



Università
Ca' Foscari
Venezia

Corso di Dottorato di ricerca in
Science and Management of
Climate Change

ciclo 34

Tesi di Ricerca

**Green Infrastructure
Network for Climate
Change Adaptation and
Disaster Risk Reduction:
performance assessment
of spatial connectivity**

SSD: BIO/07

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ABSTRACT

(English version)

A transition towards a more sustainable interaction between nature and society is fundamental for climate resilience. Nature-based solutions and green infrastructures can contribute to pursue this transformation. But the way they are designed and distributed across the landscape is crucial to build effective solutions. Ensuring they are connected through the space supports ecological functions and the flow of ecosystem services. The thesis explores the benefits of building a green infrastructure as a network to enable the desired response to societal needs in climate change conditions. The work is structured as a collection of papers, addressing the implementation and assessment of a green network at different spatial scales. The first paper presents a framework to map and build green infrastructure network applied at the regional scale. The second chapter focus on the use of water retention ponds to address water scarcity in agriculture at the river basin scale. The third paper presents an upscale to the European context, assessing the changes of land use and ecosystem services associated to an extended network of protected areas. The last paper estimates the contribution of a green network to deal with climate extreme events in cities. Results show positive effects of building a green infrastructure network for climate change adaptation and disaster risk reduction, providing insights to better manage and use a network approach from an environmental, social and economic perspective.

(Italian version)

Una transizione verso una relazione più sostenibile tra natura e società è fondamentale per una maggiore resilienza climatica. Le soluzioni basate sulla natura e le infrastrutture verdi possono contribuire a questa trasformazione. Ma il modo in cui esse sono progettate e distribuite nel territorio influenza la loro efficacia. Garantirne la connessione nello spazio ne supporta le funzioni ecologiche e il flusso dei servizi ecosistemici. La tesi esplora i vantaggi di costruire una rete di infrastrutture verdi per rispondere ai bisogni della società in condizioni di cambiamento climatico. Si tratta di una raccolta di articoli che studiano l'implementazione e la valutazione di una rete verde a diverse scale spaziali. Il primo articolo presenta una metodologia applicata a scala regionale per progettare una rete di infrastrutture verdi. Il secondo capitolo si concentra sull'uso di bacini di ritenzione idrica come risposta alla scarsità d'acqua in agricoltura a scala di bacino idrografico. Il terzo capitolo presenta un'applicazione a livello europeo che valuta il cambiamento di uso di suolo e di servizi ecosistemici indotto da una rete di aree protette più estesa. L'ultimo articolo stima il contributo di una rete verde urbana contro eventi climatici estremi. I risultati mostrano gli effetti positivi di una rete di infrastrutture verdi per l'adattamento ai cambiamenti climatici, fornendo spunti per un miglior uso di questo approccio da un punto di vista ambientale, sociale ed economico.

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INTRODUCTION¹

A network approach to Green Infrastructures: how to enhance ecosystem services provision?

Motivation and scientific background

The urgent need of a transformative change for climate adaptation is declared at the European and international level. A transition towards a more sustainable interaction between nature and society, that support human, ecosystems and planetary health, is fundamental to develop climate resilience (IPCC, 2022). To this end, nature-based solutions (NBS), nature restoration and conservation are considered key actions to pursue this transformation in several international policies and strategies: from the Convention for Biological Diversity 2021 (CBD, 2021) and the EU Biodiversity Strategy for 2030 (EC, 2020b) to the EU Adaptation Strategy (EC, 2021a), the EU Green Deal (EC, 2019a) and to Sustainable Food System Strategy (EC, 2020c). NBS act through ecosystem functions to protect and restore nature and biodiversity, and to build resilience, providing at the same time social and economic benefits (EC, 2015a). They may mitigate natural hazards by mediating flow and nuisances, or through maintenance of stable physical, chemical, and biological conditions, as for example wetlands and floodplains acting as buffers against floods, well-managed forests reducing the risk of landslides, green urban areas mitigating extremely high temperatures. As well, NBS can provide valuable recreational spaces, increasing social cohesion, offering opportunities for educational and open-air physical activities, with benefits for human health by providing shadow, absorbing pollutants, and sequestering carbon. NBS also help to foster a sustainable economic growth, by creating new jobs, supporting innovation and transition towards a more efficient use of resources.

However, being living solutions, NBS are subjected to climate and environmental changes that can undermine their functionality. This is especially true in degraded and fragmented environments. The fragmentation of contiguous areas of natural ecosystems into smaller elements, driven by urban sprawl and population growth, is one of the main pressures on environmental quality. It is expected that 68% of the global human population will live in cities by 2050, with nearly the 90% of increase occurring in Asia and Africa, and the urban population of high-income countries is expected to rise from 81% to 88% by the mid-century (UN, 2018). These trends will contribute to an increasing landscape fragmentation and degradation of ecosystems (EC, 2015a). At the current trend of soil sealing, Europe, for example, will lose up to 10-15% of the beneficial value produced by ecosystems by 2050 (Maes et al., 2015).

Landscape fragmentation intensely affects the provision of ES, since they depend on ecological functions, landscape spatial pattern distribution and interchanges of organisms and material across space (Mitchell et al., 2013). Landscape patterns and ecological

¹ This introduction is derived from Staccione, A., Candiago, S., Mysiak, J. (2022): "A Network Approach to Green Infrastructure: How to Enhance Ecosystem Services Provision?" In: Misiune, I., Depellegrin, D., Egarter Vigl, L. (eds) Human-Nature Interactions, Springer – https://doi.org/10.1007/978-3-031-01980-7_5

functions are strictly related. A change in landscape configuration leads to changes in ecosystem connectivity, i.e. the degree to which the landscape influences movements of species across ecosystems (Taylor et al., 1993). Fragmentation causes habitat loss and isolation of species, making them more vulnerable and less resilient to changes (Field and Parrott, 2017). Connectivity is fundamental for maintaining species dispersal and sustaining ecological processes. A decrease of connectivity has negative impacts on ES provision, by affecting the rate and pattern of biotic and abiotic flows, the habitats and populations dimension, and, indirectly, altering biodiversity and ecological functions (Mitchell et al., 2013).

In the 'working with nature' framework, Green Infrastructures (GI) can play an important role to address fragmentation and environmental changes by harvesting the effects of spatial configuration and composition on ecological changes. They are defined as "*strategically planned networks*" of natural and semi-natural areas with other environmental features designed and managed to simultaneously deliver a wide range of ES to the society (EC, 2013a). Being built upon interconnections, spatial interactions, and distribution of natural elements across a landscape, they can be used to plan and design green spaces, protected areas, and ecosystem restoration in an integrated and connected way, enforcing the provision of services.

What matters for ecosystem services enhancement?

The configuration and distribution of GI are fundamental for ensuring and enhancing ES provision. Studies on ES assessment highlight the need of mapping and characterizing ecosystem features. Improving landscape connectivity is important for maintaining ecosystem quality and resilience, meant as the capacity to sustain functions and services in face of disturbances and changes. It implies the re-creation or restoration of green corridors or natural areas that can facilitate and allow species movements and services or material flows across the landscape. Together with connectivity, diversity and redundancy of ecosystem features have been identified as key characteristics for building resilience for ES against disturbances and changes in the socio-ecological system (Biggs et al., 2012). Diversity refers to the variety, balance, or disparity of elements within the system, leading to spatial and ecological heterogeneity. Diverse elements would respond differently to disturbances, influencing the spread of impacts on connectivity, ensuring that some landscape patches remain undisturbed and provide refuges for the provision of services. Redundancy is the replication of elements or pathways, guaranteeing a compensation in case of losses or failures. These features secure an insurance effect of connectivity, allowing network stability and robustness (Gonzalez et al., 2017). This requires particular attention to the central areas of the ecological networks, that can destabilize the network more rapidly if degraded or lost. Designing and planning a network of green infrastructure help to meet these requirements for ES provision and achieving good levels of biodiversity and environmental quality. Indeed, diverse ecosystems distributed across the landscape that are structurally and functionally connected, i.e. both in terms of physical landscape structure itself and of organisms and material movements through this structure, demonstrate more stability and resilience compared to systems characterized by isolated components and by low-biodiversity environments (Field and Parrott, 2017)

Proximity to people, distances between habitats and ecosystem quality represent also important features for enhancing ES provision for spatial planning supported by ecological

thinking. The definition and interrelationships of landscape character, services and values are essential (Babí Almenar et al., 2018). Vallecillo et al. (2018) demonstrated how urban and peri-urban areas can have equivalent ES potential to more remote and natural ecosystems, identifying however a lower potential per unit area in degraded ecosystems. The proximity to people has a positive influence on the benefits that ecosystems can generate as services, although it is not always necessary for their provision. Analysing the connectivity requirements for ecosystem services in spatial planning, Kukkala & Moilanen (2017) found that the ideal spatial configuration for ES may be influenced by the size of local supply areas and the regional network around that support ES provision, the flow between supply and demand sites for services and the access and distribution of ES to multiple stakeholders. For planning green networks, other important aspects are interactions, synergies, and trade-offs between services. Increasing the supply of one ES can either enhance or hamper the delivery of other services. Structure, location, and scope of intervention are therefore vital in planning potential green infrastructure network configuration for services and benefits gain.

| Term | Definition |
|----------------------------|--|
| Connectivity | Degree to which ecosystems features are structurally connected and influence the movements of organisms, material, and energy through the landscape. |
| Diversity | Presence of different types of ecosystem features across the landscape. |
| Redundancy | Presence of multiple similar ecosystem features across the landscape. |
| Proximity to humans | Distances of ecosystems features providing the services (supply sites) from human population using/benefitting from the services (demand sites). |
| Quality | Level of health of ecosystems that allows good ecological functioning and services provision. |

Table 1 – Summary and definitions of the key concepts for ecosystem services enhancement.

Connectivity and green infrastructures network: collection of methodologies

Concepts, methods and tools from landscape ecology, graph theory and network analysis help to quantify the effects of landscape fragmentation and to integrate these processes and relationships into GI spatial design and management to address environmental challenges (Babí Almenar et al., 2018).

GI can be described as a network constituted by a set of core areas, considered hotspots of services and benefits, such as protected areas, forests, urban green spaces or floodplains, and corridors, as vegetated buffer strips, green alleys, or hedgerows that connect core areas to each other and to humans. Core areas and corridors can be respectively translated into nodes and links in a network language. Therefore, GI can be represented by graphs and analysed with network measures, that are used to investigate the relationships and influences between GI elements. Graph theory is a well-established mathematical approach dealing with problems of connectivity, network representation, flow and routing in networks applied to many fields. It found applications in landscape ecology studies for habitat and landscape connectivity analysis (Urban and Keitt, 2001). Graphs are used as models of landscapes, constituted by nodes typically representing habitat patches and by links that indicate a functional connection or dispersal potential. Initially applied to population analysis, their potential has been soon recognised for representing and analysing landscape structure through network measures (Galpern et al., 2011). Indeed, due to their flexibility and low data requirements, graphs can be applied to different landscape types and scales.

Graph and network analysis can highlight the favourable geographical configuration that should be maintained, restored, or built by human intervention in order to ensure diverse, redundant and connected ecosystem features of good quality. Using network centrality measures and connectivity indices enables to characterize the degree of connectivity of the landscape and to identify and rank the importance, role and contribution of nodes, and connections to the overall connectivity (Fenu and Pau, 2018). A main step is the definition of the landscape network structure and the characterization of existing components, i.e. groups of connected nodes or sub-network. It is then possible to identify cut-nodes that stabilize the network. Those nodes are the features that determine the separation of a connected component into two smaller components when removed and could maintain a network connected and stable over time.

To analyse the structure of networks and graphs, different measures or indices are available. These measures are often context-dependent and their definition is not always straightforward. Network centrality measures, such as betweenness, degree and closeness centrality, are used to investigate the type and importance of contribution of individual nodes to the system (Field and Parrott, 2017). For spatial analysis, several landscape connectivity indices also exist and can be used for the same scope. The advantage of indices is that of generally taking into consideration the position, quality, and quantity of available areas, including both the effects of landscape composition and structure on species presence and movements (Avon and Bergès, 2016). Two examples of these indices are the Integral Index of Connectivity and the Probability of Connectivity (Saura and Pascual-Hortal, 2007). These indices are more sensitive to the changes affecting landscape configurations and can detect those areas most critical for conservation. Both are graph-based indices applicable to any type and scale of landscape, computing both the overall degree of connectivity and the relative importance of each node and connection. These indices can also be partitioned to assess the type of contributions of each node, in terms of intra-patch connectivity, potential dispersal flux and stepping-stones role (Saura and Rubio, 2010).

Indices can be used to include connectivity consideration when planning new interventions for GI improvement. To do this, connectivity assessment indices and models often consider structural landscape elements as a proxy for functional connectivity, as for example using the presence of a green corridor to measure species movements potential. This bears the risk of oversimplifying the reality. But if included in a wider, scalable and replicable framework assessing connectivity, they can better inform a more integrated landscape management and support practitioners and decision makers for future development plans. For example, Bolliger & Silbernagel (2020) explored the contribution of connectivity assessment methods for a successful spatial design and implementation of GI, stressing the contribution of GI both on structural and functional connectivity to identify critical area of intervention, both for preserving or restoring connections elements. The structural connectivity is usually analysed by addressing the presence and absence of connections, the configuration of corridors and stepping-stones elements, their distances, area and amount of habitat and connections (Kindlmann and Burel, 2008). Functional connectivity analysis is more based on the probability of moving between areas, dispersal rate, search time and the number of areas. In planning perspective, functional and structural corridors are the key for material and species flows, enough to be considered fragile elements and bottlenecks of concerns. The analysis of existing network structure and the identification of critical areas can allow to find space and needs of network improvement. Improvement of the network

can follow or combine two perspectives: the site-centre and the system-centric perspective (Zetterberg et al., 2010). They respectively aim to identify critical isolated nodes in order to restore connections to them, and to identify the crucial regions for network structure where connectivity should be improved to benefit the overall resilience of the system. For GI design and implementation, this is crucial to plan and prioritize where to intervene.

GI studies often apply connectivity concepts, perspectives, and indices using spatial analysis software and techniques such as Geographic Information System (GIS) or alternative spatial-based approaches. An example is given by the combination of landscape connectivity indices with the morphological spatial pattern analysis (MSPA) (Saura et al., 2011). MSPA allows the characterization of the structure of the landscape network at binary pixel level, based on mathematical analysis of landscape configurations (Soille and Vogt, 2009). Landscape connectivity indices applied together with spatial pattern analysis have been proposed to study ecological networks at different scales, both regional and local, at different ecosystem types, to assess the current situation and to develop or restore connections. Different methods and tools are used jointly for assessing connectivity and simplifying the environmental management. This allows the comprehensive study of landscape structure characteristics though available limited data and generally open and free software. There are various software and tools available for spatial pattern and connectivity analysis (see for example McGarigal et al., 2012; Saura and Tornè, 2010; Vogt and Riitters, 2017; Watts et al., 2009), but not all have ready-to-use and well-integrated outputs and routines to be combined with graph-based connectivity analysis and indices.

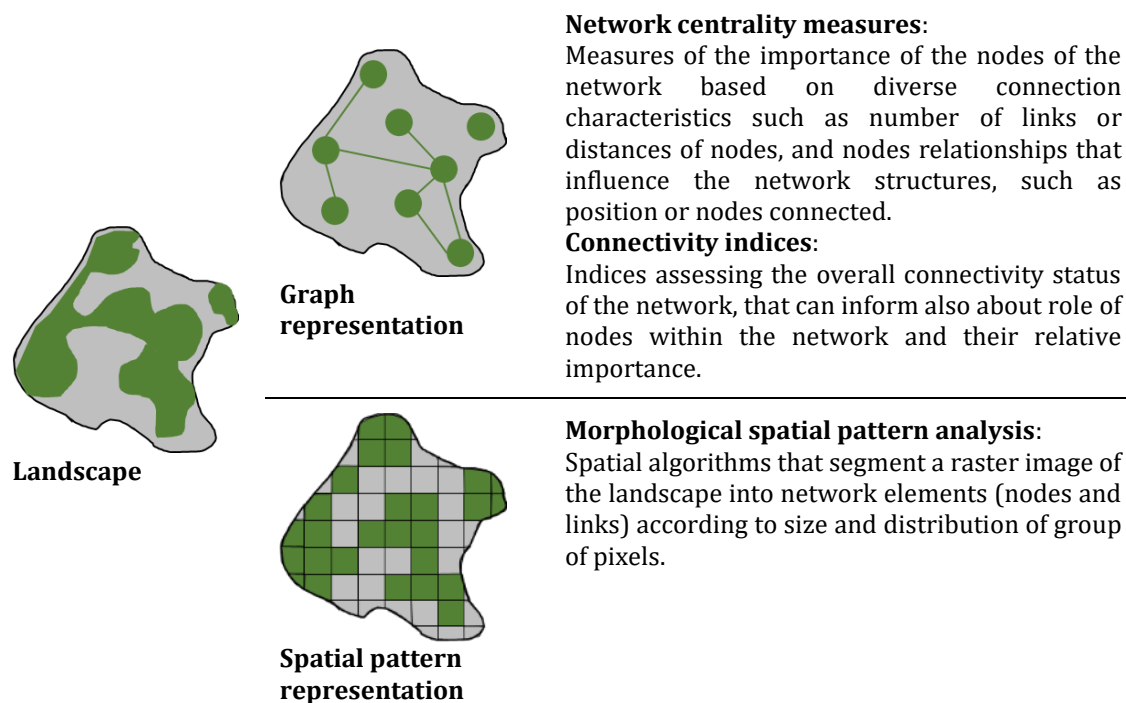


Table 2 – Summary of main methodologies collected and key concepts visualisation.

The conceptualization of GI as a network and the application of a set of network indicators to analyse its structure is increasing in the research field to foster the understanding of spatial needs for ecosystem services delivery. Research can inform policy and decision-making for managing and enhancing biodiversity and ES in a more holistic way. Liquete et al. (2015), for example, integrated the capacity to deliver ecosystem services with the

identification of core habitats and corridors, based on mapping and connectivity methods, to inform a meaningful development of GI network at EU level. This allows contributions for conservation and/or restoration goals within EU policies. Similarly, Maes et al. (2015) investigated how an expansion of the GI network across the EU would help to maintain ecosystem services level, estimating a need of about 20 000 km² of additional GI to maintain ES at 2010 levels: an increase of 2.2% in the share of GI area would be needed to face any additional percentage of artificial land. Ala-Hulkko et al. (2019) used combined network and mapping analysis to study the supply and demand of ecosystem services across Europe, showing an unbalanced distribution of ES supply and demand sites. Methodologies and results can help to identify where investments, both in terms of natural infrastructure, restoration and eventually transport, are more needed.

Planning GI as a network, while incorporating ecological, social, and economic aspects, can help to prioritize areas where intervention for restoration and conservation of connectivity are more urgent for ES. Spatial and connectivity-based methodologies can be used to characterise the network structure and inform about overall connectivity status, most important nodes, isolated and poor connected areas. This allows to identify where and how the network can be improved, taking into consideration type and quantity of nodes and connections required to ensure ecosystem resilience to environmental and ongoing climatic changes. Easy and replicable graph-based methods can be used to inform landscape managers by developing conceptual frameworks and strategies that can support them through the overall process of GI network analysis and plan: from the identification of network elements to the assessment of current condition of connectivity to the planning of future network configuration. Spatial information and landscape-based contributions can support the realization of nature-based solutions, considering location, societal challenges, alternative interventions, and their impacts to be effective also in future climate change conditions, from neighbourhood, to cities, to regional, national and international scales.

Research objective and thesis structure

Framed in this context, my project aims to investigate how to make the desired transformative change more effective in an integrated ecosystem perspective, analysing how a green infrastructure network would respond to societal needs in climate change conditions at different spatial scales. The main questions addressed are:

- i) how we can build and design an integrated green infrastructure network;
- ii) how this network would influence the provision of ecosystem services at the current and future climate change conditions;
- iii) how this network can contribute to deal with climate extreme events.

Organised as four core chapters, my thesis proposes and applies a framework to study and develop a green infrastructure network, based on the concepts reviewed in this introduction and in the related work published in *Human-Nature Interactions* Springer Book in 2022 (Staccione et al., 2022a). Chapters can be read individually and recall the key concepts and definition throughout the text. Each chapter deals with a different scale and a different purpose of intervention: the regional and river basin scale focusing on agricultural and water management, the upscale at the European level dealing with biodiversity and ecosystem services assessment, and the downscale at the local urban scale devoted to disaster risk reduction. The outputs of the thesis are aimed to provide management and policy-relevant insights to guide future nature-based interventions for climate change

adaptation and disaster risk reduction. It would help to develop a better understanding of nature-based solutions effects in quantitative terms, to identify opportunities and barriers to enable their implementation from an environmental, social and economic perspective.

The first chapter describes a framework for connectivity analysis and enhancement within the green infrastructure networks. It is meant as a guide to map the existing green infrastructure network and to develop potential future configuration of green networks. The main aim is to identify the core areas for the delivery of ecosystem services and their importance in terms of connectivity. This would help the definition of crucial areas that must be preserved and those that need to be reconnected to the network, to improve connectivity and support services flow across the landscape. Methods include morphological spatial pattern analysis, landscape connectivity metrics and graph theory elements. The analysis has been applied in the Northern Italian Plain, considering green riparian zones and the protected areas as elements of the network. The results show the potential of the framework, highlighting a very fragmented environment and prioritising the areas that need more attention in terms of both connectivity improvement and protection. This work has been published in *Environmental Science and Policy* in 2022 (Staccione et al., 2022b).

The second chapter shows an application of the framework to assess the implementation of natural water retention ponds in agriculture to face water scarcity and improving ecological functionality in present and climate change conditions. The study analyses the case of the Lamone River catchment between Tuscany and Emilia-Romagna Region (Italy). It is an important agricultural area, characterized by large seasonal variability of water flow and availability, that relies heavily on irrigation. Here, water retention ponds are systematically applied to store water in winter, for use during the dry season. The paper analyses both the benefits of ponds for the water balance at sub-catchment scale, and the environmental effects produced by ponds having an ecological functionality. Results showed that new ponds implemented to maximize landscape connectivity provide also positive hydrological effects under present and future climate change scenarios. Larger water availability for irrigation can favour additional agricultural production and provide ecological benefits. The chapter also investigates the implementation of ponds in economic terms, estimating the associated values and costs. Two innovative incentive models based on compensation of land and production lost and on tradable development rights, that can support nature-based interventions, are finally discussed together with potential funding channels. This study has been conducted in collaboration with Gecosistema srl as part of a JRC tender about landscape elements for water retention in a mountainous environment. The resulted paper was published in the *Journal of Environmental Management* in 2021 (Staccione et al., 2021).

