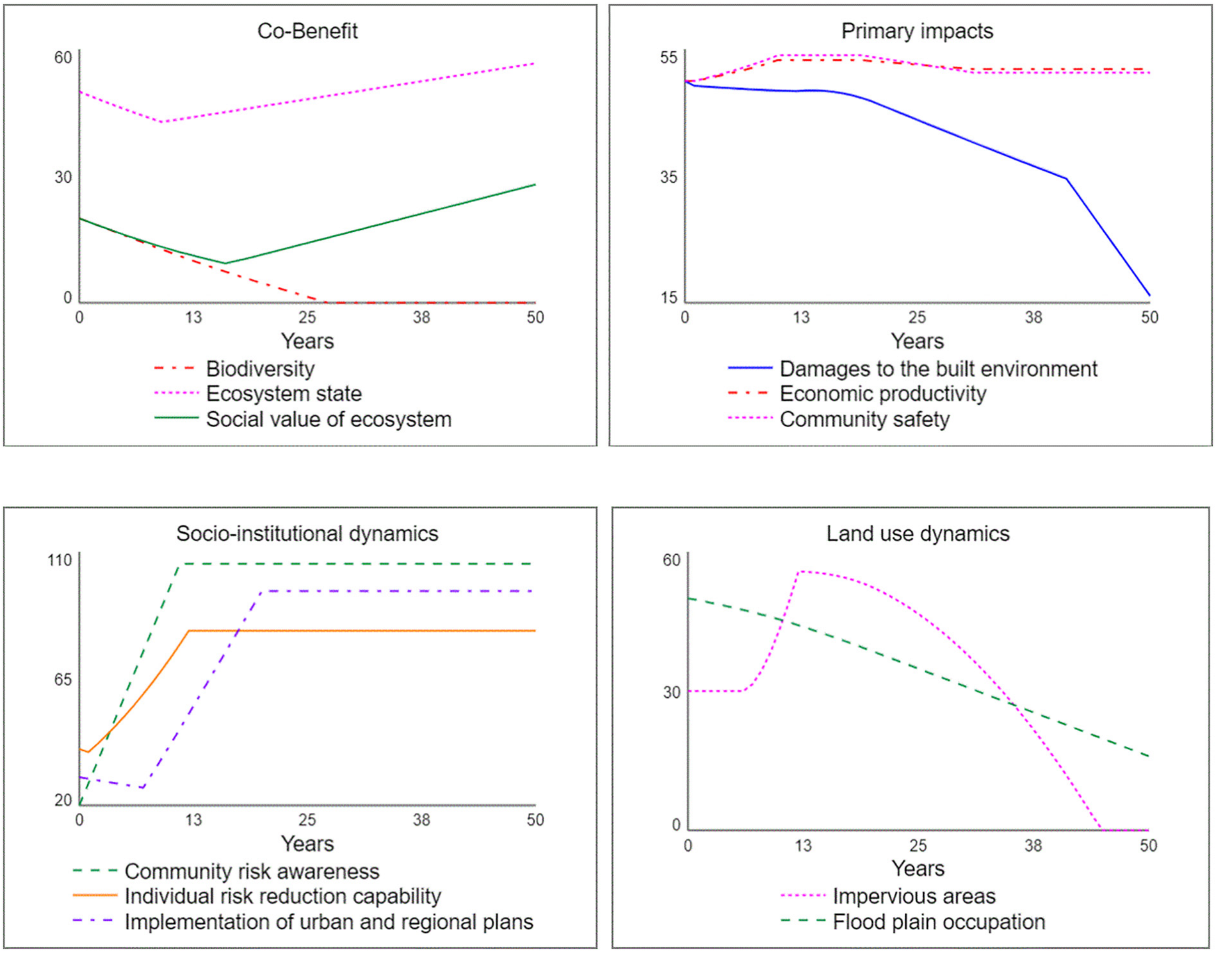

Fig. 8. Scenario 1 simulation results.

As expected, this scenario has the most effective impacts on both benefits and co-benefits (Fig. 10).

The main results of this phase of the workshop are to make the participants aware of the need to integrate different kinds of measures in order to enhance the effectiveness of NBS in producing benefits and co-benefits. Specifically, stakeholders became aware of the role played by the S—I measures capable to enhance the effectiveness of the urban and regional plan implementation. Future activities should be oriented to the design and operationalization of the set of measures to implement.