The third chapter has been developed in collaboration with the KIT Campus Alpin - IMK-IFU (Karlsruhe Institute of Technology (KIT) and Institute of Meteorology and Climate Research Atmospheric Environmental Research (IMK-IFU) in Garmisch-Partenkirchen, Germany) under the coordination of Prof. Almut Arneth and Prof. Mark Rounsevell. This work focuses on European scale studying the effects of a protected area network covering 30% of EU land with 10% under strict protection, as called for by the EU biodiversity strategy. The analysis combines the framework for improving green network connectivity with an EU-wide land system modelling approach to explore the effects of these targets on land uses and ecosystem services under different levels of protection and in a range of paired climatic and socio-economic scenarios. Results shows that the existing network of protected areas is

highly fragmented, but prioritizing connectivity when implementing new PAs could achieve the strategy's targets without compromising the provision of ecosystem services, including food production. The substantial changes in the distributions of land uses and ecosystem services are strongly influenced by climatic and socio-economic conditions, while varying the strength of protection of the network had instead limited effects. Main findings highlight the apparent achievability of the EU's protected area targets, but also the need to account for adaptation in the wider land system and its consequences for spatial and temporal patterns of ecosystem services provision now and in the future.

The fourth chapter analyses the use of green infrastructure network approach in the urban context. Rethinking cities in a more sustainable and integrated way is a key opportunity for successful climate change adaptation and mitigation. Nature-based solutions help to mitigate flood risk by regulating storm-water runoff and peak-flow. This paper investigates the effects of nature-based solutions and green infrastructure networks on pluvial flood risk in Milan metropolitan area in terms of direct economic damage to buildings and population exposed. Results show that extended urban green networks can reduce pluvial flood damages (by up to 60%) and the population exposed (up to 50%). For all analysed rainfall intensities, damages to buildings and share of population exposed decrease as green area coverage increases, with slightly higher risk reduction for lower-intensity events. 25% of additional urban green coverage can halve the expected annual damage and reduce by 40% the expected annual population exposed. The applied methodological framework makes it possible to identify priority-action urban areas and hence inform decision-making processes as for where green solutions are most efficient. The study highlights the positive contribution of green infrastructure for climate change adaptation and pluvial flood risk reduction, providing quantitative evidence that can further support the implementation of green solutions in the metropolitan area of Milan and potentially elsewhere. This work was developed in the context of EFLIP (Economic impacts of Flood risk in Lombardy and Innovative risk mitigation policy) project funded by Fondazione Cariplo.

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CHAPTER 1: CONCEPTUAL FRAMEWORK AND REGIONAL SCALE²

Mapping a Green Infrastructure Network: a framework for spatial connectivity applied in Northern Italy

Introduction

Ecosystems are a vital source of services, benefits, and goods to humans. Ecosystem services (ES) represent the benefits that people receive from the natural environment (Millennium Ecosystem Assessment, 2005). The integrity and health of ecosystems are key elements for maintaining ecological processes and functions that make it possible to provide ES and human well-being (Maes et al., 2015; Vallecillo et al., 2018). Redundancy, diversity and connectivity of ecosystems have been identified as key levers of ecosystem resilience (Biggs et al., 2012). However, global environmental changes, including urban sprawl and amplified climate extremes, are increasingly contributing to ecosystem degradation and decline of ES (IPBES, 2018, 2019a). Landscape fragmentation stands out as a main concern for ecosystem integrity (Lafortezza et al., 2013). A loss of habitats leads to more isolated and vulnerable populations that are less resilient and capable of coping with environmental changes (Field and Parrott, 2017; Lafortezza et al., 2013).

Landscape connectivity is a key pillar for maintaining species dispersal and sustaining ecological processes and functioning (Liu et al., 2017). Connectivity is highly influenced by the diversity and spatial distribution patterns of land cover types. A decrease of connectivity can have negative impacts on ecosystem integrity and further amplify loss of biodiversity and ecosystem degradation (Mitchell et al., 2013). Therefore, an improvement in functional and spatial connectivity is fundamental for increasing ES, as they depend on species and material mobility. This is particularly true for regulation and maintenance services, such as flood and erosion regulation, water quality and provision, pollination and pest control (Biggs et al., 2012; Lafortezza et al., 2013). Connectivity is meant as a proxy measure for providing potential ecosystem services, since it influences the supply and flow of services across a landscape (Mitchell et al., 2013, 2015).

To stop environmental degradation and cope with climate change impacts, the European Commission has invested in solutions based on natural and ecosystem functioning, generally known as nature-based solutions (EC, 2015b; Faivre et al., 2017; Lafortezza et al., 2017). Such solutions have been included among the main actions and investment in the new EU Green Deal, the Strategy for Biodiversity 2030, and the Strategy for Sustainable Food Systems (EC, 2019a, 2020c, 2020a). They have also been proposed for addressing societal needs while delivering multiple co-benefits and for incentivizing the integration of natural capital in development policies and programs that favour a more sustainable green economy (Eggermont et al., 2015; Kabisch et al., 2016; Maes and Jacobs, 2015).

² This chapter is derived from Staccione, A., Candiago, S. and Mysiak, J. (2022): "Mapping a Green Infrastructure Network: a framework for spatial connectivity applied in Northern Italy", *Environmental Science & Policy*, 131, 57–67– <https://doi.org/10.1016/j.envsci.2022.01.017>.

However, nature-based solutions can be affected by global environmental changes and therefore need to be “*climate-proofed*” to sustain their viability and efficiency (Calliari et al., 2019). Given the role that spatial structure and configuration play for providing ecological functions and supplying services, it is important to focus on designing solutions as elements of a wider network. In this perspective, among this type of solutions, green infrastructures (GI) are particularly crucial. GI are defined as “*strategically planned networks of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ES*” (EC, 2013). This definition underscores the role of interconnected and multi-functional ecosystem network integrating the natural system with human well-being by taking into consideration spatial interactions between ecosystems, services and people (Babí Almenar et al., 2018; Laforteza et al., 2013; Liqueste et al., 2015; Maes et al., 2015; Wickham et al., 2010). This aspect is becoming a priority issue for landscape planning and development, both at the regional and urban scale.

In physical terms, a GI network consists of i) core areas or nodes, e.g. open and vegetated areas, and ii) corridors or links that physically connect core areas to one another (Figure 1). The degree to which cores areas are joined by corridors indicates the level of connectivity: when all the elements are connected to each other, they achieve a complete (extremely high) connectivity. Landscape connectivity analysis helps the planning and managing GI as a network that can contribute to preserve and improve ecological functionality (Liqueste et al., 2015). Knowing the status and connectivity gaps of a GI network is a prerequisite for developing effective solutions to ecosystem management. Within this network, it is vitally important to protect the areas that maintain essential properties for ecosystem functioning and to avoid system collapse. Therefore, in the long term, the network and connectivity approach can serve as an ‘insurance’ for future changes and dynamics (Gonzalez et al., 2017).

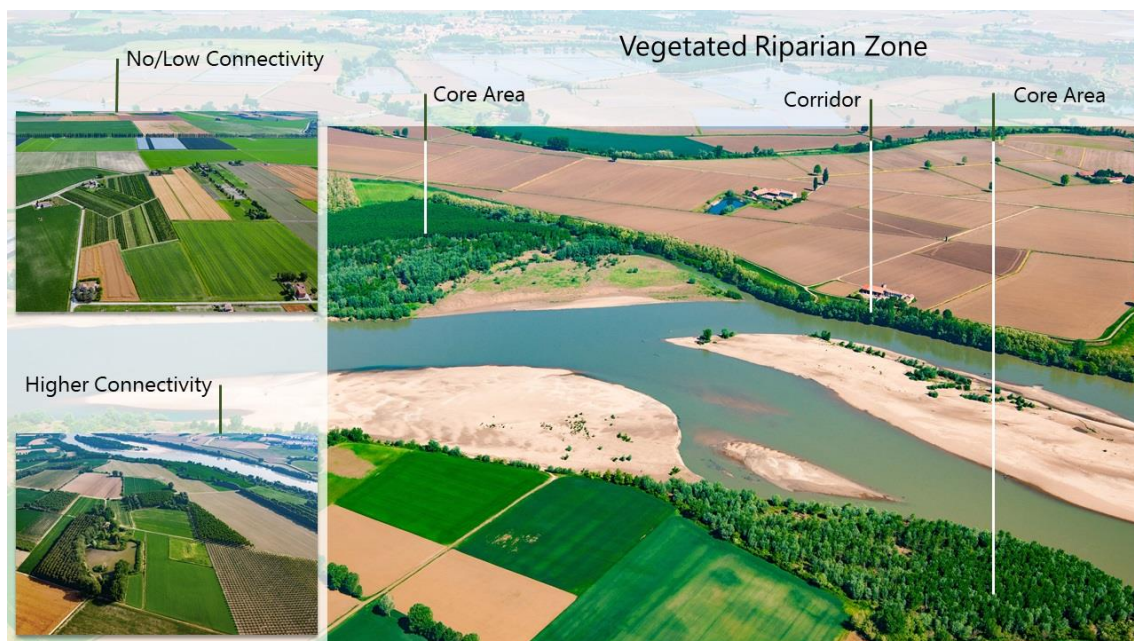


Figure 1 – Example of green network elements (core areas and corridors) and connectivity levels in the Padan plain in Northern Italy (case study). Core areas can correspond to larger green vegetated areas (e.g. small forests) serving as habitat for species and service providers, while corridors are linear green elements (e.g. vegetated riparian strips) that connect core areas and allow the movement of species and services through them. A no/low connectivity landscape is characterised by few, small, scattered green elements such as stands or clumps of trees and bushes, while a higher connectivity landscape shows larger, closer green elements, such as small wooded areas, connected by such features as buffer trees bordering roads, cultivated fields and vegetated riparian strips.

Because of increasing environmental and climate challenges, and in acknowledgment of the role and importance of connected GI networks for ecological functioning, this paper intends to address the needs of fostering connectivity in GI networks planning. This chapter is devoted to developing a general framework that can be used at different scales (local, regional, national, international) and in different contexts (e.g. urban, agricultural, freshwater ecosystems) to better build GI networks by:

- (i) analysing the spatial configuration and connectivity of existing GI networks;
- (ii) identifying where to concentrate future efforts to improve or maintain connections.

Here, the framework applied to explore the GI network in the Padan Plain in Northern Italy. First, we characterise the network as being made up of protected areas under the Habitat and Bird Directives (the Natura 2000 sites), as well as nationally designated protected areas and vegetated riparian zones. Second, we estimated their connectivity status and gaps. Lastly, we considered potential intervention scenarios for improving or preserving the network, by simulating the addition of new core areas and corridors or removing existing ones.

Material and methods

The conceptual framework

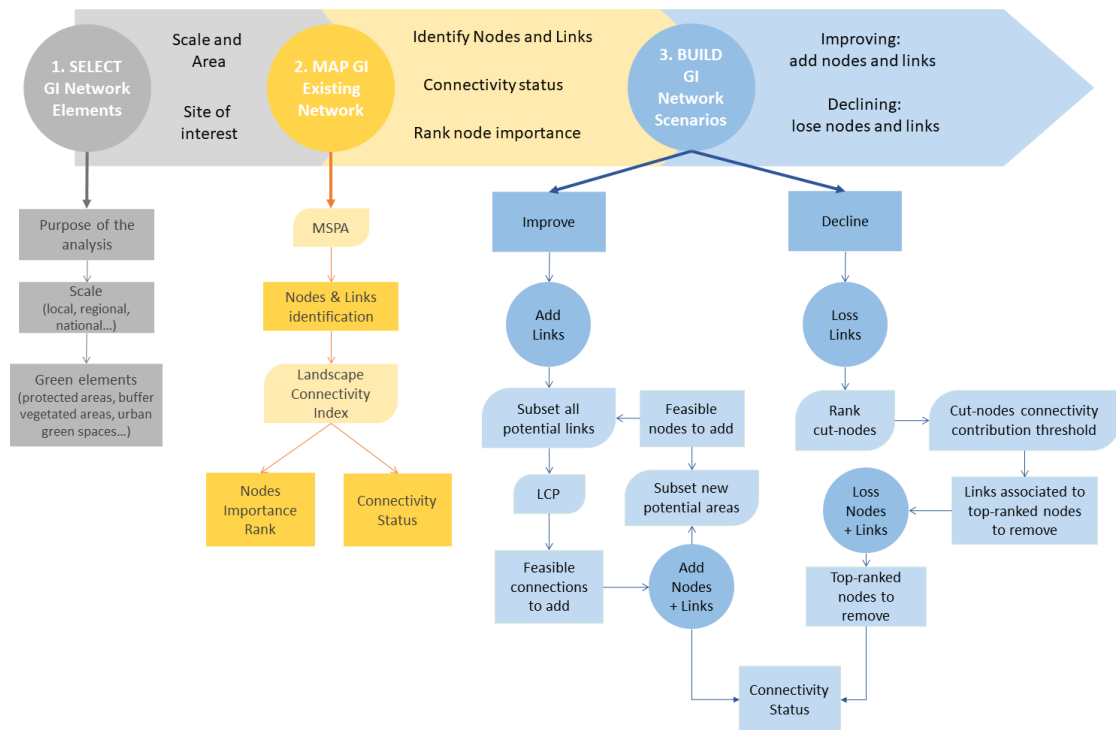


Figure 2 – Conceptual framework for GI Network analysis. The framework consists of three main steps: 1) the green elements of the network are selected according to the purpose and scale of the analysis; 2) the nodes and links of the network are mapped and identified through morphological spatial pattern analysis (MSPA) and a landscape connectivity index is computed to assess connectivity status and nodes importance; 3) nodes and links are added or removed to build network scenarios by improving or declining, according to a least-cost path (LCP) analysis and cut-node definition that identify the new feasible or most important existing elements, to obtain an assessment of the potential new network's connectivity status.

The conceptual framework (Figure 2) we developed builds on concepts and methodologies used in the fields of landscape ecology, spatial planning, graph theory and network analysis, as presented in the thesis introduction. The initial selection of network elements (step 1) contextualises the application of the framework according to scale, ecosystem type and scope of the study. This guides the definition of specific green elements that can constitute the network in that area. The second step combines methods of morphological spatial pattern analysis (MSPA) and landscape connectivity analysis for studying the existing GI network. MSPA is useful for mapping and characterising the network elements (Soille and Vogt, 2009), while the connectivity analysis helps to measure how spatial composition and configuration can affect ecological services and functional dependency (Babí Almenar et al., 2018; Liu et al., 2017). Here, we used landscape connectivity indices to assess connectivity of the GI network and the most important contributing elements. Indices address the importance of nodes by taking into consideration the position, quality and quantity of available areas, including the effects of both landscape composition and landscape structure (Avon Catherine and Bergès, 2016). The assessment of connectivity makes it possible to identify the critical areas that should be preserved or reconnected to the network. The third step (3a) develops network scenarios for future nature-based interventions. For the improvement scenario, we based our analysis on the idea of connectivity and redundancy for building resilience (Biggs et al., 2012) and integrating site- and system-centric perspectives (Zetterberg et al., 2010). The site-centric approach aims to identify isolated or more exposed nodes, while the system-centric perspective aims to identify crucial regions for the network structure in order to add or restore nodes and links that increase system resilience. The study of a scenario of network reduction (step 3b) seeks to identify nodes and links whose loss can undermine system stability. A vulnerable network is manifested when single connections or a single path exists, and the potential movement within the landscape is reduced (Rayfield et al., 2011). The analysis of network reduction would simulate the further fragmentation of the network and the consequent potential degradation of core areas and their ecological functioning.

The various steps, variables and metrics included in the framework can be modified according to the case study analysed by increasing the detail and complexity of the analysis. The framework can be applied entirely or just partially in order to focus on specific issues or processes. In the following sections, the chapter presents the simplest architecture that provides a first overview of the GI network and the potential connectivity needs to be applied to the case study of the Padan Plain. This can guide more specific investigations and subsequent landscape management decisions.

1) Selecting GI network elements

The choice of what is considered as a part of the GI network is context specific and is determined by the purpose and scale of the analysis. According to the scale, the green elements of interest can be different. At international, national and regional scale larger protected areas, national parks, forest landscapes or floodplains can be considered important, while local scales can privilege smaller and more specific elements, such as urban parks, ponds or tree buffer strips and hedgerows. Generally, protected areas can be considered at each scale, having different dimensions and potentially bridging and influencing various network scales, such as connecting the local green network of a city with its surrounding regional network. They support the creation, maintenance and management of the ecological network, as based to connect also distant nature protection

areas across the landscape by improving network potential and ES provision (Fenu and Pau, 2018). Then, green elements can also be defined according to the type of ecosystem analysed. Examples of green features in urban areas include parks, green roofs or walls, rain gardens or green alleys; in agricultural ecosystems these can be water retention ponds, buffer strips or forested infiltration areas; or in freshwater ecosystems, wetlands and vegetated riparian zones can be important. The definition of the elements of interest can also be narrowed in relation to the issues analysed, selecting those that can respond better, for example, to flood risks or water scarcity, heat waves or air quality, recreational scope or pollination needs.

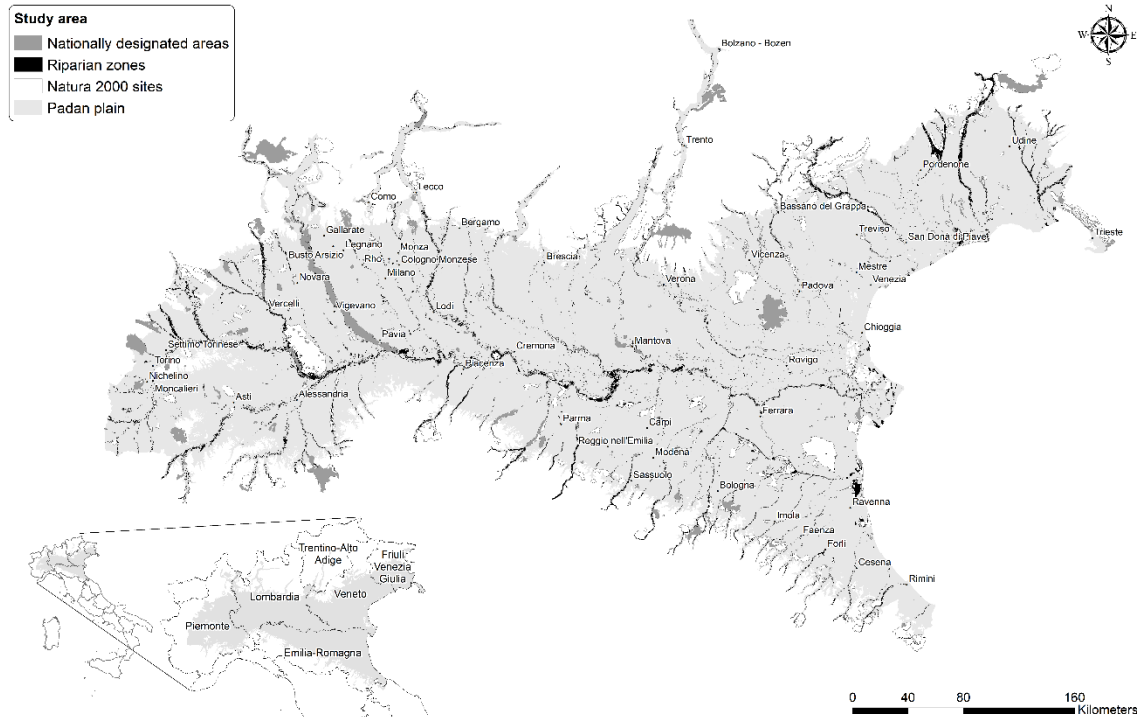


Figure 3 – The Padan Plain in Northern Italy and the areas constituting the GI used for the analysis (Natura 2000 sites, nationally designated areas and vegetated riparian zones).

To test the framework, as a first step we selected the Padan Plain area (Figure 3), an alluvial plain generated by the Po River, located in Northern Italy, a highly developed area extending over 48.000 km² and home to about 20 million inhabitants. The area includes 5 administrative regions: Piedmont, Lombardy, Emilia-Romagna, Veneto, and Friuli-Venezia Giulia. In line with the definition of “plain” of the National Statistical Office (ISTAT, 1958), we have chosen contiguous land area whose altitude is lower than 300 meters above sea level (MSL). The Padan Plain is particularly important at the national and international level, since it is an important industrial and agricultural production area in both Italy and the rest of Europe. The area experienced huge environmental transformation and urban development in the past and today is a representative region suffering major impacts of environmental and climate change, with a negative alteration of the services it provides (Pham et al., 2019). It is among the most polluted regions in Europe, subject to intense rainfall leading to floods and alternating with periods of severe water scarcity and droughts, and to a rise in sea level that is exerting critical pressure in its coastal areas (Domeneghetti et al., 2015; Da Lio and Tosi, 2019; Montanari, 2012; Pozzer et al., 2019). However, the abundance of protected areas established in the region presents an opportunity for environmental restoration, biodiversity, and ecosystem services. Hence, in accordance with

the type of ecosystems and the regional scale, we selected protected areas and vegetated riparian zones as elements of the network, specifically Natura 2000 sites and nationally designated protected areas.

Natura 2000 is a network of designated sites for protecting Europe's biodiversity and habitats listed in the Habitats and Birds Directives (EC, 1992, 2009). They are recognised as valuable refuges for threatened species and as environments that can support positive ecological functions and services, especially as regards climate change mitigation and adaptation, tourism and recreation, food production, ecosystems and water quality (Bastian, 2013; EC, 2013c). The same holds true for nationally designated areas, though protected by national legislation. Vegetated riparian zones play an important role in providing different functions and services. They are the transitional areas at the interface between land and freshwater ecosystems, strongly influenced by stream water. They support European objectives for biodiversity and environmental quality (Biodiversity Strategy, Habitat and Birds Directive, Water Framework Directive) and are therefore embedded in the network (Copernicus, 2015).

To perform this analyses, we used data obtained from the European Environment Agency (EEA, 2019b, 2019a) for the Natura 2000 and nationally designated sites, and high-resolution riparian vegetation zones detected by the Copernicus Land Monitoring System to analyse vegetation near rivers, lakes and streams (Copernicus, 2015). Only vegetated land surface was included in the analysis, leaving out protected marine and freshwater bodies as well as sites occupied by water habitats for more than 70% of the surface. Excluded water habitats are those classified by the Natura 2000 typology as marine areas, sea inlets, tidal rivers, estuaries, mud flats, sand flats, lagoons, inland water bodies and coastal areas (categories N01, N02, N06 and N24) (EEA, 2019b). Protected land areas only partially included in the case study have been included in the analysis.

2) Mapping the existing GI network status

Once a set of green elements is defined, this can be mapped and characterised as a network.

MSPA extracts the nodes and links constituting the GI network. It identifies the geometry of the network by using mathematical morphology algorithms to segment a binary representation of the landscape based on size and distance of groups of pixels (Soille and Vogt, 2009; Vogt et al., 2009). The process divides the network elements, highlighting the core areas or nodes and the corridors or links. We performed MSPA with the open-source GuidosToolbox software (Vogt and Riitters, 2017). The spatial network was then translated into a graph to compute a landscape connectivity index. The connectivity index can inform on the overall status of network connectivity and on the role and importance of nodes. Nodes contribute differently to the overall connectivity. Their importance is a measure of their single contribution to connectivity, used to identify and rank the most relevant nodes for network maintenance. The top-ranked nodes are those that most support connectivity within the network and whose preservation should be prioritized to ensure ecological quality across the landscape.

For the analysis in the Padan Plain, the Integral Index of Connectivity (IIC) was used (Pascual-Hortal and Saura, 2006). The IIC is a straightforward index based on binary connections between nodes (presence or absence of connections) and considers the node attribute (in this case the area) with low data requirements, making it a suitable means for

easily informing landscape management. It ranges from 0 to 1 and increases with a higher connectivity. We computed the overall value of connectivity and consequently defined node importance in terms of percentage, following the formulation of Pascual-Hortal and Saura (2006). IIC can be partitioned into three fractions to analyse the roles of nodes and their single contribution. Index fractions represent i) intrapatch connectivity, which is the degree of connectivity within a patch; ii) flux, which is the potential flux associated with a node, indicating the quality of connection between patches; iii) connector role, i.e. if a node acts as stepping-stone or connecting element between two nodes in the landscape, facilitating dispersal and mobility (Saura and Rubio, 2010). Here, we considered the connector role of nodes (*IICconnector*), which is particularly important for establishing and preserving connectivity, and used nodes areas as a node attribute.

The IIC computation is performed by means of the Conefor 2.6 software (Saura and Torné, 2009; Saura and Tornè, 2010), which is well integrated with the outputs of MSPA analysis.

3a) Building Network Scenarios – an improvement

In building a network improvement scenario, the framework followed a two-phase approach to add potential new connections and core areas, mainly based on distances and paths between nodes (Galpern et al., 2011; Urban et al., 2009). The new network elements can be represented by the implementation of specific green features important for the case study analysed.

As a first step, the framework includes the identification of potential new connections. Among all the potential links, the framework considered only direct and closer connections according to linear Euclidean distance thresholds, to exclude unfeasible links between very distant nodes and the already existing connections. As distance thresholds are linked to the maximum reachable distance of ecological flow and depend on the type of services, species and flow considered (Du et al., 2018; Mönkkönen and Reunanen, 1999), they may influence the resulting configuration of the network and should be linked to the specific management goals. Here, since we tested a general application of our framework, we considered the Euclidean centroid-to-centroid distance values between existing core areas. We selected three different distance thresholds (1km, 2km and 4km) to perform the different scenario improvements separately. The selected thresholds measure 1st quartile, median and 3rd quartile values of existing distance, representing the most common distances between nodes in the case study area (see Annex 1.1). When selecting new connections, another important element to be considered is the re-connection of components, i.e. subnetworks or groups of nodes interconnected and isolated from the rest of the network. Hence, the framework privileged only those connecting two or more different components, while excluding new potential links within the same component. This also make it possible to favour the connection of isolated nodes that count as single different components. Once the node pairs to be connected have been defined, the least-cost path (LCP) analysis identifies the feasible connections that could be restored among all the potential links. LCP analysis measures the minimum cost path between two nodes, taking into consideration landscape characteristics. LCP is largely used in landscape ecology to define the movements of wildlife across a landscape in terms of landscape structure and ability to disperse in the area. It can be applied to identify potential green corridors that allow the movement and flow of material, energy and life for supporting ecosystem services (Balbi et al., 2019; Lee et al., 2014; Wei et al., 2018; Zhang et al., 2019). In this analysis, we computed the LCP analysis

through the R's *gdistance* package to compute (van Etten, 2017), by using normalised proximity values as cost raster base.

As a second step, the framework includes the analysis of potential new nodes to improve the network. As in the first step, the distances between existing nodes are used to identify the need and location of additional nodes. Nodes that are too far apart to establish a link remain isolated or disconnected in the first step. They can be reconnected through the implementation of a new core area that acts as stepping-stones to reduce the distances (Herrera and Sabatino, 2017; Saura, 2014). This approach identifies suitable areas for implementing new nodes. Based on previously defined distance thresholds, the maximum distance between nodes is used to define locations where nodes can act as additional stepping-stones. Suitable areas already containing nodes and belonging to the same component were excluded. When the new nodes are added to the network, procedures to add links and the IIC index for the new networks can be performed iteratively. For all the added nodes, we considered the same area, selected on the basis of the median value of the existing core area size (around 1 ha).

3b) Building Network Scenarios – a decline

The framework can also explore potential network decline by isolating and removing some of the existing nodes and their connections. The removal of cut-nodes, i.e. key nodes that maintain larger connected components and that can cause their disaggregation into smaller separated components, simulates a decrease in connectivity. Cut-nodes are those top-ranked nodes identified according to the importance value of their connectivity (Fenu and Pau, 2018). This ranking makes it possible to identify critical nodes, based on their topological positions, that maintain connectivity. The selection of cut-nodes to be removed takes into consideration the capacity of each node to provide a significant increment of connectivity. The analysis computes the cumulative contribution of nodes to define an index threshold for cut-nodes. To select the cut-nodes in the Padan Plain, the *IICconnector* value was used, setting the threshold at 0.001. Around this value the contribution of connectivity reaches a steady status, with no further significant increase.

The decline scenario, following a two-stage process, simulates first the removal of links associated with the top-ranked nodes by exploring the potential fragmentation due to corridor loss and habitat isolation (Urban and Keitt, 2001). The loss of these key links leads to the increasing number of isolated nodes and to the disaggregation of network components. The second step analyses the further loss of cut-nodes. This scenario can be potentially associated with the degradation of isolated habitat, causing the loss of high ecological value areas. Lastly, the IIC index for the resulting networks can be performed again.

Scenario analysis has been performed through QGIS and the R statistics software.

Results

Mapping current GI network status



Figure 4 – Graph representation of the existing GI Network in the Padan Plain area. Dots and lines represent nodes and links of the network. The isolated nodes are reported as white stars, and the connected nodes as black dots. Links are represented by black lines. The size of nodes represents their relative importance in terms of connector values (IICconnector rank).

We mapped the status of the current GI network (Figure 4). The case study area is predominantly occupied by core areas or nodes (69.19%), whereas connections or links cover only a small portion (4.31%). More specifically, the network consists of 2708 nodes (of which 657 are isolated), 5115 connections and 1030 components. The nodes are distributed across the entire area, with higher frequency along the river courses. The Emilia-Romagna region has the largest number of nodes (26%), followed by Piedmont (24%), Lombardy (21%), Friuli-Venezia Giulia, Veneto (13%) and Trentino-Alto Adige (4%). Friuli-Venezia Giulia ranks first in nodes per unit of area. Trentino-Alto Adige is the most disconnected region (53% of its nodes are isolated), whereas Friuli-Venezia Giulia has the lowest percentage of isolated nodes (18%). The landscape index IIC for the entire Padan Plain indicates a low degree of connectivity (IIC = 0.010485).

The size of nodes shows the rank of nodes importance according to the IICconnector fraction (rankings associated with other IIC fractions are reported in Annex 1.2). Nodes with the highest IICconnector values are mostly located along water courses. They are aggregated in clusters mainly located along the Po River around Alessandria, near Piacenza-Cremona and in the area between Ferrara and Bologna. In the northwest, there is a cluster in the surroundings of Novara, while the north-east has two important areas near Bassano del Grappa and Pordenone. In the south, some clusters lie along Po tributaries flowing from the Apennines in Emilia-Romagna, especially between Parma and Bologna, and south of Rimini. The plain zone between Milan and Venice and those at south of Turin appear to be poor in connection elements.

Building GI network scenarios: network improvement

The results of the LCP analysis identify suitable connections, showing an increase in connected nodes and a decrease in components. The resulting connections, the new number of components and isolated nodes are reported in Table 3.

| GI Network Scenarios | 1km | 2km | 4km |
|----------------------|------|------|------|
| New feasible links | 5328 | 5968 | 8061 |
| Components | 905 | 732 | 468 |
| Isolated nodes | 540 | 425 | 247 |

Table 3– Network characteristics results in the different distance scenarios improved with the addition of links.

For each distance threshold, a set of nodes resulted suitable for improving the network. In the 1km-scenario 56 nodes have been added, 61 nodes in the 2km-scenario and 75 nodes in the 4km-scenario. Additional new links reduced the number of components and isolated nodes. The resulting numbers are reported in Table 4.

| GI Network Scenarios | 1km | 2km | 4km |
|----------------------|------|------|------|
| New feasible nodes | 5433 | 6130 | 8224 |
| Components | 891 | 714 | 474 |
| Isolated nodes | 537 | 415 | 261 |

Table 4 - Network characteristics results in the different distance scenarios improved with the addition of nodes and links.

An example of the mechanism for improving the GI network scenarios by adding links and nodes is reported in Annex 1.3.

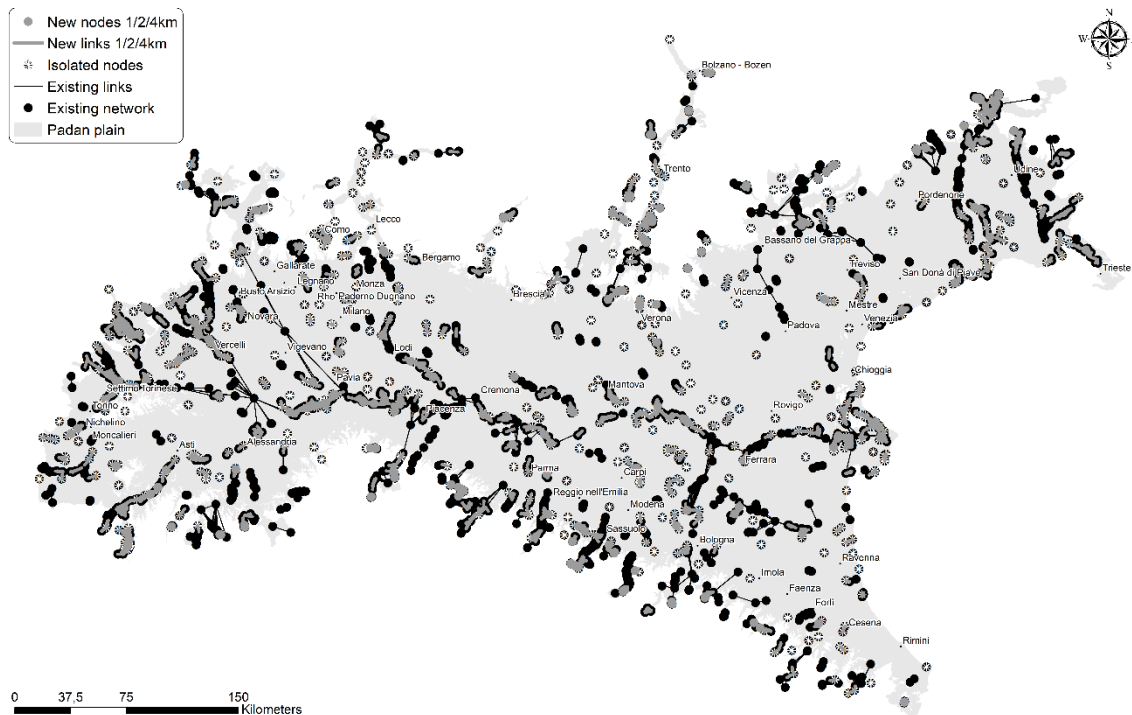


Figure 5 – GI Network improvement scenarios: additional nodes and links for the different distance threshold.

New connections in the improvement scenarios, located mainly along water courses, follow the existing network structure (Figure 5). A great improvement can be noted along the Po River, in the surroundings of Turin, Pavia, Cremona, Mantua and the Po delta area (Chioggia). Other improved spots are in the southwest area of the Padan Plain (Asti) and in

the northwest near Vercelli. In the northeast, the area of Rovereto, between Trento e Verona, and the plain between Pordenone and Trieste have several new connections, most of them referring to the 2km and 4km scenarios. The new nodes that can help improve connections are distributed across all the Padan Plain, generally following the river asset. However, it is to be noted that the northern plain between Milan and Venice and the zone of Ravenna has fewer new nodes and less improvement in connections.

IIC results show an improvement in the potential connectivity status (Table 5). IIC values, both in improvement scenarios and in the existing networks, are very low, indicating a low connectivity status and scarce improvement. However, this could be attributable to the large number of nodes included in the network, since the maximum value of IIC (IIC=1) is associated with a complete graph, where all nodes are connected to each other. The absolute value of IIC may not be so significant but given the percentage increase of connectivity with respect to the existing network, the gains in connectivity are more explicit (Table 5). A concrete sign is also given by the reduced number of components and isolated nodes in the different scenarios compared to the current network.

| IIC | 1km | | 2km | | 4km | |
|----------------------------|----------------|------------|----------------|------------|----------------|------------|
| | absolute value | % increase | absolute value | % increase | absolute value | % increase |
| New Links | 0.0104905 | 0.052 | 0.0106821 | 1.880 | 0.0115522 | 10.178 |
| New Nodes and Links | 0.0105101 | 0.239 | 0.0106851 | 1.908 | 0.0116906 | 11.498 |

Table 5 – IIC results in the different distance scenarios improvements.

Building GI network scenarios: network reduction

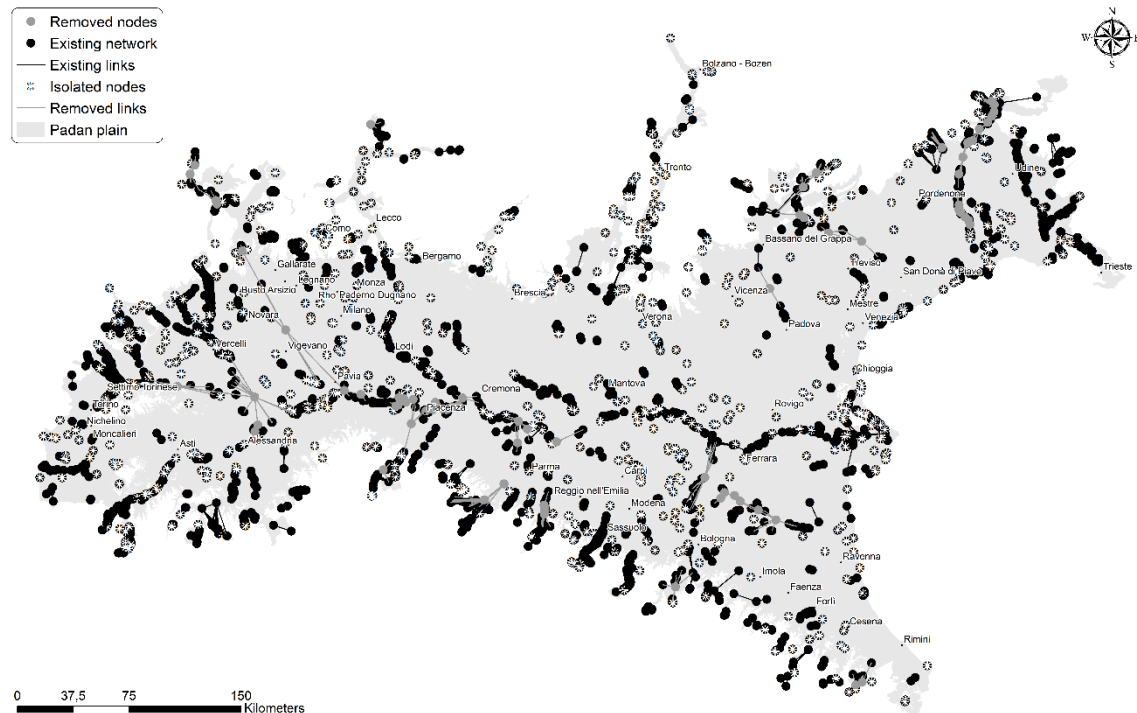


Figure 6 – GI Network decreasing scenario: nodes and links removed.

According to the IICconnector threshold, we identified 90 cut-nodes and 503 associated links.

With the selected nodes and links removed, the number of components increased: +206 when only links were deleted, and +116 when the nodes were also removed. An example of the network reduction scenarios mechanism is reported in Annex 1.3.

The network decline (Figure 6) impacts predominantly the northwest in the area of Alessandria and between Busto Arsizio and Pavia. A significant reduction resulted in the vicinity of Piacenza, Cremona, and Parma. In the southeast, link losses occurred south of Ferrara and in Rimini, while the northeast was affected north of Treviso and in the northern part of the Tagliamento River (Pordenone).

The IIC index shows a significant reduction in both scenarios (Table 6).

| IIC | IICconnector threshold = 0.001 | |
|--------------------------------|--------------------------------|------------|
| | absolute value | % decrease |
| Removed Links | 0.0097316 | 7.185 |
| Removed Nodes and Links | 0.0051627 | 50.761 |

Table 6 - IIC results in the reduction network scenarios.

Discussion

The framework presented in this paper has been developed to bring together and systematize existing methods and tools for assessing landscape connectivity. As such, it can be used to inform decision-makers on the location of new green infrastructures by using a network system perspective and to help to plan the green infrastructure network. The method presented has low data requirements and can be performed with open-source software. There are many methodologies and different tools for connectivity analysis, such as those presented by Fenu and Pau (2018) and Saura et al. (2011), but generally they are not included in a structured, comprehensive framework. Usually, frameworks or schemes specifically devoted to connectivity assessment focus more on spatial prioritization needs for ecosystem service enhancing (Kukkala and Moilanen, 2017), or refer to the understanding of interactions and interdependencies of multi-ES across the landscape (Field and Parrott, 2017), but their integration into a spatial planning and management approach, with explicit reference to a green infrastructure network, is lacking. Generally, the GI frameworks developed until now have different aims and a limited use of connectivity or network approaches. For example, Lique et al. (2015) has presented a methodological framework to identify the GI elements supporting ecosystem services and functional connectivity, but without any reference to network assessment or development planning. Laforteza et al. (2013) proposed a framework embracing the benefits and functions of green infrastructure based on multi-scale, functional and temporal approach, disregarding their spatial configuration.

This framework contributes to overcoming these gaps by supporting the analysis of existing GI network connectivity to develop future interventions. The case study of the Padan Plain highlighted the isolated or connection-poor regions and those that need serious attention in regard to connectivity improvement and restoration. They are mainly located in the southwest and central area, between Milan and Venice, an extensively agricultural area. These results reflect the findings of the national Italian report on soil consumption, which have identified the highest value of natural land conversion, fragmentation and soil depletion in this area (ISPRA, 2021). The report showed high negative impacts of soil consumption on providing ecosystem services. Agricultural production, carbon

sequestration and habitat quality decreased, with an associated decrease in their economic value. The loss of water retention capacity was particularly critical for the Padan Plain, with negative consequences for both water storage and impeding excessive runoff. The same needs and urgency of limiting land fragmentation and soil depletion are highlighted by the Common Agricultural Policy framework, which calls for integrating a green network into agricultural ecosystems to increase biodiversity and environmental quality, goals for whose achievement Italy is still generally lagging behind (Magaudda et al., 2020). But analysing a green network status can contribute to addressing these needs by supporting a greener sustainable growth into regional and national landscape planning and decision-making, as promoted by EU strategies and policies (EC, 2019a, 2020c, 2020a).

The analysis of network improvement identifies the connections and nodes that would support the development of a GI network at the landscape scale. Here, the identification of new nodes is associated with distance thresholds and feasibility is given by the shortest existing path. Most of the improvement is occurring along the river, by improving connectivity especially from northwest to east. This reflects the importance of rivers, which constitute a natural vital network for species across the landscape, acting as corridors between ecosystem features (Seliger and Zeiringer, 2018). The importance of the river network is visible not only for single landscapes, for it also supersedes administrative boundaries, allowing the improved Padan Plain GI network to play an intermediate role in connecting the regional network to the national and international GI network with the more local or urban network of green spaces. Network improvement in the Padan Plain would help achieve European and international targets of building a more coherent transnational nature network for supporting a collaborative restoration and protection of biodiversity and ecosystems, as outlined in the EU Biodiversity Strategy for 2030 and in the Convention for Biodiversity (CBD, 2010; EC, 2020a; EEA, 2020a).

The framework proposed could support decision-making to plan or prioritise interventions, by identifying the theoretical new links and nodes. Decision-makers can compare the existing land cover to evaluate the best sites for new green areas or corridors among those identified in the scenario. Many of the isolated nodes could be reconnected thanks to the addition of new nodes acting as stepping-stones. At the same time, from the current situation, the nodes with the important role of connector elements can be derived. This can inform protection and conservation actions. Their loss can lead to a high degree of fragmentation, causing the collapse of many connections, as seen in the reduction scenario southwest of Milan, in the northeast and along the Emilia-Romagna's side of the Po River. While the framework provides an overview of all the potential options, useful for driving future nature-based implementations, it is not developed to give a ready-to-use plan for network development. The analysis can provide more than a single link for reconnecting different components or isolated nodes, but the feasible connections are fewer or more complicated realize when compared to the existing land cover, such as if they cross a high-speed way or an urban area (Annex 1.3). In this sense, decision-makers and planners should use it as a guide for further investigation. Road and transport infrastructures, together with urbanization, could have severe impacts on ecosystem connectivity and services, and spatial planning should be more cross-sectoral, integrating development needs with environmental protection and restoration goals, and with a closer collaboration between science, policy and management sectors (Angelstam et al., 2017).

Our methodology can be tailored and detailed along with the specific case study. According to the scale and scope of the analysis, different features can be modified and applied either entirely or just partially. For example, the sites included in the network as elements of interest can vary in relation to the scale (local or regional level), and the type of environment analysed can be more specific (urban areas, agricultural land, or freshwater ecosystems). This would be influenced also by the scope of planning and the ecosystem services that should be enhanced with the GI network, such as climate change adaptation, flood protection, recreational activities, or nature conservation. The network can be studied by using different types of data or indices. Network elements can be identified by using several satellite data and products, such as those available in the Copernicus Land Monitoring Service (e.g. imperviousness, grassland, forest type, water), and land cover/land use maps at various levels of detail, resolution, and spatial scale, such as the national high-resolution land cover map developed for Italy (Congedo et al., 2016). These data and products can also be easily used in combination with census data, for example on environmental sites, population or buildings (Salvati et al., 2012). Defining node attributes, distance thresholds or resistance surface would depend on the combination of characteristics from these datasets. Distance definition is important in defining connection feasibility and can be associated with the dispersal capacity of species or material flux, which take into account not only linear distances. There are also several indices and metrics for investigating network connectivity at the landscape level, such as the Probability of Connectivity, Harary Index, Landscape Coincidence Probability, Flux and Patch Cohesion (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007), which can be chosen according to the scope of the analysis. The IIC is among the easiest indices also able to investigate the different role of nodes. It works well on a large scale, especially for temporal and requirement computation. The index is more efficient for identifying critical nodes and their importance ranking than for assessing overall connectivity levels. With a high number of nodes, the overall value may not be immediately clear, resulting generally low, and the computation could be slow. This can be a limit. However, the percentage increase or decrease of the index highlights changes in network connectivity status and facilitates understanding results.

Analysing a GI network can include several steps and yield an increased complexity in the decision process. Additional variables can be used to characterise the nodes and links of the network and to investigate existing relationships other than the spatial one. Together with area and location, other attributes can refer to biophysical and economic measurements associated with land cover or ecosystem types, such as those promoted in the Italian soil consumption report (ISPRA, 2021). Other variables can deal with climatic risks and vulnerability. However, changing input data and variables can require changes in the tools, model or metrics used. By using satellite images, MSPA can be used in combination with more specific tools to characterise the network elements in particular contexts. For example, geographical object-based image analysis and ensemble learning algorithms can be a useful for mapping and defining the main units of river networks (Demarchi et al., 2020). Lastly, in addition to spatial relationship, the analysis may include further investigation on connectivity influence on process occurring in the network. Models such as Bayesian belief networks can be used in place of least-cost and based-distance models to provide insights on conditional dependencies of both natural and human variables, which can be particularly useful in assessing vulnerability drivers (Taramelli et al., 2020).