A preliminary model validation was performed through participatory exercises, which supported also fine-tuning the equations of the model. Specifically, stakeholders were asked to draw, according to their own perception of the problem and considering their specific expertise, the basic shape (e.g. power-law, sigmoidal, etc.) of one or more of the selected variables, both in the BAU condition and in the Scenario 3. Supporting material was prepared to facilitate the discussion, and to provide a basis for the identification of the most common shapes. Referring to (Sterman, 2000), the most typical modes of behavior in dynamic systems were identified and explained: fundamental modes (exponential growth, goal-seeking and oscillation), non-linear interactions of the fundamental modes (S-shaped growth, Growth with overshoot, Overshoot and collapse), equilibrium and randomness. Starting from these functions, the stakeholders either selected the most representative of the investigated variable(s) or drew their own function. Additionally, stakeholders were also asked to provide details on specific characteristics of such functions, such as thresholds, time steps, or upper/lower limits. This result supported improving the correspondence between model predictions and problem perception.

6. Discussion

The research activities presented beforehand, contribute to progress on the issues raised by the research questions identified in the Introduction. Firstly, considering how to perform an integrated evaluation of the NBS potential in terms of risk reduction and co-benefits production, the results described in this work demonstrated the suitability of an SDM-based approach in overcoming one of the key limits of the existing frameworks, that is the lack of structured representations of their multi-dimensionality. This work demonstrated the capability of the SDM to include multiple variables (both qualitative and quantitative) and multiple dimensions (e.g. technical, social, and environmental) into the analysis and, on the other hand, to explicitly analyze system evolution with time. Nevertheless, several simplifications were introduced in the model – e.g. in the physical risk modelling, variables expressed in a dimensionless form, etc. – that might be considered a drawback of the implemented approach. Ongoing activities are already oriented to support the integration of the information provided by more specific models and tools in the SDM.

Secondly, participatory SDM and the described framework of analysis enabled the improvement of NBS design process taking into account the wide range of objectives and dimensions involved. In fact, the process starts from the analysis of stakeholders' problem understanding and the identification of individual priorities in risk management goals and co-benefits production, but aims at reaching consensus on the key objectives that should be addressed by NBS and on the design of measures/strategies. However, SDM helps also visualizing the effects of NBS introduction and exploring the potential trade-offs between different beneficiaries and co-benefits. In this regard, the same research