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CHAPTER 2: RIVER BASIN SCALE³

Natural water retention ponds for water management in agriculture: a potential scenario in Northern Italy

Introduction

Ecosystems can provide means for mitigating natural hazard risks and boosting societal resilience, locally or regionally. They can contribute to water regulation through intrinsic characteristics and associated functions, by acting on soil infiltration capacity and water retention, and by providing space for water storage (Uy and Shaw, 2012). Managing ecosystems and building solutions based on ecosystem services (ES) can contribute to limiting negative effects of droughts and floods and to recharging groundwater, with additional benefits for water quality, soil protection and biodiversity.

Compared to engineered - or grey - solutions, nature-based solutions (NBS) and green infrastructure (GI) (Cohen-Sachman et al., 2016; EC, 2013a, 2015b; Hodgson et al., 2016; Masi et al., 2017) can be cost-effective and provide additional benefits (EEA, 2015; IUCN, 2015), beyond the specific functions for which grey solutions are designed, such as food and water provision, clean air, water and soil, recreational and aesthetic functions (IPBES, 2019b). For this reason, NBS gain in policy effectiveness, from the local to the national and the global level, to tackle environmental and socioeconomic challenges (Faivre et al., 2017; Laforteza et al., 2017). It has also been demonstrated that NBS and ecosystem services have beneficial effects on the productivity of businesses in the water sector (Aldieri et al., 2020).

Green Infrastructure is defined as *“a strategically planned network of natural and semi-natural areas, along with other environmental features designed and managed to deliver a wide range of ecosystem services”* (EC, 2013a). GI acts at the spatial planning and development level, by providing alternative infrastructures based on natural functions, and by using ecological networks between high quality areas. It can be combined with traditional and built infrastructure. GI stresses the idea of green connected spaces, by featuring biodiversity and socio-ecological aspects as core elements. Landscape connectivity has been considered largely as fundamental for maintaining environmental quality, species dispersal, key ecological processes, and ES provision (Liu et al., 2017; Mitchell et al., 2013, 2015; Vallecillo et al., 2018). It can favour ecological movements, functions, and services, in accordance with the composition and configuration of the landscape in its quantity and distribution of land cover types. Connectivity could be enhanced by creating networks that maintain and restore healthy and well-connected ecosystems. This would mean planning single NBS as a GI network, distributed and connected across the landscape for the purpose of limiting ecosystem fragmentation and other environmental problems (Laforteza et al., 2013; Liqueste et al., 2015; Maes et al., 2015).

³ This chapter is derived from Staccione A., Broccoli D., Mazzoli P., Bagli S., Mysiak J. (2021): “Natural water retention ponds for water management in agriculture: a potential scenario in Northern Italy”, Journal of Environmental Management – <https://doi.org/10.1016/j.jenvman.2021.112849>

Natural water retention ponds organised into networks can improve connectivity and so enhance their benefits by addressing water issues due to climate change, while preserving environmental quality and agricultural productivity. The integration of a green infrastructure network in agricultural ecosystems is also included among the priorities of the Common Agricultural Policy framework, for increasing biodiversity, sustainable use of resources and environmental quality (Magaudda et al., 2020). The study of sustainable use and management of water resources has been largely explored, highlighting the positive influence of ecosystems and ecological processes in a variety of contexts. It has been analysed and assessed through methods that include the use of the ecological footprint and carrying capacity of water resources (Wang et al., 2020), hydrological modelling (Dobriyal et al., 2017; Gao et al., 2017), artificial intelligence methods (Niu and Feng, 2021) and multi-criteria decision-making tools (Behboudian et al., 2021). However, there has been as yet no clear investigation that highlights the potential ancillary benefits of nature-based solutions planned as a network to address water scarcity and sustainable use of hydrological resources in the agricultural sector.

The chapter proposes the application of GI networks to implement natural water retention ponds in agriculture in order for dealing with water scarcity and environmental quality degradation exacerbated by climate change. The aim is to analyse the costs and benefits associated with the implementation of connected water retention ponds, in both environmental and economic terms. This has roots in the hypothesis that the benefits to be gained from the implementation of NBS as a potential strategy for climate change adaptation, outweigh its costs. We investigate the effects of ponds on water availability for irrigation, and on the flow regime of rivers. At the same time, we explore their role as elements of a GI network for maintaining and improving landscape ecological connectivity. We perform our analysis with reference to present and future climate change conditions. Finally, we investigate possible mechanisms for their financing and management, through an evaluation of costs, benefits, and barriers to implementation supported by stakeholders and interviews with experts, which lay the basis for a business model development.

Materials and methods

Case study area

The Lamone River basin is located within the Po River Basin District, on the border between the Regions of Emilia-Romagna and Tuscany (Italy). It originates in the Apennines and flows northeast, reaching the Adriatic Sea north of Ravenna. The basin area of 530 km² consists of 12 sub-catchments (Figure 7). Agricultural land covers more than 47% of the river catchment (Benini and Marazza, 2009). The area is important for the production of kiwi and other fruits, grapes and olives, as well as arable crops. Kiwi production is a key component of the agricultural sector in the Romagna area (Betti et al., 2019). The upstream part of the basin hosts 700 hectares (ha) of kiwi crops (16% of Romagna kiwi crops), producing on average 250 quintal (q, hundreds of kg) per ha (Regione Emilia-Romagna, 2018).

The river has a torrential regime with marked seasonal variability. The flow rate peaks in spring and in autumn, and low flows occur in summer and winter. Water availability, i.e. the deliverable water volume in the river, is ca. 100 Mm³ from November to May, whereas only 15 Mm³ from June to October (Regione Emilia-Romagna, 2015). The total amount of abstraction permits (including domestic, industrial and irrigation uses) is around 31 Mm³/year, of which 13 Mm³/year is used for irrigation in the dry summer season (Regione

Emilia-Romagna, 2015). The high abstraction in summer causes water scarcity. Therefore, water retention ponds are recommended to satisfy agricultural water demand and maintain ecological flow, as required in the Po River Basin District's Water Management Masterplan (AdBPo, 2015).

Water retention ponds are built mostly by excavation. Soil characteristics make it possible to use the deeper clay layer as a bottom impermeable component, while the excavated gravel is sold to partially cover costs. Additional construction elements include pumping systems to collect water from the river and to irrigate crops from the ponds. While no weirs are present, a common practice is to install removable pump hoses. The existing ponds are designed to maximise water storage volume with low land requirements and no regard for ecosystem functions. However, retention ponds can be designed for improving ecological performance by creating buffer vegetation, designing gentler side slopes, and building floating islands that serve as refuges for wildlife and aquatic fauna.

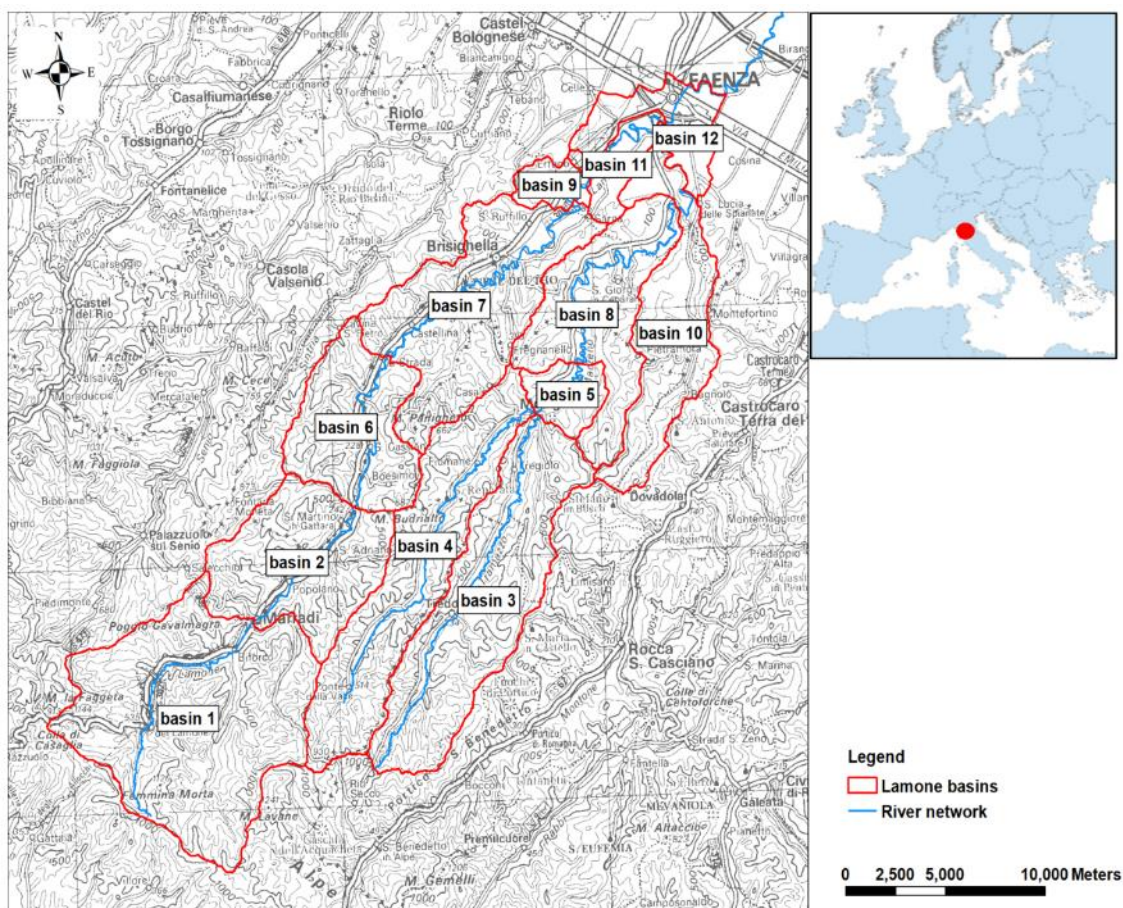


Figure 7 - Lamone River sub-catchments.

Assessment of the effects of ponds

This study aims to quantify the ecological and hydrological effects of a system of additional ponds on both water balance and ecological connectivity in the Lamone area. To this end, we followed the approach proposed in chapter 1 (Staccione et al., 2022b). We have identified suitable sites for the construction of new ponds. We have computed a landscape connectivity index to estimate the ecological importance of each potential site as a node of the GI network. Finally, we have selected only those sites that show a minimum importance for connectivity and ecological functionality in developing a potential implementation

scenario of ponds. The additional water storage volume is used to improve water availability and river flow regime, while costs and benefits are identified and quantified as far as possible.

Suitability analysis for the siting of ponds

A suitability map for assessing the feasibility conditions for locating ponds is the basis for a preliminary screening. The suitability map is obtained by overlapping georeferenced layers of land surface properties (data from Regione Emilia-Romagna, 2019b). A suitable condition is reached when proper criteria are satisfied: linear distance from the river network, land cover type (agricultural land), and terrain slope. These criteria are intended to describe the feasibility of pond realization given the main physical constraints, such as the capacity of water abstraction from the river, the need for water for irrigation, and the presence of a favourable topography and natural depressions. Threshold values of distance and slope have been extracted by digitalizing 296 existing ponds and identifying their frequency distribution. Likewise, we considered the shape and size of the area to identify those better suited for allocating ponds also in terms of space availability. All the values over the 3rd quartile for the slope and distance from the river have been excluded, considering higher slope and distance more difficult and costly to construct. Sites whose areas and shapes prevented the construction of ponds because too small or narrow (area and shape values lower than 1st quartile) were also excluded. Values are reported in Annex 2.1. On the basis of these suitability criteria determined the most favourable areas for installing new water retention ponds. Of the favourable areas, we will select those that contribute most to the connectivity of the GI network, in order to define an implementation scenario of ponds.

Quantification of connectivity effects

The study considers water retention ponds as elements of a green infrastructure network together with natural elements (vegetated riparian zones) and protected areas (Natura 2000 sites). These have been chosen for their capacity to sustain higher biodiversity and healthy ecosystems, that make it possible to maintain good ecological functions and flow of ecosystem services across the landscape (Bastian, 2013; EC, 2013c; Fenu and Pau, 2018). We quantified the effects of ponds in terms of how they may improve landscape connectivity, used as an indirect measure of ecological health and quality. The connectivity status of the GI network is understood as a proxy for the ecological and environmental benefits associated with each scenario.

In order to identify and map the elements acting as nodes and links in the GI network, we performed a Morphological Spatial Pattern Analysis (MSPA) (Saura et al., 2011; Vogt et al., 2009; Vogt and Riitters, 2017). MSPA uses a binary raster map including the network's elements of interest (the foreground - Natura 2000 sites, riparian zones, and water retention ponds) and performs a series of morphological operations to segment the foreground. The segmentation of the spatial pattern uses the size of foreground pixel groups and distance between pixels to characterize core areas (nodes) and connection elements (links). We used data available in regional geographic databases (Regione Emilia-Romagna, 2017; Regione Toscana, 2016) and within the local component of Copernicus land service (Copernicus, 2015).

A landscape connectivity index is then computed to assess the importance of nodes and links for the maintenance of the GI network. In this analysis we used the Integral Index of

Connectivity (IIC) (Pascual-Hortal and Saura, 2006), a simple binary index which considers, with a graph-based approach, whether two areas are connected or not. IIC provides information about the connectivity status of the entire network considered. This value also makes it possible to calculate the nodes' importance, by quantifying the contribution of each single node to the network (Pascual-Hortal and Saura, 2006). IIC can be partitioned into three fractions to investigate the type of contribution of each node to the connectivity (Bodin and Saura, 2010; Saura and Rubio, 2010). Of interest here is the *IICconnector* fraction, which values the role of nodes as stepping-stones, i.e. nodes that facilitate connections between other nodes across the landscape, a crucial factor for supporting connectivity. Node analysis is important for identifying and ranking nodes that should be restored or protected as a priority for maintaining and improving the network's connectivity and ecological status.

MSPA has been performed with the GuidosToolbox software (Vogt and Riitters, 2017). Landscape connectivity indices and the importance of nodes are computed by using the Conefor 2.6 software (Saura and Torné, 2009; Saura and Torné, 2010), which is well integrated with the GuidosToolbox outcomes.

The connectivity analysis performed on the existing network has been successively used to define the implementation scenario. We integrated the suitable sites for constructing new ponds within the existing network. The node rank (*IICconnector* fraction) of the new potential network has been used to select the suitable sites that contribute most to improving connectivity. We included in the implementation scenario suitable areas that act as connector elements and provide an increasing contribution in connectivity up to a steady status of *IICconnector* value (Annex 2.3). The assessment of nodes within the network makes it possible to prioritize the new interventions in terms of ecological functions and connectivity improvement. The effects of these new ponds on the water balance have been assessed in the next section.

Water balance effects

Water balance at sub-catchment scale and related effects of water retention ponds have been described by Flow Duration Curves (FDC). The FDC is a plot of river discharges as a function of frequency of exceedance over a given period. Its integral is the total volume of water flowing in the river. The FDC of unaltered (natural) river discharges can be modified by adding or subtracting the discharge released or abstracted during the period of interest. The abstractions from the river cannot exceed the river flow and should preserve the Minimum Ecological Flow (MEF).

FDCs was used to estimate the River Water Balance according to the scheme of Figure 8(a), following the methodology described in Cassani et al. (2009): at a given river section, the sum of all abstractions in the upstream catchment is represented by the maximum volume V and the corresponding flow rate q_{max} , assuming MEF left in the river. Discharges released to the river count as negative abstractions (e.g. the return flows from wastewater treatment plants). When the FDC is below the MEF, no abstraction is allowed, and when instead the natural FDC exceeds $MEF + q_{max}$ new abstractions may occur. The permitted abstractions depend on the available flow when the FDC is between MEF and $MEF + q_{max}$. Thus, we considered the integral of FDC for flows above $MEF + q_{max}$ as an indicator of water availability (WA) for the river or for new abstractions. The analysis is repeated at each section of

interest moving downstream, adding permitted abstractions along the river, and modifying the FDC accordingly.

Along with WA, the ratio of the volumes of abstractions (net of releases) to the volumes of natural flow was computed to obtain the Water Exploitation Index (WEI+) (EEA, 2019c). Figure 8(b) shows the effects on FDC moving downstream related to cumulate abstractions and return volumes used to compute WEI+ index (details in Annex 2.4).

Finally, indicator 'days of no withdrawal' (1-X in Figure 8(a)) shows when available flow is below the MEF and all abstractions are suspended. Having a lower real FDC, as in Figure 8(b), due to abstraction upstream, means that the altered FDC curve can fall below the MEF a higher number of days compared to the natural one, particularly during the summer season. This effect can be counteracted by moving abstractions to the winter season, as described further on.

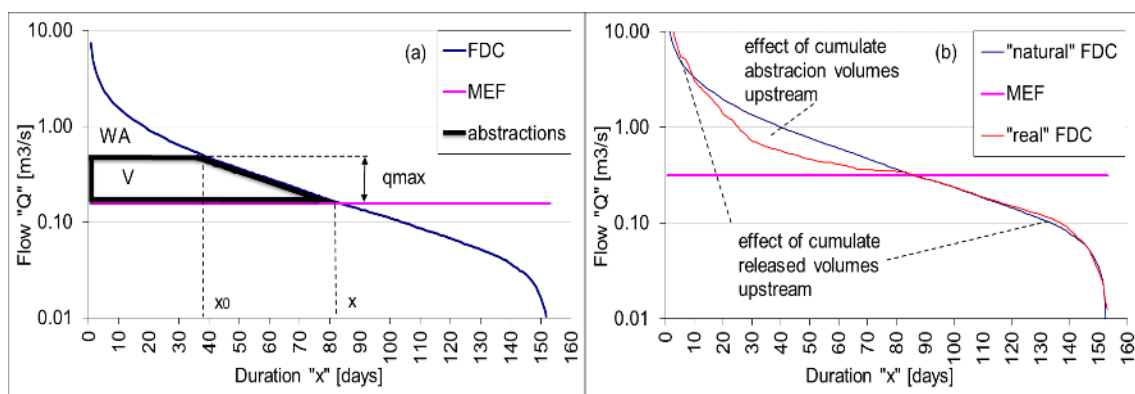


Figure 8 - Schematic representation of Flow Duration Curve, according to water flow (Q) over time (x). Figure (a) shows the upstream flow duration curve and the allowed amount of derived volume V (adapted from Cassani et al. (2009)), figure (b) example of real FDC downstream affected by cumulate abstractions and released volumes upstream.

For the analysis we aggregated data to two conventional periods: the irrigation season, “summer” (May to September), and the non-irrigation season, “winter” (October to April). The data used are updated to 2016. The FDCs for the 12 sub-basins have been evaluated using a statistical regionalization of measurements from gauging stations, as discussed in Cassani et al. (2009), for the winter and summer periods separately (provided in Annex 2.5). Abstractions were estimated by using data from both permitting and estimates (e.g. infiltration, abstractions not subject to permitting etc.) from several sources (see Annex 2.6). The analysis yields seasonal estimates of WA and WEI+ (called “seasonal”, sWEI+) for the present situation. For the implementation scenario of new ponds, abstractions for irrigation are increased by the volume of ponds during winter and decreased by the same volume during summer, to reflect the shift in abstracted volumes from summer to winter that is enabled by the ponds. This leads to slightly reduced WA and increased sWEI+ in winter (where additional abstractions impinge less on water availability because of the higher natural flows) and, on the contrary, greater WA and lower sWEI+ in summer when flows are lower for both the season and the effect of present withdrawals.

Repeated under climate change (CC) scenarios derived from hydrological models, the analysis makes it possible to simulate the future evolution of seasonal water availability.

For simulating CC scenarios, we have downloaded available FDCs coming from the E-HYPE hydrological model (Hundecha et al., 2016) for the entire Lamone catchment under both

present and CC conditions. The ratio of HYPE modelled curves under CC and present scenarios provides a correction factor for each quantile of the FDC (delta change method), which can then be applied to more accurate regional local FDCs to modify them in CC conditions. A brief description of the method (see also Trzaska and Schnarr, 2014) and the E-HYPE derived correction factors are provided in Annex 2.7.

In the case of new ponds, current withdrawals are reduced as a function of available pond volumes in the different scenarios. The volumes of the ponds correspond to the avoided withdrawals during the summer period, and the same withdrawals are shifted towards winter season, when the ponds are filled and their effect on the water balance is substantially negligible.

Water retention ponds characteristics

The pond design considered embeds features that enhance their ecological functionality. These include mild-sloped sides with vegetated buffers along the shorelines and vegetated floating islands that facilitate the nesting of birds. We referred to excavated ponds, with no weirs or dams, since inline ponds are more costly and may have negative ecological impacts. To simulate the effects and quantify the costs, we opted for schematic circular-shaped ponds. Their storage volume is estimated by radius r and height h (Figure 9). We opted for $\frac{1}{4}$ slope banks, milder than the traditional $\frac{1}{2}$ and reflecting a larger pond area compared to conventional design. We consider potential storage volumes of 10,000 m³, 50,000 m³, 100,000 m³ and 200,000 m³ (see Annex 2.8).

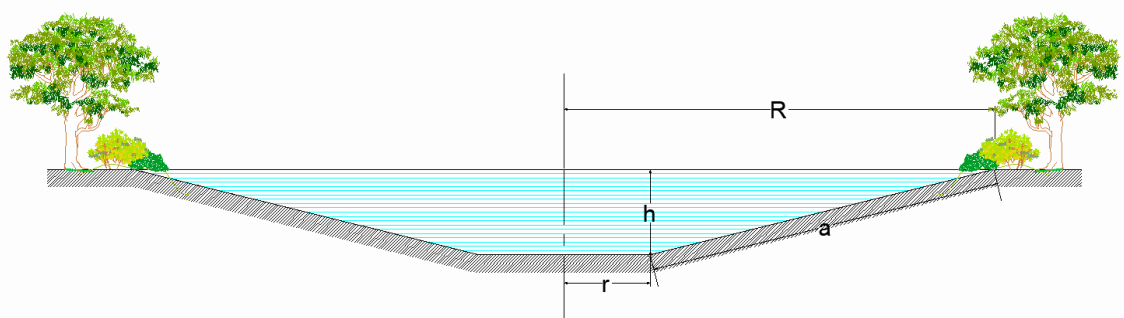


Figure 9 – Water retention pond – excavation scheme. R is the top radius of ponds, while r is the base radius; h is the height and a refers to the bank slope.

Value and cost estimation

Water retention ponds, built for irrigation needs, may also contribute to biodiversity and habitat protection, landscape diversity and aesthetics, with recreational and social benefits, temperature and climate regulation (EC, 2013d). The underlying value can be assessed in terms of biophysical or ecological processes, in monetary terms or according to individual preferences, demand and willingness to pay (Barth and Döll, 2016; Häyhä and Franzese, 2014; OECD, 2006).

We analysed the benefits of water retention ponds in terms of agricultural yields and environmental conditions. We compared the contribution of additional ponds to those of existing ponds, under present and future climate change conditions. Effects on agricultural yield and environment are evaluated by means of river water balance. We estimated i) the effects of ponds in supporting ecological connectivity in the area; and quantified ii) the effects of ponds for the flow regime of the river; and iii) the value of ponds for farmers in

terms of yield production granted by irrigation from ponds. The latter have been defined in economic terms according to their capacity to support more water-demanding and profitable crops in a sustainable way. Kiwi production has been used as measure, being a valuable cultivation with the highest water requirements in the area.

Along with benefits, we quantified the costs of building traditional ponds and the extra-cost associated with a greener construction, based on the simplified design described above with gentler slopes and floating islands. The costs include investment (excavation costs and land value), and operational and maintenance (energy for pumping, vegetation management and desilting) costs. To estimate construction costs, the analysis uses public price lists, considering excavation, bottom waterproofing and perimeter fencing.

Farmers and water authorities have been interviewed to complement and corroborate the assessment of costs and benefits. Interviews offer deeper insights into the benefits but also potential drawback, barriers, and funding sources. Interviews addressed the management of water retention ponds and associated withdrawals from the river, values and benefits, construction and maintenance costs, potential barriers to adoption and conversion to a more ecologically oriented design.

Results

Effects quantification

Landscape connectivity results

The MSPA performed for the existing GI network revealed 504 core areas and 124 corridors (map in Annex 2.9). The network presents many components (322), i.e. groups of interconnected nodes that are isolated from the rest of the network. MSPA, and the derived graph representation of the network, provides a first insight into the connectivity status. Most ponds, largely localized north of the basin, result as isolated, while most of the links are along the river asset connecting protected areas and vegetated riparian zones. The IIC value results as 0.194, showing a low degree of connectivity, since it ranges from 0 to 1 and increases with connectivity. Similar values have been associated with forest areas degraded and fragmented by intense urbanization (Pujiang Huang et al., 2016) and to agricultural areas with high possibility of enhancing ecological flow by improving connectivity (Borda-Niño et al., 2017). The analysis of the existing GI network shows that connectivity within the Lamone River basin can be generally improved.

The computation of node importance highlighted those that most contribute to enhancing the connectivity within the network. These nodes have higher connector values (IIC_{connector} rank – Figure 10) and function better as potential stepping-stones to facilitate connections between other core areas. They are mainly located along the river, connecting it to water retention ponds and protected areas.

New water retention ponds supporting irrigation needs can also help to improve connectivity if well-located. Figure 11 shows the implementation scenario of potential ponds used in the water balance analysis. Suitable areas have been ranked and selected according to the IIC_{connector} values (maps in Annex 2.10). The selection includes areas that provide a minimum contribution toward improving network connectivity (IIC_{connector} > 0,001 - corresponding to 35 potential ponds). Below this threshold (equal to a cumulative volume of 5.3 Mm³) there is no significant increment of connectivity (Annex 2.3).

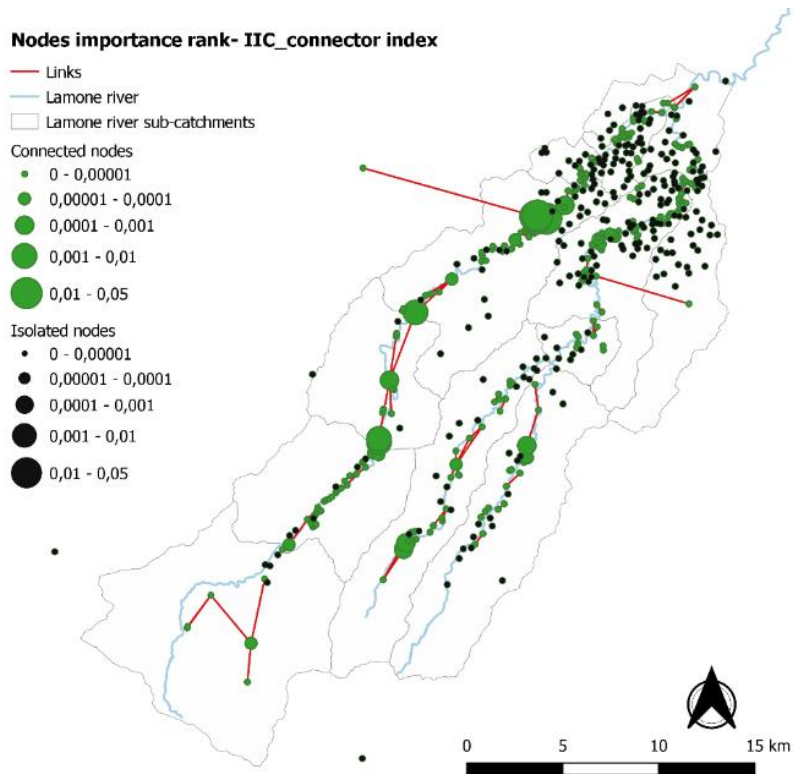


Figure 10 – Node importance rank according to the IICconnector component.

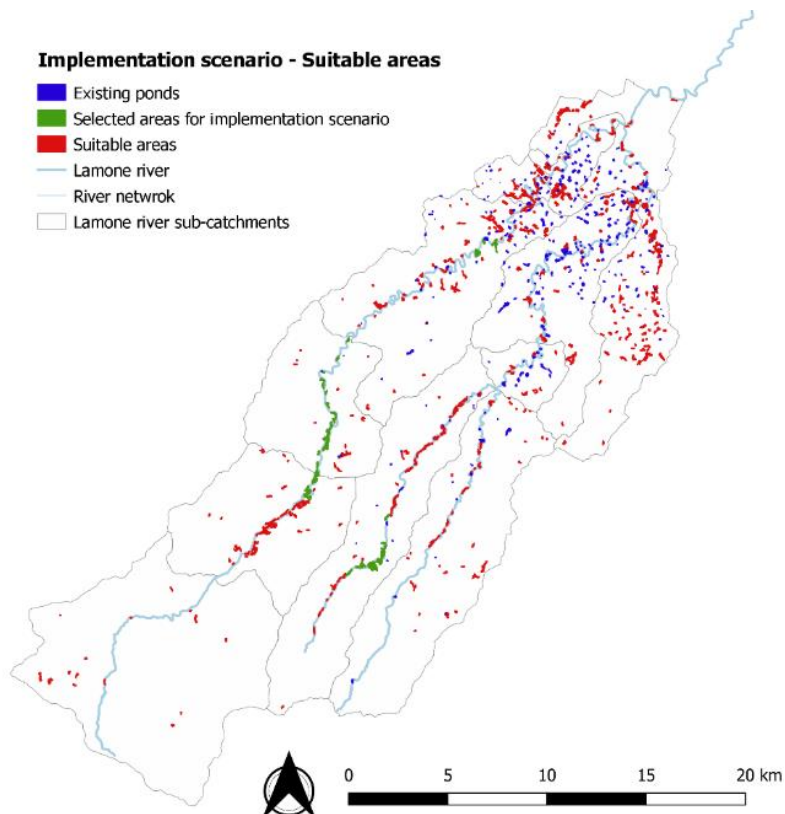


Figure 11 - Map of the suitable areas identified in the Lamone River catchment, and selected areas of potential implementation scenarios

Water balance

Water balance has been calculated both at present conditions and under climate change scenarios, with and without considering the implementation of new water retention ponds. For the volume of new ponds, we assumed an average depth equal to 5 meters. The set of new ponds considered provides an additional volume of 5.3 Mm³, divided between subbasin 7 (0.7 Mm³), subbasin 6 (1.9 Mm³), subbasin 2 (0.8 Mm³), and subbasin 4 (1.9 Mm³). This additional volume makes up about 40% of the existing storage ponds volume within the whole Lamone catchment (12 Mm³).

Table 7 and Table 8 report the index of average water availability values during the summer period, calculated under present and CC scenario conditions. Values in CC scenarios are calculated as the mean value of all models available in E-HYPE model (minimum and maximum values reported in brackets). Hereafter we will refer to present conditions (reference period 1991 - 2011) and to 3 different CC scenarios named 2020 (2012 - 2040) 2050 (2041-2070) and 2080 (2071-2100).

| Water availability - summer | | | | |
|-----------------------------|--------------------|-------------------------|-------------------------|-------------------------|
| present conditions | | CC scenarios | | |
| basin ID | [Mm ³] | 2020 [Mm ³] | 2050 [Mm ³] | 2080 [Mm ³] |
| 1 | 2.925 | 2.75 (1.02÷4.31) | 3.12 (1.30÷6.92) | 3.45 (0.94÷13.29) |
| 2 | 4.905 | 4.65 (2.11÷6.94) | 5.14 (2.46÷10.73) | 5.58 (1.89÷20.05) |
| 3 | 3.873 | 3.87 (2.20÷5.59) | 4.20 (2.47÷8.11) | 4.49 (1.96÷14.89) |
| 4 | 3.052 | 3.05 (1.71÷4.41) | 3.30 (1.91÷6.40) | 3.53 (1.52÷11.82) |
| 5 | 4.032 | 4.00 (2.09÷5.98) | 4.35 (2.38÷8.73) | 4.65 (1.74÷16.39) |
| 6 | 6.433 | 6.11 (2.91÷9.00) | 6.69 (3.32÷13.75) | 7.23 (2.57÷25.47) |
| 7 | 6.127 | 5.76 (2.06÷9.10) | 6.40 (2.52÷14.56) | 7.00 (1.59÷28.07) |
| 8 | 1.311 | 1.27 (-1.04÷3.65) | 1.70 (-0.70÷6.99) | 2.07(-1.45÷16.30) |
| 9 | 5.467 | 5.09 (1.37÷8.46) | 5.75 (1.84÷13.96) | 6.34 (0.91÷27.56) |
| 10 | 0.627 | 0.69 (-1.00÷3.27) | 1.14 (-0.96÷7.07) | 1.83(-1.05÷17.66) |
| 11 | 1.179 | 0.82 (-2.81÷4.10) | 1.46 (-2.35÷9.47) | 2.04(-3.26÷22.76) |
| 12 | 3.628 | 5.03 (1.81÷11.31) | 5.95 (1.41÷18.89) | 7.98 (2.05÷43.42) |

Table 7 - Water availability in summer – CC scenarios and no actions (existing ponds)

| Water availability - summer | | | | |
|-----------------------------|--------------------|-------------------------|-------------------------|-------------------------|
| present conditions | | CC scenarios and NBS | | |
| basin ID | [Mm ³] | 2020 [Mm ³] | 2050 [Mm ³] | 2080 [Mm ³] |
| 1 | 2.925 | 2.75 (1.02÷4.31) | 3.12 (1.30÷6.92) | 3.45 (0.94÷13.29) |
| 2 | 5.065 | 4.81 (2.27÷7.10) | 5.30 (2.62÷10.89) | 5.74 (2.05÷20.21) |
| 3 | 3.873 | 3.87 (2.20÷5.59) | 4.20 (2.47÷8.11) | 4.49 (1.96÷14.89) |
| 4 | 3.298 | 3.29 (1.96÷4.66) | 3.54 (2.15÷6.64) | 3.77 (1.76÷12.07) |
| 5 | 4.255 | 4.22 (2.31÷6.18) | 4.57 (2.60÷8.90) | 4.88 (1.98÷16.59) |
| 6 | 6.809 | 6.49 (3.28÷9.37) | 7.07 (3.70÷14.12) | 7.61 (2.95÷25.85) |
| 7 | 7.195 | 6.82 (3.12÷10.17) | 7.47 (3.59÷15.63) | 8.06 (2.66÷29.14) |
| 8 | 1.534 | 1.49 (-0.82÷3.85) | 1.92 (-0.49÷7.16) | 2.29(-1.21÷16.50) |
| 9 | 6.537 | 6.16 (2.44÷9.53) | 6.81 (2.90÷15.02) | 7.41 (1.98÷28.63) |
| 10 | 0.851 | 0.88 (-1.00÷3.48) | 1.33 (-0.96÷7.25) | 1.99(-1.05÷17.88) |
| 11 | 2.238 | 1.87 (-1.76÷5.16) | 2.51(-1.30÷10.54) | 3.10(-2.21÷23.83) |
| 12 | 4.945 | 5.99 (1.84÷12.62) | 6.90 (2.61÷20.20) | 8.78 (2.07÷44.73) |

Table 8 - Water availability in summer – CC scenarios and realization of new potential ponds (NBS)

Results show a high variability associated with the several combinations of CC scenarios. According to the scenario considered, both an increase and a decrease of water availability are expected. This in some way contrasts with the general expectation contained in the recent technical report by the Regional Environmental Agency (Regione Emilia-Romagna, 2020), which reported a water availability decrease in the region, projecting by 2050 a general increase in temperature and decrease in precipitations.

For this reason, we shall discuss results with and without considering the implementation of new water retention ponds in present and CC scenarios with reference to the worst-case situation (lower water availability induced by CC). All results are reported in Annex 2.11 and 2.12

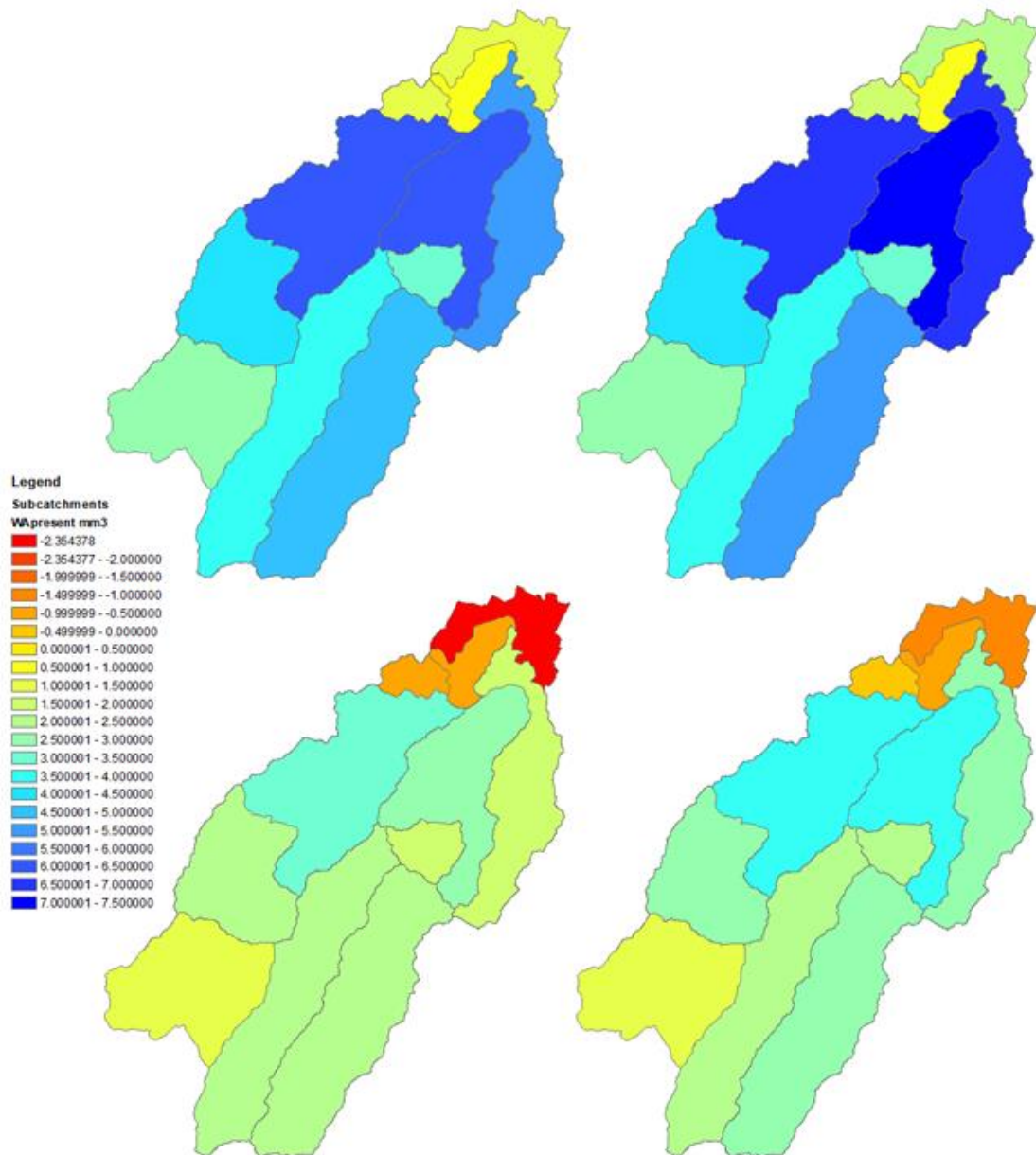


Figure 12 - WA in summer –scenario 2050 (worst case) with and without the realization of new potential ponds (NBS) - lower part, and present (w/wo NBS)- upper part

Figure 12 compares WA index in summer, both for 2050 worst case scenario and present conditions. A comparison of summer variation for 2050 worst-case and present conditions with and without the realization of new ponds is reported in Annex 2.11 and 2.12 for all the indicators. WA reflects an appreciable improvement of summer flow variability when adopting NBS, especially for downstream basins (for example 4.95 Mm³ vs. 3.96 Mm³ for basin 12 on average in present conditions). When the NBS are not considered, the river results being constantly at MEF or below. This amount of water is taken from the river in the winter period, which shows a modest reduction in WA; a mitigation effect is evident even in the worst CC scenario, but it cannot alone fully counteract the local shortage of resource in the most stressed sub-catchments.

Days of no withdrawal and sWEI+ behave similarly (improvement in summer and slight worsening in winter), but changes are less evident than in WA. sWEI+ reflects a lower overall appropriation of the river in summer, and days of no withdrawals reflect shorter duration of drought. In summer periods, a modest decrease of WEI+ (a few % points) and reduction in days of no withdrawals by none to 10-15 days are expected. This can be explained in part by considering that the new pond locations reflect suitability and connectivity analysis, not necessarily matching most stressed sub-basins in terms of present withdrawals.

Value and cost estimate

As resulted from the water balance analysis, ponds benefit farmers and the environment by increasing water availability also even in climate change conditions, as they preserve water flow above the MEF, especially in downstream sub-catchments.

During the interviews, farmers and authorities confirmed the key role of ponds for irrigation. Indeed, the main value of water retention ponds is related to agricultural water demand in the dry season. They are considered the only effective way to preserve agricultural productivity. The ponds can increase the monetary value of agricultural land that can cope with water needs.

Additional ponds increase water availability by around 5.3 Mm³, which at the same time can be used for agricultural needs and to support environmental quality. We considered crop water needs, crop yield and economic revenue associated with kiwi production to estimate the value of ponds. We report the extra-revenues derived from kiwi production according to the irrigation capacity of ponds and the costs of building ponds with a greener approach, deriving the economic value of 1 m³ of water.

The value of ponds is strictly linked to the agricultural productivity supported by irrigation. Crop water needs for kiwi are the highest in the region (5100 m³/ha - Consorzio di Bonifica della Romagna Occidentale, 2018). The implementation of new ponds would make it possible to cover an additional surface of around 1000 ha of kiwi cultivation, without compromising the water balance of the river. Data vary among different sources, LBR studies and databases, but kiwi production has a very high value, providing an economic revenue of around 20-50 €/q, with an average yield of 150-230 q/ha (data from Altamura and Bertazzoli, 2014; Betti et al., 2019; CREA, 2019; Rinaldi Ceroni, 2014). The result of these values is that 1 m³ of water can support the production of around 20-35 q of kiwi.

Pond costs have been defined in terms of their construction, while from the interviews other costs have been considered negligible. For the schematic ponds previously described, we

considered the excavation (9.50 €/m³), the waterproofing of the bottom (9.50 €/m²) and perimeter fences (5.19 €/m) (Regione Emilia-Romagna, 2019a). Area cost has been determined by the value of land for kiwi crops (Regione Emilia-Romagna, 2019c), while the unit cost of floating islands has been evaluated for those with a 1% extension of the total pond area (Regione Piemonte, 2019). Additionally, green ponds require more space to store the same volume of water, which should be subtracted for crops. For a water storage of 50.000 m³, consistent with an average farm pond, a greener pond needs an additional surface of around 2000 m². This could correspond to a kiwi yield reduction of 30-45 q and a gain loss of up to 1500-2000 €/year, which should be figured into the extra-cost of greener ponds.

According to these data, values and costs of ponds resulting for 1 m³ of water are reported in Table 9.

| | | |
|-------------------|-----------------------------------|---|
| Value | 0.7-1.3 €/m ³ | Extra revenues of kiwi production supported by ponds irrigation |
| Cost grey | 12 €/m ³ | Construction cost for traditional ponds |
| Cost green | 14 €/m ³ | Construction cost for green ponds |
| | 0.03-0.05 €/m ³ /year* | Cost of production loss due to a reduction in crops area |

Table 9 – Value and costs of water retention ponds computed for 1m³ of water stored. *Referred to a 50.000 m³ pond.

Interviews reported that the manner of constructing water retention ponds used in the Lamone River basin is not completely grey. Natural clay is used to impermeabilize the bottom without employing traditional concrete- or plastic-based methods, combined with artificial pumping of water. The result is that ponds are good spots for biodiversity and environmental quality. Through the pumping system, small fishes and molluscs enter the ponds, attracting birds as a food source and helping to clean water and pond bottoms of algae. Additionally, the pumping system cannot empty the ponds completely, maintaining the ecosystem over time. Experts have observed over time the increasing proliferation of animals, birds and vegetation around the ponds. Increasing the adoption of greener water retention ponds, according also to landscape connectivity approach, can improve these outcomes.

Greener ponds can support and make possible economically and socially profitable ancillary activities for farmers. Some examples, already in place in the area, are a side production and sale of wood, and the organising of social and educational farm visits, labs and activities for kids, schools, and families.

However, experts identified some barriers for greener pond implementation, especially related to reduced efficiency. The higher surface required can cause loss of water stored during summer from the higher rate of evaporation. Another risk is associated with vegetation close to the pond banks, which can reduce impermeabilization and increase water infiltration due to root growth in the soil.

The limitations around pond renaturalization are also linked to legislative and normative indications. Ponds must be protected by fences for safety reasons and cannot be completely accessible to animals and people. Sometimes, authorities indicate contradictory laws and norms, especially in reference to vegetation in the proximity of ponds: some laws require vegetation along banks to follow a more nature-based approach, while others require that trees be planted at a certain distance, for safety and retention efficiency purposes.

An economic barrier are the additional costs of a green pond, such as vegetation maintenance, potential ponds bank stability issues, involving to animals and vegetation, and the needs and difficulty of access to funding supports and incentives to cover these extra costs.

Discussion

Previous sections have shown that green water retention ponds provide valuable positive benefits to the environment and farmers. Designing and planning green ponds based on a network approach can contribute to enhancing these benefits. It helps to identify existing ecological hotspots to preserve and protect, and to facilitate the connections and flow of biodiversity and ecosystem services, or to prioritize ponds that should be re-naturalized and converted to more green solutions. Including this information in the landscape and environmental management can favour ecological connectivity improvement. On these bases, the chapter proposed an implementation scenario for new ponds, that could respond to irrigation needs by following an ecological and multifunctional perspective. The optimal location of ponds in terms of connectivity may not be the most suitable for maximizing hydrological benefits. But new ponds, even if not entirely used inside their sub-catchment, can benefit the entire river basin by sustaining water flow and allowing withdrawals in the most stressed catchments downstream. In this case the costs will be partly sustained by the effective benefits. At the river basin scale, new ponds can make agriculture more sustainable and environmentally friendly in terms of irrigation, increasing potential production and increased profit for farmers. Green ponds require additional surface for their construction, at the expense of crops, but they could support the conversion of uncultivated land, or very low-value land, thus increasing farmers' profits.