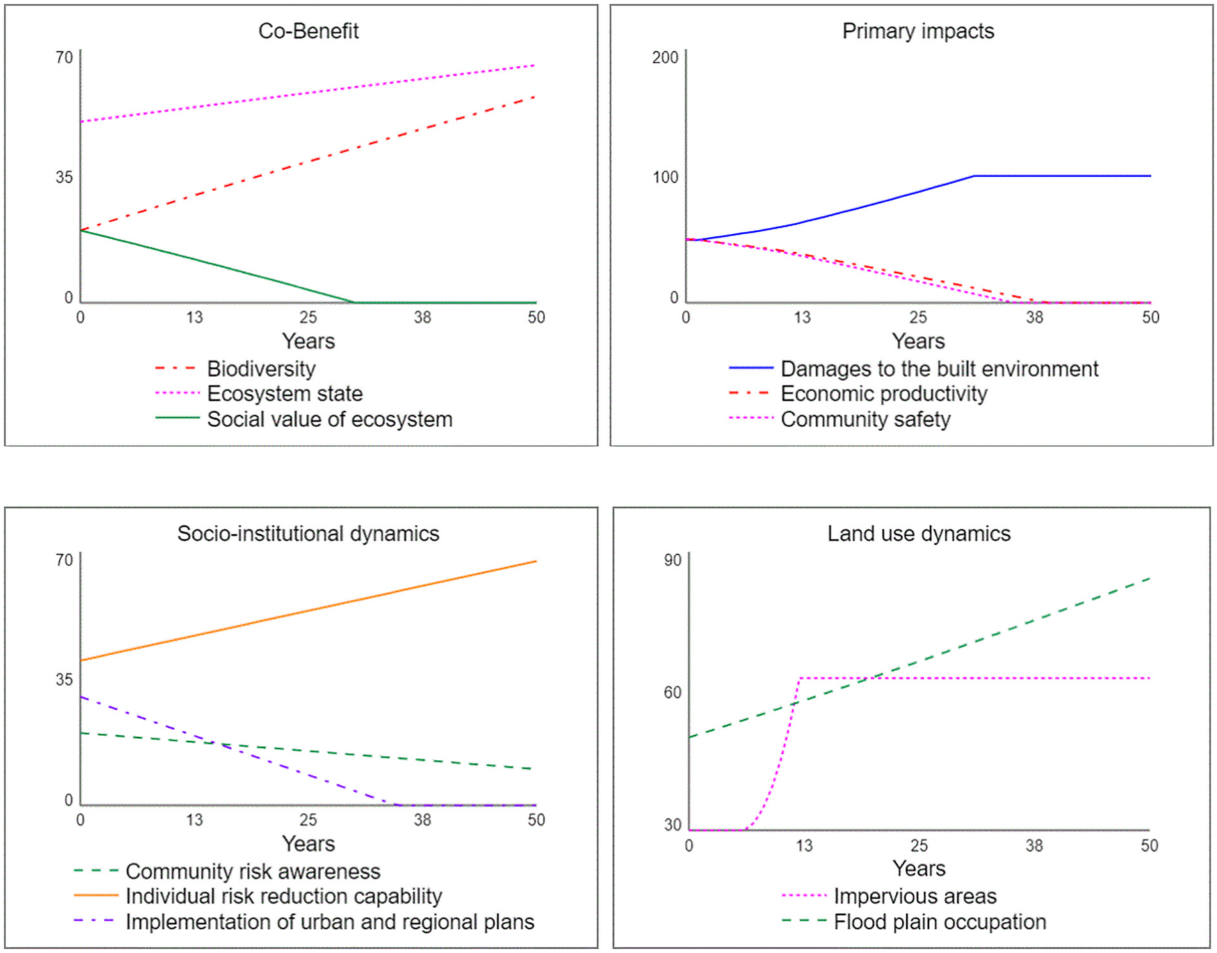

Fig. 9. Scenario 2 simulation results.

group is currently working on the analysis of differences in stakeholders' values and perceptions of co-benefits, to support identifying strategies that may generate win-win situations and solve potential conflicts on NBS implementation and impact evaluation. Accounting for these differences could be the key for finally enhancing their social acceptance and, thus, facilitate their implementation.

Thirdly, considering the problem of combining and implementing multiple measures, the proposed model supports an assessment of the impacts of different actions and explores the potential combination of different strategies and their synergistic effects. Particularly, the proposed model allows analyzing the multiplicity of impacts of several NBS, as well as the potential and the synergistic effect of S—I measures. In this direction, the use of scenario analysis proven to be a key resource to perform a comparative analysis of the impacts of different strategies, and a useful tool to describe the benefits and co-benefits produced both individually and in combination. Although additional efforts are needed to better represent and model the impacts of NBS along with S—I measures, and to describe how specific strategies mutually interact, the process itself represents a step forward in supporting active engagement, knowledge sharing and co-design across several stakeholders and experts, from high-level decision-makers to communities and local organizations. It should be also considered that, despite SDM could support decision-making at a strategic, system-wide level, it has limited applicability in the analysis of individual or micro-behaviors.

Lastly, as far as the issue of how to use participatory tools to increase NBS social acceptance and viability is concerned, it should be remarked that the whole process helped breaking down some socio-institutional barriers related to the limited knowledge and bringing together different stakeholders in the discussion. The active involvement of stakeholders throughout the process is crucial in order to move beyond individual perception and problem understanding, and to support building a shared view of the problem under consideration. Additionally, defining a shared problem frame and group model facilitates interdisciplinary and cross-sectoral communication and collaboration. Given the multiplicity of risk-management goals and impacts, the active participation of stakeholders in the process of identification of benefits and co-benefits, along with the definition of connections between such elements and the NBS, is of utmost importance in raising awareness about NBS effectiveness. This was highlighted by the increasing interest and participation in project activities. Especially during the 2nd stakeholder workshop, participants became aware of the multiplicity of dimensions that could be positively impacted by a combination of measures. The involvement of both institutional actors (policy- and decision-makers) and communities/organizations represented a relevant opportunity for including knowledge and creating a richer picture. Nevertheless, it should be considered that the participatory SDM represents one possible description of the system, reflecting the knowledge of the involved subset of stakeholders.

7. Conclusions

Stemming from the need to drive a shift in the strategies used to deal with water-related risks, the present paper proposes a framework based on participatory SDM to support assessing the multi-dimensional impacts of NBS. Specifically, this work aims to go beyond the characterization of NBS effectiveness in dealing with water-related risks, highlighting and valuing their capability to produce a wide range of co-benefits, which represents their value added with respect to grey