Benefits have been estimated in the analysis and observed by experts and stakeholders, but this is not actually translated into a profitable value users and society. Hence, the key question is to design financial incentives that capture the value of these benefits, or in other words, to innovate the business model applied by farmers in order to accomplish collective objectives. After exploring the existing funding channels for the NBS, we propose two schemes for incentivising and supporting their use.

Funding channels

NBS are included in many investment opportunities at the European level thanks to their multifunctionality and their contribution to EU goals for smart, sustainable, and inclusive development. They are supported by the European Fund for Strategic Investments (EIB, 2019; EC, 2019b), which comprises, among others, the European Agricultural Fund for Rural Development (EAFRD). NBS implementation can be involved directly or indirectly in these policies by promoting connectivity between urban and rural areas, social inclusion, tourism, eco-activities, and sustainable development, and by enhancing the quality and supply of natural resources, natural capital protection, human health, employment and recreational functions (EC, 2013a, 2013e; Irene et al., 2011). Large NBS funds are connected to European research and innovation programs (EC, 2010). A more specific instrument for financing NBS is the Natural Capital Financing Facility (EC, 2019b), established by the European Investment Bank to support conservation and NBS projects through flexible finance facility and technical assistance support facility (EIB, 2019). It is open to public and private institutions working to preserve the natural capital project by providing loans and investments.

These European initiatives promote NBS investments across all sectors. The recent European Green Deal and the associated Strategies on Biodiversity and Sustainable Food Production (EC, 2019a, 2020c, 2020a) are now boosting and financially supporting the implementation of the NBS also in the agricultural sector. But the more dedicated financial support is related to the Common Agricultural Policy (CAP), which fosters rural development strategies and projects (EU, 2013). CAP is funded by EAFRD, which tailors the national Rural Development Program (RDP) to face different priorities, including ecosystem protection and nature-based actions (EC, 2019c). In Italy, RDPs are managed at the regional level. In the Lamone River Basin, the RDP funded several projects for supporting rural population and economic activities, including viability, water distribution systems, irrigation systems, river restoration and maintenance. Through RDP 2007-2013, Emilia-Romagna supported many infrastructural projects to improve the availability and management of water resources. For water retention ponds, RDP established a contribution of 4.2 € million over a total cost of 10 € million to build 7 common ponds, for a total water storage of around 775,000 m³ (Consorzio di Bonifica Romagna Occidentale, 2015). Today the RDP 2014-2020 (MIPAF, 2017) is the main financial channel that exists for promoting water retention ponds, though it entails a private contribution of around 30%. Following the droughts of 2017, the Ministry of Agriculture established some additional funds for projects facing water availability issues. In the Lamone catchment, the Ministry funded the creation of 3 common ponds for a cumulative water storage of 820,000 m³, with a contribution of 14 € million from the State and 2.5 € million from local farms (Consorzio di Bonifica Romagna Occidentale, 2019).

Incentive schemes for NBS

The existing incentive model for farmers, mainly based on RDP subsidies, supports retention ponds construction, and riparian vegetation restoration and protection. There are different measures incentivising on-farm natural water retention measures and nature preservation, including habitat connectivity. The incentive scheme can be a grant to partially covering the incurred (construction) costs, or annual payments rewarding farmers for environmental stewardship. These schemes can be combined with fiscal incentives addressing either income or property taxes. Farmers are eligible to deduct part of the construction costs from their taxable income base or are exempt from the agricultural land property tax, where this applies.

The disadvantage of the above model is a relatively low response rate to the offered incentive due to high administrative efforts and low perceived utility. In addition, the public administration has no or very low control over the spatial connectivity of the established ponds. To overcome these barriers, we have identified two innovative incentive models that are based on compensation of land and production lost due to the construction or conversion of retention ponds in a greener approach.

The first incentive scheme compensates the farmers for the land or production 'lost' to green ponds by an equivalent amount of publicly owned land or collectively produced crop yields. Under this scheme it is assumed that there is publicly owned agricultural land within the same neighbourhood community, and that this land is cultivated. The collectively owned land may include public or private land subjected to collectively held rights. The 2010 agricultural census revealed that collectively held agricultural land accounts for around 5% of the utilised agricultural area and embraces, among other types of terrain, permanent

grasslands, forests and water bodies, but also orchards and arable land (Greco, 2014; ISTAT, 2010a). It has different names across the Italian regions ('*comunalie*' in the Emilia-Romagna region). Under a simple swap-scheme the agricultural land/production lost to water retention ponds is compensated by equivalent shares of the collectively held land or yields from such as land. The compensation may be estimated as a function of the land lost or as a nominal share (%) of the community production from collectively held land.

Community agriculture holds a great potential for local food production and marketing, environmental stewardship and education, ecosystems, and biodiversity preservation. Community agriculture offers solutions for a sustainable, healthy food supply and food systems, by simultaneously improving dietary and nutrition quality and hence health of community members. Farm-to-school programs are examples of environmental education, reconnecting students' experience of rural life with their food habits. Extensive farming, organic farming, and conservative soil management play an important role for environmental stewardship. The '*servicization*' of farming, that is the shift from selling goods to offering services, as for example through agritourism, provides opportunities for business model innovation and income diversification, with sizeable benefits for communities.

The second incentive scheme works on similar compensation principles but rewards farmers in monetary terms by converting the land lost in tradable development rights (TDR). The principles on which TDR rely are simple: zoning policies impose limits to land development associated with positive private benefits and external costs. As a result, the prices of developable land increase while undevelopable land loses value. The skewed distribution in the benefits of the zoning policy is counteracted by separating the development land rights (DRs) from the remaining bundle of property rights and creating a market for their exchange. Property owners who are zoned out are compensated by selling their DRs to owners of developable land. The latter are obliged to buy the DRs but the price they pay is capitalised in the increased value of the developable land (Ward, 2013). The TDRs have been applied in the Netherlands (Janssen-Jansen, 2008), France (Renard, 2007) and experimentally in Germany (Mueller et al., 2010). The primary objective is to limit soil consumption (EC, 2012) or conserve nature (Harman and Choy, 2011). In Italy, some principles of land taxes and TDRs have been proposed to limit soil sealing and urban sprawl (Realacci, 2013). The proposal currently in parliamentary commissions foresees a two-to threefold increase of development costs and limited transfer of development quotas. This approach would partly move the contribution for NBS to private sector investments.

To show the applicability of proposed schemes, we estimated their potential in the Lamone River basin. We refer to provincial and municipal data for the computation. For the first scheme we used the last census of agriculture, which amounted to around 3650 ha of collective properties in Emilia-Romagna (ISTAT, 2010b). The construction of a green pond with 50,000 m³ of water volume requires an additional land area of 2000 m² that should be compensated to the farmers. By applying the proposed scheme based to the simple share of common lands, the 43.3 ha of '*comunalie*' in the province of Ravenna can compensate the land loss of around 215 new ponds with these characteristics. This would double the volume involved in the implementation scenario. The compensation payment would correspond to the farmers a share of land or yield from the common lands equivalent to the land lost. Hence, they could cultivate the new land obtained or gained from their collective yield share, while at the same time sharing the associated management and costs. The second scheme

also considers extra construction costs, since farmers are only economically compensated for all the potential losses over time. Assuming a water volume of 50,000 m³ for all the ponds of our implementation scenario, we estimate the cost of TDR on a time frame of 20 years. We considered the planned area for residential buildings in Faenza and the housing price: 484,000 m² for 1250 €/m² (Agenzia delle Entrate, 2019; Comune di Faenza, 2009). The cost to be compensated for a green pond included the extra-cost of construction (2 €/m³) and the production loss due to crop area reduction (2000 m² in this case) around 0.75-1 €/m² per year. The extra-cost to be compensated for the entire implementation scenario represents 0.02 of the total value of the developable area considered, meaning a DR value of around 30 €/m². To compensate a single pond of 50.000 m³ over 20 years, 5000 m² of developable land are required. The total developable land planned in Faenza could cover around 95 ponds. This scenario takes into consideration only the residential developable areas and could further be extended to productive areas, which in Faenza account for 1.3 Mm² of land.

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CHAPTER 3: EUROPEAN SCALE⁴

Exploring the effects of protected areas on the European land system

Introduction

Protected Areas (PAs) are a key tool to address biodiversity loss. PAs are spatially defined and legally managed areas for the long-term conservation of nature with related ecosystem services and cultural values (Dudley, 2008). The main goals of PAs are to safeguard habitats and species, and to maintain essential ecological processes supporting life and the delivery of ecosystem services. PAs also play an increasing role in climate change policies and strategies, reflecting the strong links between ecosystem functioning, nature's contributions to people, and nature-based solutions (EEA, 2021).

International agreements manifest the need for a greater use of PAs to address climate change and reverse the growing degradation and fragmentation of natural systems. The UN Convention on Biological Diversity's Aichi Target 11 aimed to protect 17% of global terrestrial land by 2020 using "effectively and equitably managed, ecologically representative and well connected systems of protected areas" (CBD, 2010). The UNEP 'Protected Planet Report 2020' stated that the 17% area target had nearly been achieved (UNEP-WCMC and IUCN, 2021). Meanwhile, the EU's Biodiversity Strategy for 2030 set a more ambitious target of 30% of land to be protected, with 10% under strict protection that leaves natural processes essentially undisturbed (EC, 2020a).

However, as the Protected Planet Report 2020 recognised, a focus on the expansion of protected areas has sometimes overshadowed consideration of their effectiveness (UNEP-WCMC and IUCN, 2021). The rapid continued loss of biodiversity despite increasing PA extent underlines the danger of this focus (Butchart et al., 2015; Kearney et al., 2020; Visconti et al., 2019). PA effectiveness is influenced not just by size but also by management and level of protection, biophysical, geographical, economic and governance contexts, relative distributions and interconnections (MacKinnon et al., 2011; Shah et al. 2021). Butchart et al. (2015) showed that a PA network designed only on the basis of extent would require nearly double the area of a network based on effectiveness to meet the Aichi target for all countries, ecoregions, sites, and species.

One of the main ways to improve PA effectiveness is through better connectivity (Hilty et al., 2020). The maintenance of intact, healthy, well-functioning and diverse ecosystems that support species and natural processes is severely impeded in fragmented environments (Damschen et al., 2019; Saura et al., 2014). The establishment of connections among PAs facilitates ecological flows and offers secure habitat refuges. Moreover, PAs that link across different spatial scales, have various dimensions, and are heterogeneously distributed, can bridge various network levels and play intermediate roles between local green networks

⁴ This chapter is derived from Staccione, A., Brown, C., Arneth, A., Rounsevell, M., Essenfelder, A.H., Seo, B. and Mysiak, J.: "Exploring the effects of Protected Areas Networks on the European land system", submitted for consideration in the Journal of Environmental Management.

and surrounding regional, national and international networks (Cumming et al., 2015; Langemeyer and Baró, 2021; Zulian et al., 2021). This also enables PAs to provide robust adaptation options as climate change shifts the distributions of species and habitats (Elsen et al., 2020).

Many policies now prioritise the connectedness of PAs for biodiversity conservation goals, ecosystem service provision, and climate change adaptation (CBD, 2021). The EU Biodiversity Strategy stresses the need for a coherent and resilient Trans-European Nature Network (EC, 2020a). Together with PAs, Europe is investing in Green Infrastructure (GI) networks in the GI Strategy, the EU Green Deal, the Strategy for Sustainable Food Systems and research funding programs (EC, 2013, 2019, 2020b, 2021). GI networks link natural and semi-natural areas, and are strategically designed to deliver multiple ecosystem services, protect biodiversity, and enhance natural capital. Only around 7-10% of global protected land can be considered connected (Saura et al., 2017, 2018, 2019; UNEP-WCMC and IUCN, 2021; Ward et al., 2020), but European PAs have relatively good connectivity, especially for long-distance dispersal and transboundary connections (Santini et al., 2016; Saura et al., 2017, 2018). This is mainly due to the Natura 2000 Network (N2000), within which most sites (80%) are connected by unprotected natural or semi-natural ecosystems, and 40% are fully connected by forests (EEA, 2020a), although the strictness of protection is very low in most cases.

As European PAs grow, they will require stricter protection and further integration with other ecosystem elements to foster landscape functionality and services (EEA, 2020a). Increasing the size and connectedness of PAs could lead to competition with other land uses, especially where strong protection is enforced. Extractive services, such as food, fodder and timber production, might decline in these cases, leading to an intensification on remaining production-designated land or displacement of production elsewhere. Because protected areas are intended as long-term designations, these effects might also vary with time, especially under the impacts of global change. It is therefore necessary to analyse PA networks as embedded in the wider land system to ensure that ecosystem services are not unnecessarily compromised, whether directly or indirectly, and accounting for future uncertainty in climatic and socio-economic conditions. Addressing this challenge requires coherent cross-sectoral analyses that not only account for biophysical but also socio-economic conditions across a range of possible future scenarios (Chatzimentor et al., 2020).

In this paper, we bring together these requirements to investigate the potential impacts of a larger, better-connected PA network on the European land system. We develop such a network based on the EU Biodiversity Strategy 2030 targets and assess its effects across the EU in terms of ecosystem services and land use, under current and future climate change and socio-economic scenarios. To do this, we combine a methodology for network improvement with an EU-wide, integrated land system model and: i) analyse the current connectivity status of the EU's PA network; ii) identify potential improvements in this network to achieve the target of 30% of EU land protected and 10% strictly protected; iii) model land use and ecosystem service changes across different levels of protection and different pairs of climatic and socio-economic scenarios; and, iv) assess the possible impacts of the expanded PA network on ecosystem services across the EU in the future.

Data and methods

The analysis of the European network of PAs was based on the conceptual framework for GI Network developed in the first chapter (Staccione et al., 2022), with small adjustment related to the scope and scale of this case study. We followed a three-step procedure to design the network: i) selecting network elements according to the scale, area, and purpose of the analysis; ii) mapping the existing network, identifying nodes and links and assessing connectivity; iii) constructing potential scenarios based on additional connectivity elements and distances between protected sites. We then applied climate and socio-economic change scenarios to the CRAFTY-EU agent-based model of European land use change (Brown et al., 2019, 2021), to assess the changes induced by the improved network configuration on the provision of a defined set of ecosystem services.

Case study areas

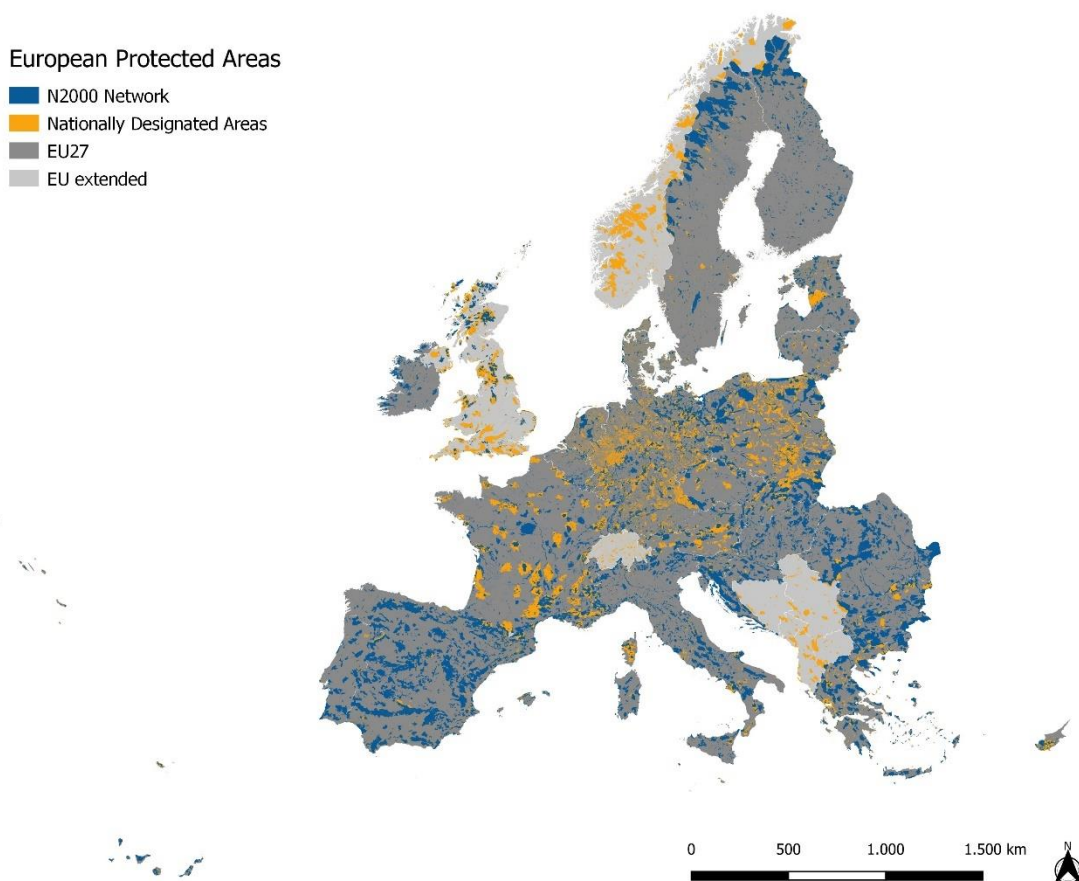


Figure 13 - European Protected Areas. The map shows the N2000 sites (in blue) and the nationally designated sites (in yellow).

The analysis was undertaken at the European scale. The European Biodiversity Strategy for 2030 (EU BS 2030) identified around 26% of EU27 terrestrial land under protection, considering PAs under both the Natura 2000 (N2000) Network (18%) and national legislation systems (8%) (EC, 2020a). We retained the focus on the EU27 domain (a land area of 4,131,745 km² (EEA, 2020b)) for the analysis of network improvement. To reach the 30% protection target, a further 4% of the EU's area must be protected, corresponding to 165,400 km². Strictly protecting 10% of land corresponds to an area of around 413,000 km². However, since connectivity does not necessarily respect administrative boundaries, we

referred to a larger European scale to define network structure and status, including the UK, Norway, Switzerland, and the Balkans in the computation.

To be consistent with the EU BS 2030, we used data related to N2000 sites and national designated areas from the European Environment Agency (EEA) dataset (EEA, 2019b, 2019a), including only terrestrial sites. Following the EEA procedure to distinguish terrestrial and marine sites, we intersected PAs with the European coastline, filtering out sites that had less than 5% terrestrial area (Telletxea, 2014). Europe has almost 27,000 N2000 terrestrial sites and more than 100,000 nationally designated areas on land, and these overlap one another in some cases. The spatial extent of sites varies significantly, from a few square meters up to around 5,000 km². Of the non-EU countries that were included, only the UK belongs to the N2000 network, with the others having only nationally-designated sites. The distribution of protected sites is shown in Figure 13

We also considered the level or strictness of protection. This is defined by the IUCN in eight categories according to PA management objectives, from the strictest protection level, where human presence is minimal, to the lowest, where human presence and use of resources sustainably coexist with nature (Dudley, 2008). This information is available in the EEA datasets only for the nationally-designated areas (EEA, 2019a). When overlapping, we attributed the same classification of national areas to the N2000 sites, and otherwise filled missing information with data from the UNEP World Protected Areas database (UNEP-WCMC, 2021). In Europe, most sites belong to the lower classes of protection strictness (Annex 3.1).

Protected areas network analysis: map of the current status

Connectivity measures the degree of landscape influence on potential movements across land supporting species dispersal, ecological functioning, resource and services provision (Mitchell et al., 2013, 2015). To analyse connectivity in the existing PA network, we followed the methodological procedure of the GI Network framework: characterising first the network elements as nodes (i.e. core areas) and links (i.e. corridors) and then investigating the connectivity status of these together. The network characterisation is based on morphological spatial pattern analysis, which identifies the groups of pixels acting as nodes and links according to their shape and relative distances through mathematical morphology algorithms (Soille and Vogt, 2009). For this analysis, we used the GuidosToolbox software, fed by the European PAs raster with a resolution of 200 m (Vogt and Riitters, 2017). Results were converted into a graph representation of the network, to highlight connected and isolated areas. To assess connectivity, we used the Integrated Index of Connectivity (IIC), which evaluates the overall structural connectivity, i.e. the physical links between landscape features, and ranks the contribution of each node to the network (Pascual-Hortal and Saura, 2006). This is a landscape connectivity index based on binary presence/absence of connections at node level, helping to simplify computation in large network cases. The IIC ranges from 0 to 1, where 1 indicates a complete graph, i.e. all nodes are connected to each other. We computed the index with the R application of the Conefor software (Saura and Torné, 2009).

Protected areas network improvement: configuration for Biodiversity Strategy 2030

Here, we partly applied the GI Network framework, defining new links between existing areas rather than defining new areas, to account for the priority given to such new links and

the far greater uncertainty involved in locating new areas. We used these new links to achieve the Biodiversity Strategy 2030 target (+4% of protected land to give 30% in total) as well as improving connectivity itself. We used cost-distance connectivity analysis considering the current network, distances among PAs, and existing land covers, refining the framework procedure in the process.

As first, we identified the potential corridors among protected sites. All the possible links between nodes longer than 10 km among the PA boundaries (edge-to-edge distance) were removed. We used a large distance threshold of 10 km in order to include more potential connections. The linear lengths of existing corridors suggest that longer connections are likely to be unfeasible (Annex 3.2). In order to prioritize the connection of isolated sites, we excluded already-connected pairs of nodes and pairs belonging to the same component, i.e. group of interconnected nodes.

Secondly, we defined the most feasible connections for the new network configuration. This is done by a least cost path analysis, using R's *gdistance* package (van Etten, 2017). We fed this analysis with a 'conductance' (the inverse of cost) raster in which PAs had a value of 1 (i.e. maximum conductance / no cost), unprotected areas had a value of 0.1 and built-up areas had a value of 0 (no conductance) (Annex 3.3). This made it possible to exclude connections through built environments and favour connections minimising unprotected land requirements. The raster values are intended only to give a generic reflection of the ease of protecting land on the basis of area requirements, and we do not attempt to represent any ecological or connectivity value of different land types. For each cell, we used the mean value of the 8 adjacent cells, assuming that cells adjacent to PAs are easier to connect through, and cells next to urban areas are more difficult.

Finally, we selected the connections to be added in the network configuration for the Biodiversity Strategy 2030 targets. We considered the corridors within the EU27 countries, even where these formed part of transboundary connections with non-EU countries. We ranked all the new feasible potential connections by cost (i.e. type of cells crossed) and length (i.e. linear distance between connected PAs), prioritising links with lower costs and shorter length. This is based on the hypothesis that these could be more easily implemented. We then computed the cumulative area covered by the new corridors to identify those needed to reach the PA coverage target of 30%. We assumed a corridor width of 500 m, but also tested a width of 1000 m. The corridor width was defined from the literature as a feasible average value for the scale and distances of our analysis to support a wide range of ecological and wildlife needs without impinging too much on surrounding land uses (Ford et al., 2020; Loro et al., 2015; Samways and Pryke, 2016).

Protected areas network assessment

The network and improved configuration network maps were used as land use raster inputs in the CRAFTY-EU model to assess their impacts on ecosystem services in different climate change and socio-economic scenarios. The model simulates land use outcomes as a result of decision making and competition among individual agents representing land managers, driven by societal demands for ecosystem services and by scenario-based variation in includes human, social, financial, manufactured and natural capitals arising from climatic and socio-economic change.

CRAFTY-EU is an application of the CRAFTY agent-based land use modelling framework to the EU27 countries plus Norway, Switzerland and the UK (Brown et al., 2019; Murray-Rust et al., 2014). CRAFTY-EU is based on a grid of cells at 10 arcminute resolution (approximately 13km in Europe). Each cell has defined levels of a range of capitals (locational attributes), which describe the availability of particular social, environmental or economic resources. A non-spatial population is assumed to exist and to generate demands, defined exogenously, for the goods and services included in the model. Each cell may be managed by a single land use agent. These agents represent single or multiple land managers operating within the cell and are able to leverage the available capitals to provide a set of provisioning, regulating, cultural and supporting ecosystem services. Each agent has a production function that maps capital levels onto service provision levels and is assigned a competitiveness value based on the level of unmet demand for the services they produce. Agents, grouped into agent functional types (AFTs; Arneth et al., 2014), have several attributes that directly affect land use change, the two most fundamental being abandonment and competition thresholds. If an agent's competitiveness falls below their giving up threshold, which defines the minimum return an agent is willing to accept from a cell, it abandons the cell, which then becomes available to other agents. If an agent that does not currently own a cell has a competitiveness greater than an incumbent agent's, and if the difference is larger than the incumbent's giving-in threshold, the incumbent relinquishes its cell to the competitor – having been, in effect, 'bought out'. An agent searching for land can therefore only take over unmanaged (abandoned) cells, or those on which it can outcompete the existing agent. These processes are mediated by three stochastic elements: 1) an abandonment probability that determines the likelihood of an agent abandoning their cell at any particular timestep, and search abilities that determine 2) the number and 3) the order of cells that are searched for competition at each timestep. These stochastic elements reflect the non-deterministic nature of the underlying processes but are found to have negligible effects on system-scale outcomes in most CRAFTY applications. The model is open-access and further details of model components, assumptions and performance can be found Brown et al., 2019 and 2021, and in the supporting information (TRACE evaluation document) of Brown et al., 2022.

We imposed the new corridors in the land use baseline, as input to CRAFTY-EU. In this step, we introduced four PA network configurations to the model, based on different protection levels for existing and new areas. These imposed changes have knock-on effects for simulated land use, agent behaviour and production functions (Table 1), but cannot be overridden by CRAFTY. The rationale for this approach is that the model simulates the effects of imposition of a protected area policy (based purely on proximity of existing protected areas), without introducing assumptions and uncertainties into the design of the network itself.

By assigning IUCN categories to PAs, we defined strict (IUCN cat. Ia, Ib, II) and not-strict (IUCN cat. III-VI) levels of protection for the existing PAs and used these in the Existing Protected Area (EPA) network configuration. For new corridors, we then defined the links between two strict PAs and between strict and not-strict PAs as strictly protected, and the links between two not-strict PAs as not-strictly protected, in the Network Protected Area (NPA) configuration. We then re-defined all new corridors as strictly protected (Strict NPAs) and finally re-defined all PAs and corridors as strictly protected (AllSs) (**Errone.**

L'origine riferimento non è stata trovata.) Each configuration was imposed immediately in its respective model run.

| Network configuration | Description |
|------------------------------|---|
| EPAs | Existing Protected Areas with current levels of protection (strict, not strict) |
| NPAs | EPAs + New corridors with levels of protection related to the PAs being connected |
| Strict NPAs | EPAs + New corridors all with strict level of protection |
| AllSs | Existing PAs with strict protection + New corridors all with strict protection |

Table 10 – Network configurations used to assess ecosystem services impacts in the model.

In CRAFTY-EU, we interpreted the two levels of protection as constraining the potential production of extractive services (crops, livestock, and timber), i.e. reducing the ability of intensive forms of management to generate goods without precluding them altogether. For the strict level, all of the protected area was assigned as non-productive for extractive services to represent undisturbed natural processes as in the European Commission's definition of strict protection. For the not-strict level, we reduced the productivity by 50%, therefore allowing some production of extractive services in the PAs but less than outside of them. The 50% threshold was chosen as a transparent scaling factor in the absence of any 'known' value. We did not assume any other effects on ecosystem service provision or land management but allowed these to emerge from simulated land use change.

The implementation of protected areas therefore allowed land use change to occur freely (through simulated processes of competition and abandonment) in response to scenario conditions and changes in the protected area network. In the absence of any such changes, the model was found to maintain the initial land use map, which incorporated the current European PA network. The model was also parameterised to prioritise food production over other ecosystem services, with food production receiving twice as much benefit per unit of unmet demand.

We analysed the modelled changes in food crops, meat and timber production, carbon sequestration, recreation, and landscape diversity, investigating examples of provisioning, regulating and cultural ecosystem services. Food, meat and timber production levels were based on dedicated agricultural and forest models underpinning CRAFTY-EU, while carbon sequestration, recreation and landscape diversity were based on a land management ranking (both described in Brown et al., 2019). International trade in food and timber were accounted for in EU demand levels, meaning that only the appropriate levels of domestic production were modelled in each scenario (Brown et al., 2021). We did not vary demand levels across the protected area configurations, ensuring comparability but also potentially neglecting increased demand for regulating and cultural services under stricter protection.

Protection of land affects productivity for food, meat, and timber, with ultimate levels of service provision determined by agent dynamics and scenario-based capital changes. Importantly, this means that the model accounts not only for direct effects of loss of production within the PA networks, but also its indirect consequences, including compensatory adjustments elsewhere in the land system. Because the model is agent-based and non-optimising, these indirect consequences can in principle be large, affecting agent decisions and competition for land across spatial and temporal extents; mirroring real-world land system change that is an emergent rather than imposed or optimised process at the EU scale.

The ecosystem service changes were assessed for each network configuration and level of protection under current climate conditions (2016 – baseline) and paired climatic (RCP) and socio-economic (SSP) scenarios: RCP2.6 – SSP1, which represent a green and low-emission future with stringent climate policy; RCP4.5 – SSP3, representing an intermediate future scenario characterised by the lack of international cooperation; RCP8.5 – SSP5, characterising a high-emission future based on fossil-fuel and highly technological development (O’Neill et al., 2017; van Vuuren et al., 2011). The trends in the capitals and the main variables characterising the scenarios in the model are described in Table 11 and Table 12.

| | RCP2.6 – SSP1 | RCP4.5 – SSP3 | RCP8.5 – SSP5 |
|--|---|--|---|
| Climate change/ climate impacts | ↘ ↘ Very low | → Intermediate | ↗ High |
| Socio-economic change | ↗ Economic growth, stable government, social cohesion, international cooperation | ↘ Limited and ineffective political responses | ↗ Social and economic development, fossil fuel exploitation, strong technology improvement |
| Land use change (intensification) | ↗ Quite intensive land management | ↘ Tendency to extensification and abandonment | ↗ Large areas of intensive management, despite slight increase in extensification. |
| Supply | Crops ↘ Undersupply | ↘ ↘ Large shortfalls | ↗ Surplus |
| | Meat ↘ Undersupply | ↘ ↘ Large shortfalls | ↗ Surplus |
| | Timber ↘ Undersupply | ↘ ↘ Large shortfalls | ↗ Surplus |
| | Env. Services ↗ ↗ Large increase | ↘ Decrease | → Intermediate |
| Demand | Crops ↗ Increase | ↘ Decrease | ↗ Increase |
| | Meat ↘ ↘ Large decrease | → ↗ Stable/slight increase | ↗ ↗ Large increase |
| | Timber ↗ Increase | ↘ ↘ Large decrease | → Intermediate |
| | Env. Services ↗ Increase | ↘ Decrease | ↘ ↘ |
| Population | → Stable | ↘ Decrease | ↗ ↗ Large increase |
| Food imports | ↘ Decrease | ↘ → Slight decrease | ↗ Increase |

Table 11 – Trends of main variables characterising RCP-SSP scenarios in the land use modelling (based on Brown et al., 2019, 2021).

| | RCP2.6 - SSP1 | RCP4.5 - SSP3 | RCP8.5 - SSP5 |
|---|-------------------------------------|-------------------------------------|-----------------------------------|
| Human capital | ↗ Slight increase | ↘ ↘ Large decrease | ↗ Slight increase |
| Social capital | ↗ Slight increase | ↗ Slight increase | ↗ ↗ Large increase |
| Financial capital | ↗ ↗ Large increase | ↘ ↘ Large decrease | ↗ ↗ Large increase |
| Manufactured capital | ↗ ↗ Large increase | ↘ ↘ Large decrease | ↗ ↗ Large increase |
| Natural capital (crops, forests, grassland productivities) | → ↘ Highly variable decreases | → ↘ Highly variable decreases | → ↗ Variable but increasing |

Table 12 – Trends of the capitals characterising the RCP-SSP scenarios in the land use modelling. These are general trends; spatio-temporal patterns may differ, especially for natural capitals (based on Brown et al., 2019, 2021).

The timeframe of simulations covered the period from 2016 up to mid-2080s, including the maximum period available for other CRAFTY-EU inputs. The long-term time horizon allows to capture the slow changes induced by PAs and to take into consideration the evolution of RCP-SSPs scenarios over time. For each scenario (baseline and RCP-SSP pairs) and each level of protection configuration, we ran 10 different simulations to capture the effects of model stochasticity on results (40 runs per scenario, 160 in total), recording all model outputs on an annual basis.

Results

The EU PA Network

The existing PA Network

The existing European network of PAs is characterised by many core areas (43,663 nodes), grouped in 21,647 components, and connected by 26,019 links (Figure 2). However, more than one third of the nodes are isolated (14,979 nodes). This indicates a low level of connectivity, confirmed also by the IIC index value (IIC = 0.0043). The low IIC value is also influenced by the large number of nodes, which exponentially increases the number of links needed to approach full connectivity, and by the presence of ‘islands’, which have very limited connections. The IIC index highlights some important nodes (larger blue nodes) for the overall connectivity of the network, especially in Eastern Europe (Figure 14).

The distribution of PAs, both nodes and links, is not homogeneous across countries. The area covered by protected sites varies significantly among countries (Figure 15– EPA). There are countries that already have 30% of land protected (Belgium, Luxemburg, Lithuania, Poland, Cyprus, Greece, and Hungary), and others that are far from this target (especially the countries outside the EU27 domain). However, most existing PAs are not-strictly protected.

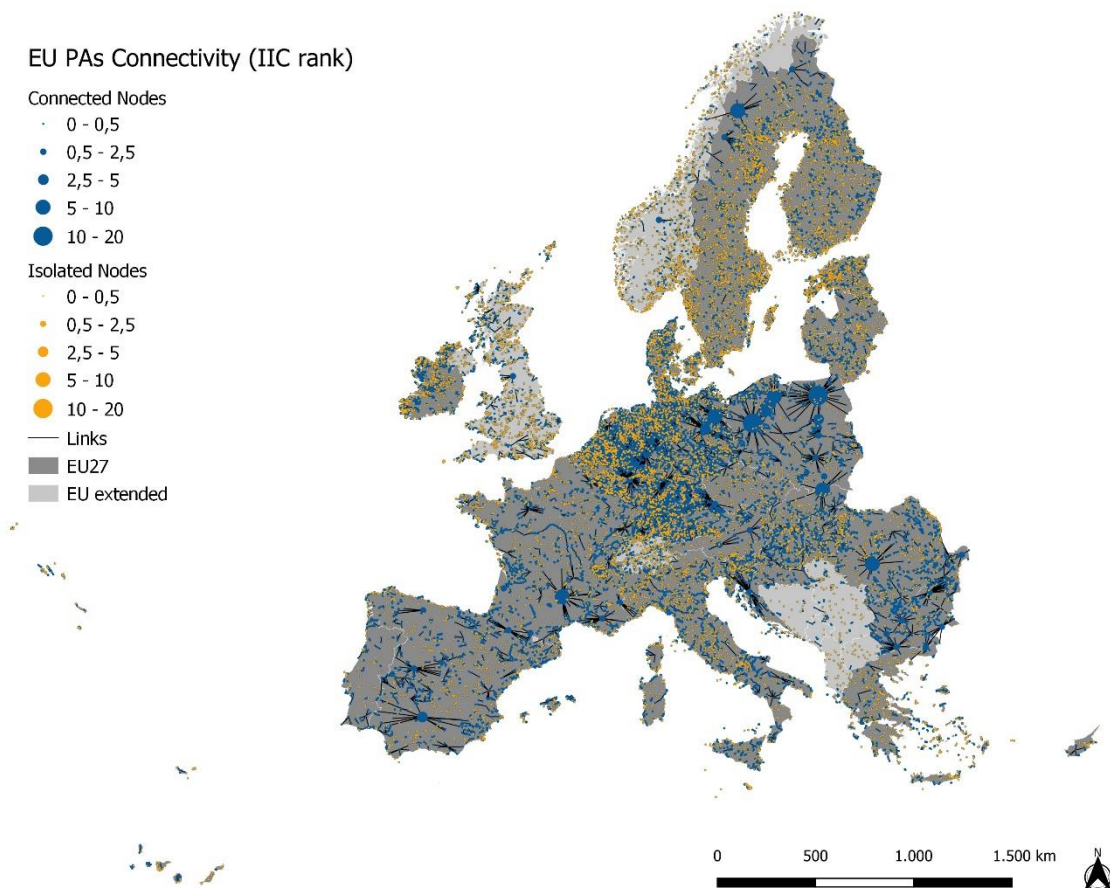


Figure 14 – Graph representation of the existing European network of PAs (EU extended domain). Dots and lines are the elements characterised as nodes (or core areas) and links (or corridors) of the network. Blue dots represent connected PAs, while yellow dots are isolated PAs. Corridors are reported as black lines. The size of dots is related to the IIC rank, showing the relative importance of each node to the overall connectivity of the network.

The improved network configuration for Biodiversity Strategy 2030

The improved network configuration includes more than 90,000 new pair connections, covering a total area of 167,527.5 km² (at 0.5 km corridor width), equal to 4.05% of EU27 land. Corridors span distances of between 1 and 10 km among PA boundaries, including across country borders (around 3,000 connections, corresponding to around 4% of new protected areas). They also intersect and join each other, creating wider areas of protection that can act as stepping-stones among PAs or that can merge PAs. The results of the connectivity analysis for the new network shows an increase in IIC value from 0.0043 to 0.0071 (65% increase), a total number of 120,928 links and a substantial reduction of components (7,534).

The distribution of new corridors differs between countries (Figure 15 and Figure 16). The highest numbers are located in Central Europe (Germany, Belgium, Luxemburg, and the Netherlands), because there are many existing PAs close together in this area. Most of the new connections are between PAs that are not strictly protected, and so are themselves not strictly protected in the NPA configuration (Figure 15). In the Strict NPA configuration (where all new connections are strictly protected; Figure 16), strictly protected areas would cover 9.2% of EU land, close to the target of 10%. Therefore, Strict NPAs is the configuration that comes closest to achieving the Biodiversity Strategy 2030 targets for the protected area network.

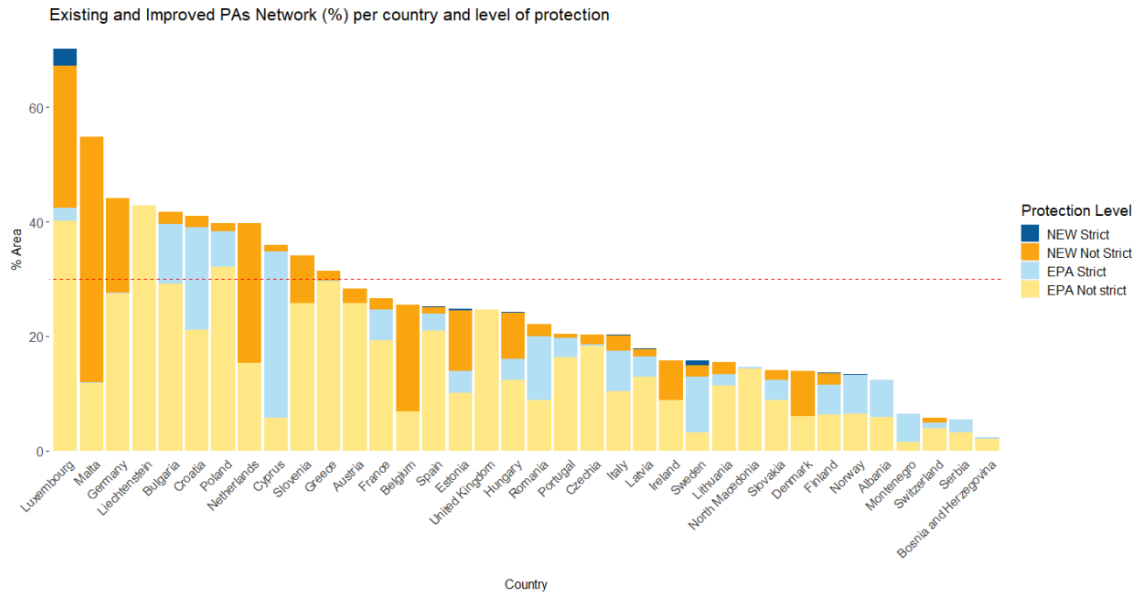


Figure 15 – Percentage of areas under strict and not-strict protection per country. Bars show the existing protected areas (light yellow and blue) and the improvement associated with the new corridors (dark yellow and dark blue). The level of protection of network improvement refers to the NPA configuration. In the Strict NPA configuration, the improvement is entirely classified as strictly protected. The dashed red line shows the 30% protection target of the EU Biodiversity Strategy 2030.

European Network

- EPAs - Strict Protection
- EPAs - Not Strict Protection
- New Corridors
- EU27
- EU extended

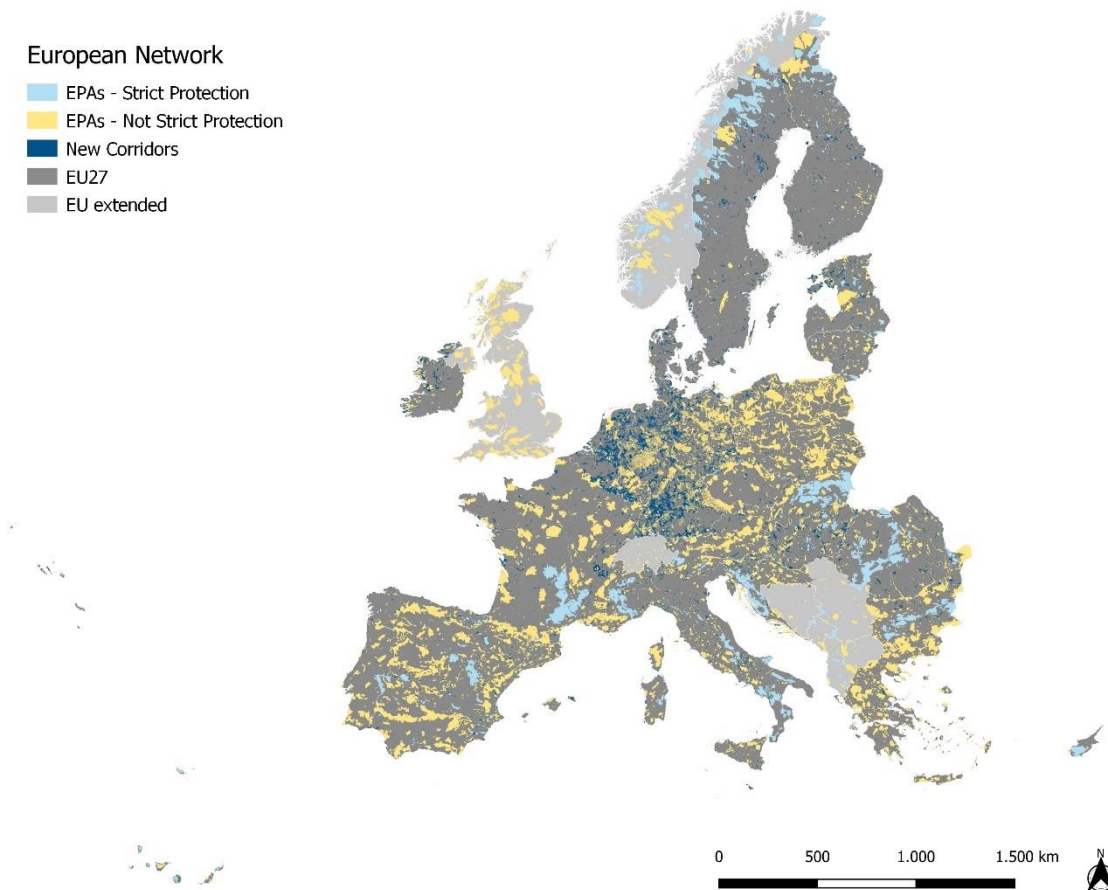


Figure 16 – Improved European Network. The map shows the spatial distribution of existing PAs per level of protection (light yellow and blue) and the new corridors (dark blue).

The impacts of EU PAs Network

To spatially report the impacts of the EU PA Network, we show here only the maps for the Strict NPA configuration, which closely matches the Biodiversity Strategy targets. Maps for the other network configurations are available in Annex 3.4 and 3.5 and show similar changes with slightly varying magnitudes to those presented here.