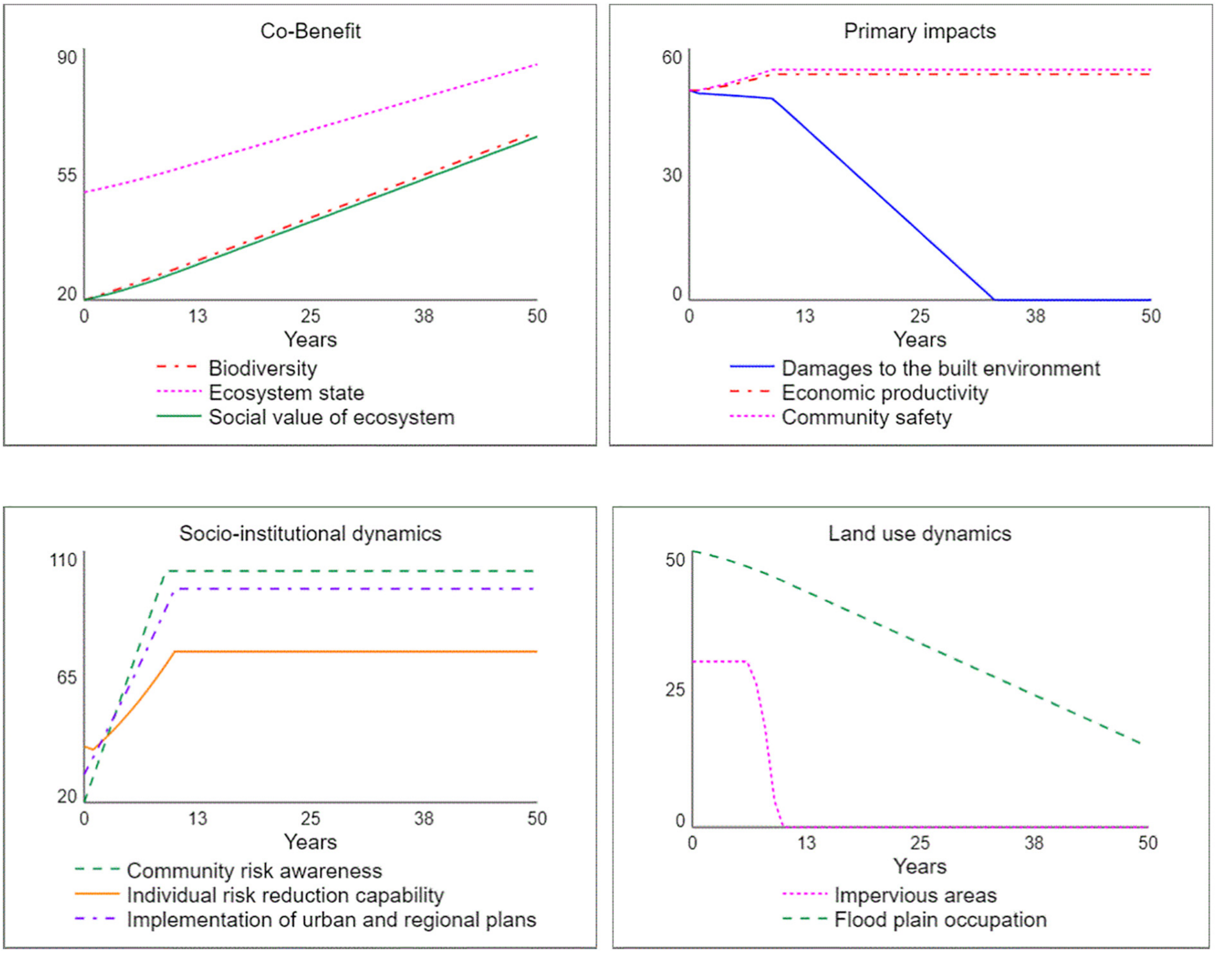

Fig. 10. Scenario 3 simulation results.

infrastructures, and should contribute overcoming the existing barriers to their mainstreaming. The adopted approach is based on two steps: a) the identification of the most relevant goals according to the stakeholders' perception, which are then related to the co-benefits produced by NBS; b) the development of a participatory SDM, capable to analyze the multidimensional effectiveness of the selected measures with respect to such goals. The approach is strongly based on the participation of stakeholders throughout the process. The proposed model, based on the activities that have been carried out in the Glinščica river (Ljubljana, Slovenia), represents a step forward in NBS assessment and analysis, showing a relevant potential in quantitatively valuing the impacts associated to their introduction. It is currently characterized by some elements of uncertainty and worth of additional research (e.g. the assumptions, the lack of spatial information, the absence of an economic evaluation of the selected strategies) before it can be considered fully capable to support decision-making processes. Additional research efforts are already being performed in this direction, as well as in the critical comparison between the potentialities and limitations of the proposed modelling approach in different cases.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.07.059.

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