Land use changes

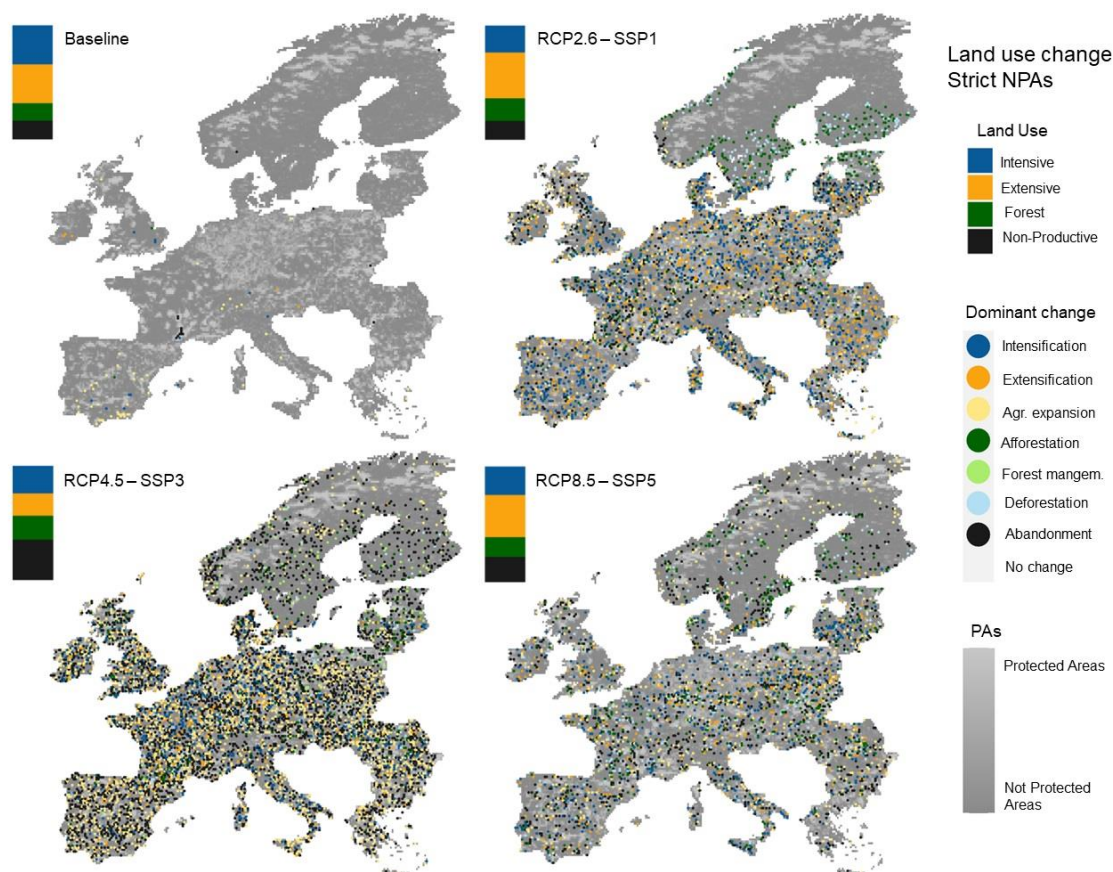


Figure 17 – Dominant land use changes in 2080s from enhanced network connectivity under the Strict NPA configuration, for baseline conditions and for three different future scenarios. Dominant changes are computed with respect to the EPA configuration in each scenario. Changes are classified as: Extensification – intensive land use changing to extensive, Intensification – extensive land use changing to intensive, Afforestation – forest on previously unforested land, Deforestation – forest changing to unforested land uses, Abandonment – active management of any sort changing to unmanaged, Agricultural expansion – non-agricultural use to intensive or extensive agriculture, Forest management – unmanaged or semi-natural forest to managed forest. The bar charts represent the final percentage of broad land cover types per scenario, grouped in four main categories: Intensive (intensive arable farming, intensive agroforestry mosaic, intensive farming, intensive pastoral farming), Extensive (mixed farming, mixed pastoral farming, extensive agroforestry mosaic, peri-urban, extensive pastoral farming, very extensive pastoral farming, multifunctional), Forest (managed forestry, mixed forest), Non-productive use (unmanaged land, unmanaged forest, minimal management, urban). PAs are represented as a share of area in the cells.

The impacts of enhanced PA network on land use changes vary significantly across scenarios (Figure 17), but did not vary significantly with model stochasticity, which changed only some individual cell management. In general, extensification and abandonment occur within protected areas as a direct result of the imposition of the network, but also occur indirectly in other areas. Similarly, agricultural expansion and intensification occur not only in direct compensation for reduced production, but also in more widespread, complex and scenario-dependent forms. Slightly more consistent are the extent and broad locations of

deforestation, afforestation and new management of existing forests (see North-Eastern Europe in particular). Major changes in terms of intensification, extensification and agricultural expansion occur in unprotected and low-protection areas (where only small proportions of cells fall within the network). At higher levels of protection, conversely, changes are mostly related to abandonment.

In the baseline conditions, minimal changes emerge between the 2080s land use maps with and without the network. When Strict NPAs are imposed in the baseline, we observe some agricultural expansion in southern Europe, mainly in Spain, and small abandonment in southern France. The NPA configuration shows similar results, while the AllS configuration produces more abandonment, also in eastern Europe, some intensification in the south and afforestation in the north (Annex 3.4). RCP2.6-SSP1 is characterized by a balance of extensification and intensification in land use spread across the entire territory, except for higher latitudes where changes in forest management prevail. Similar but smaller changes are visible in RCP8.5-SSP5, where the model adapts to the imposition of the PA network with limited agricultural expansion (including into forests) and intensification compensating for abandonment and extensification elsewhere. RCP4.5-SSP3 shows the greatest changes; predominantly abandonment and agricultural expansion that are widespread across Europe even in marginally productive areas, with clear geographical trends only in forest management changes and agricultural intensification. **Errore. L'origine riferimento non è stata trovata.** shows these changes more in detail for Northern Europe and Iberian Peninsula. These same general land use trends hold true for each scenario in the NPA and AllS configurations (Annex 3.4). Increasing the level of protection, i.e. from NPAs to Strict NPAs to AllSs, amplifies but does not substantially alter the changes (Annex 3.4).

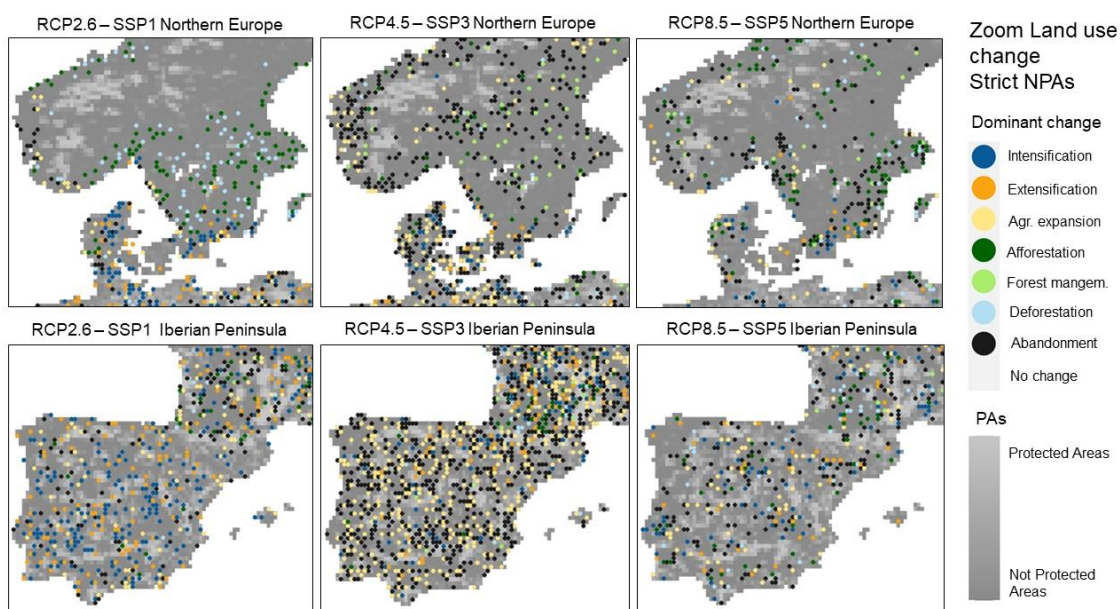


Figure 18 – Dominant changes occurring in Iberian Peninsula and Northern Europe

Ecosystem service changes

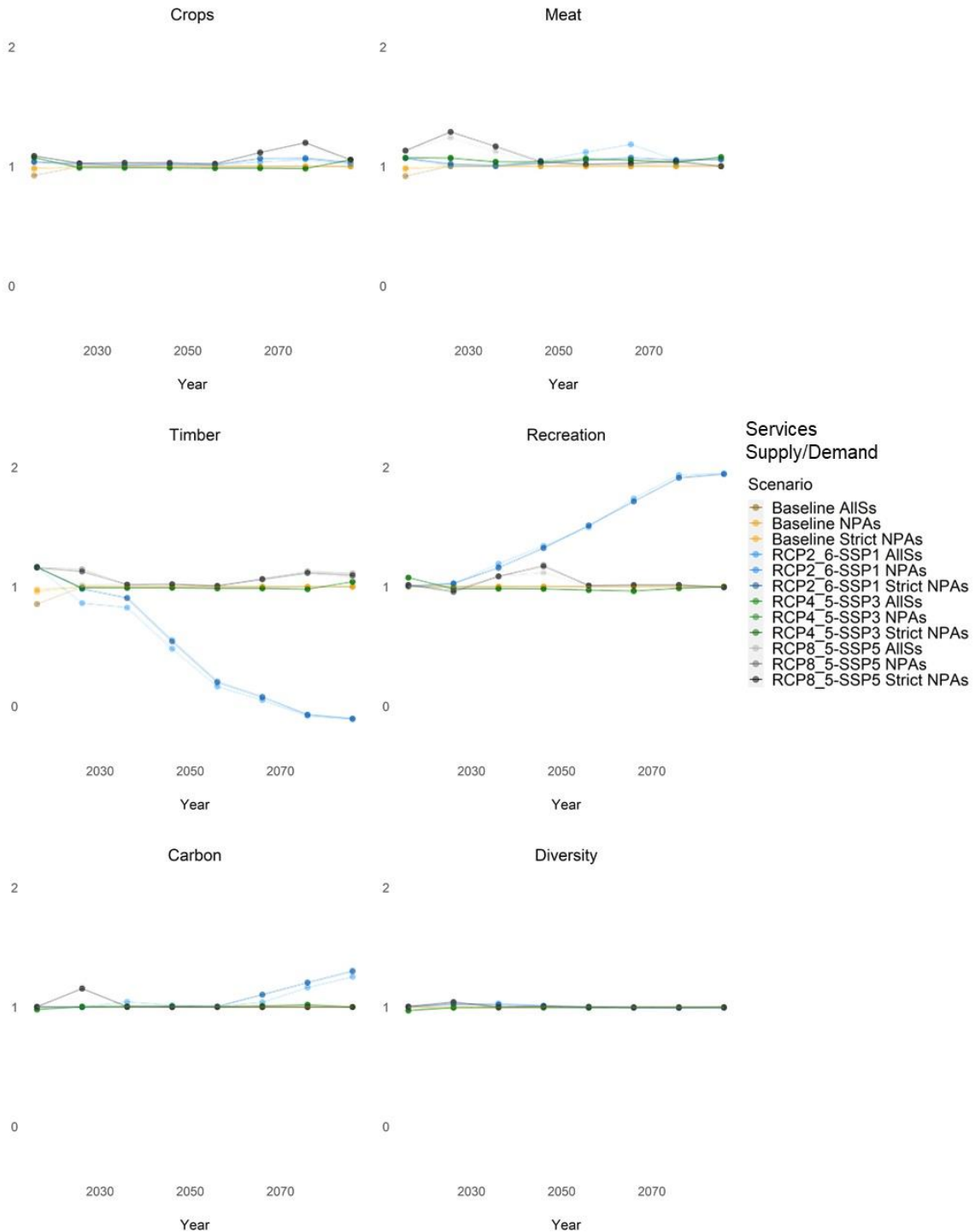


Figure 19 – Trends of services supply/demand for each network configuration in climatic and socio-economic scenarios. The y axis reports the ratio between supply and demand scaled by the size of demand: positive values indicate that supply is equal to or greater than demand.

Increasing the extent or protection level of PAs generally did not undermine the EU-wide supply of ecosystem services. The supply of services continues to meet demand up to the end of the century for all the network configurations and scenarios, except in the case of timber production in RCP2.6-SSP1, where shortfalls were nevertheless almost identical

across PA network configurations (Figure 19). This scenario is characterized by an extensification of land management that increases recreational amenity but also competition for land, leading to a lack of timber production. While there are large changes in absolute values of demand and supply in all scenarios (service supply and demand trends are reported in Annex 3.5), the ratio of supply to demand is relatively stable in most cases.

Comparing the extractive services (crops, meat and timber production) and non-extractive services (carbon sequestration, recreation and landscape diversity) spatially reveals that the supply-demand balances shown in Figure 19 are produced in quite different ways with and without the PA network. Changes in extractive services occur in aggregated areas, decreasing within the PA network and increasing in unprotected by productive land, while non-extractive service changes are more widespread (Figure 20 and Figure 21, and Annex 3.5). Geographical patterns are apparent, however. Extractive services increase especially in southern Europe, while losses in production are more concentrated in central and northern Europe within PAs. Non-extractive services mostly increase within PAs across the entire territory, with a resulting decline outside PAs, especially in the south.

The patterns of changes in crop production and recreation provision when the Strict NPA configuration is imposed are shown in **Errore. L'origine riferimento non è stata trovata.** Figure 21. In the baseline conditions, crop production increases most in southern Europe and in the UK, with declines in central Europe where PA densities are highest. The opposite occurs for recreation, with major losses in the south (Spain, Greece and the Alps) and to some extent in the north of Europe. These service-level changes often occur without transitions between broad land use classes (Figure 17) but reveal within-class adaptations to the PA network.

RCP2.6-SSP1 is characterized by larger increases in crop production in southern Europe, alongside some PA-related losses in the same area. In this scenario, recreation declines are concentrated in areas of increased crop production, but increases are distributed across the entire EU, except for Scandinavian countries. Similar patterns of recreation change can be observed in both scenarios RCP 4.5-SSP3 and RCP8.5-SSP5. In the first, more widespread land use change means that recreation changes occur also at higher latitudes and are less concentrated in the south. Crop production changes in RCP4.5-SSP3 are mainly located in western-central Europe, Italy and the UK, in terms of both gains and losses. RCP8.5-SSP5 is the scenario with the smallest changes in crop production between NPA configurations, and these are mostly located in Spain and Italy.

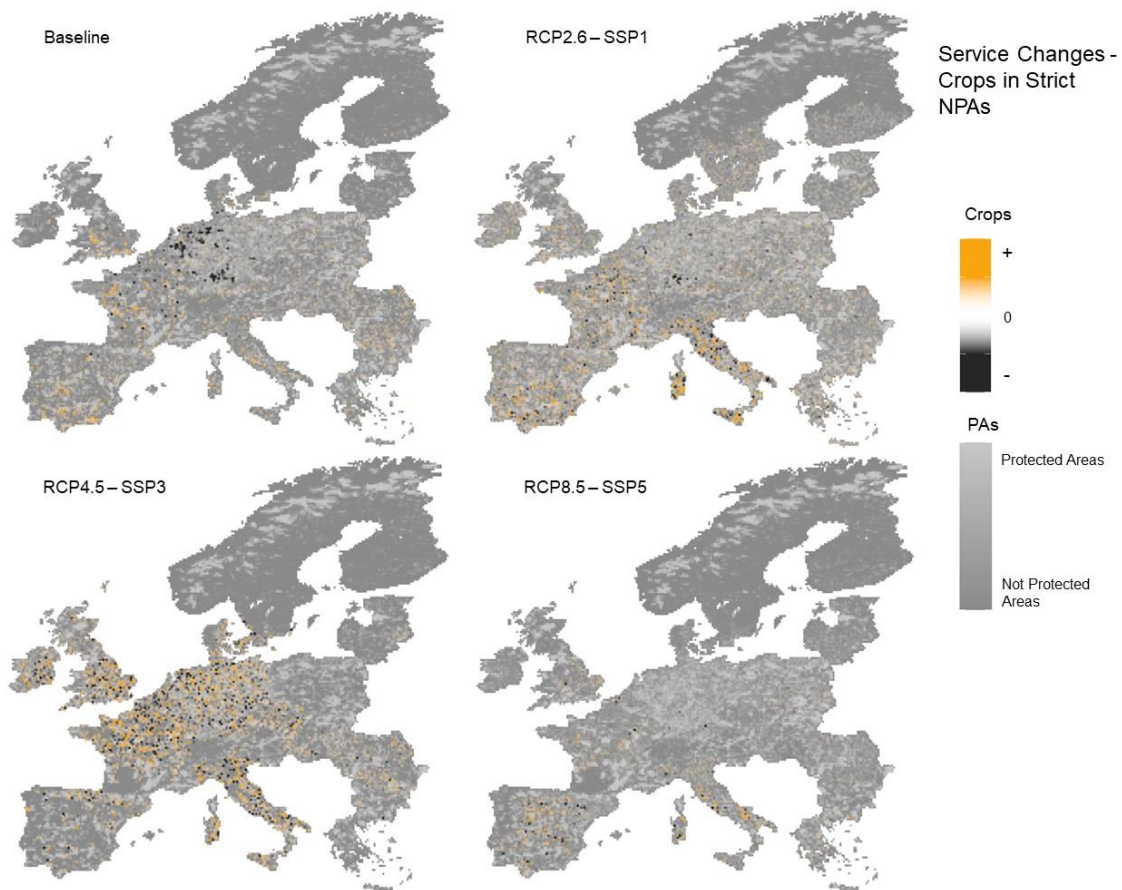


Figure 20 – Changes in crop production across Europe in 2080s in each scenario, with the Strict NPA configuration compared to the EPA configuration (change values are ratios of production within each cell). Yellow dots represent gains (+), while black dots represent losses (-) in production. PAs are represented as a share of areas in the cells.

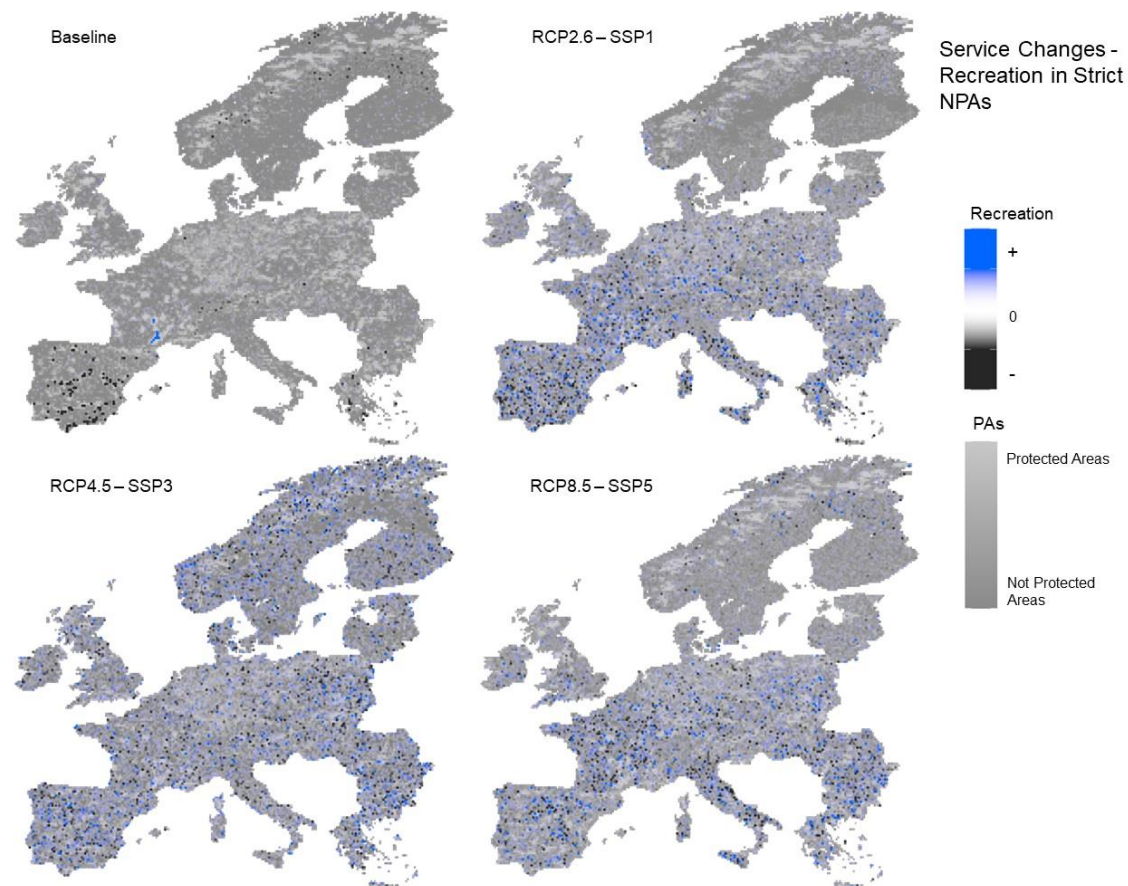


Figure 21 - Changes in recreational services across Europe in 2080s in each scenario, with the Strict NPA configuration compared to the EPA configuration (change values are ratios of provision within each cell). Blue dots represent gains (+), while black dots represent losses (-) of recreation. PAs are represented as a share of areas in the cells.

Discussion

We analyzed the effects of a protected area network covering 30% of EU land with 10% under strict protection, as called for by the EU biodiversity strategy. We found that prioritizing connectivity when implementing new PAs could achieve the strategy's targets without compromising the provision of ecosystem services, including food production, in Europe (and hence would be unlikely to lead to international displacement effects). However, we also found substantial changes in the distributions of land uses and ecosystem services within Europe, with the nature of these effects being strongly influenced by climatic and socio-economic conditions. While our findings therefore imply that a protected area network of this kind is an achievable goal, it is also one that would require careful implementation to avoid negative externalities in the rest of the land system, including effects not modelled here such as agricultural pollution or socio-cultural impacts.

In the RCP2.6-SSP1 scenario, the imposition of a PA network leads to extensification of land use (primarily inside the network) and intensification (primarily outside the network). Competition for land is strong (timber is under-supplied in this scenario with or without the PA network), and so land use changes in response to the PA network have knock-on effects in many areas. Knock-on effects are far larger in RCP4.5-SSP3, however, which displays massive agricultural expansion and, conversely, abandonment, despite lower demand levels overall. Impacts of the network were smallest in RCP8.5-SSP5, with some abandonment and afforestation but little intensification or extensification.

These scenario-specific dynamics are rooted in scenario conditions. The politically and socially dysfunctional nature of SSP3 severely limits options for agricultural production and intensification, with manufactured, human and financial resources all becoming very low during the scenario (Brown et al., 2019). As a result, the PA network causes expansion of agriculture rather than intensification, and this occurs over very large areas because the production benefits are so small. In happening over large areas, it also produces successive waves of extensification and abandonment across Europe. While these have minor net effects on ecosystem services as simulated here, there is clear potential for major gross impacts depending on the locations affected and their precise ecosystem service dynamics. RCP8.5-SSP5, in contrast, has high capital levels despite large climate impacts on natural productivity, low competition for land, and many viable options for changing production methods and technological development. This results in the network a small amount of change, mainly in the form of intensification compensating for PA-associated loss of production. In other words, SSP5 can be seen as more resilient and flexible, despite the pairing with the high-end RCP8.5 climate scenario (in which some possible impacts such as extreme meteorological events are not modelled), while SSP3 is more unstable and fragile. Results from SSP1 lie between these extremes because this scenario has relatively high capital levels but also intense competition for land, meaning that changes around the PA network tend to affect other areas. These scenario-dependent forms of adaptation to the imposition of the PA network are analogous to land change archetypes that have been identified around the world, where biophysical and socio-economic context changes the dominant form of land use change (Dornelles et al., 2022).

In contrast to the strong scenario differences, we find that alternative network protection levels have limited influence on the forms or distribution of land use changes. Instead, protection levels influence the ‘intensity’ of changes, increasing the extent of dominant forms of change. This indicates that the reduced level of production imposed by the PA network has consistent effects within scenario contexts.

Other studies investigating European PA networks have highlighted their potential in supporting ecosystem services provision and biodiversity conservation. EEA (2020a) found that within PAs the provision of multiple services is 4% (6% for at least one service) larger compared to unprotected and disconnected landscape elements, showing also less pressures for services within the network. Hermoso et al. (2020) assessed an EU GI network to improve connectivity among conservation areas and maintain ecosystem services, finding greater capacity in the network to provide services compared to conservation-only zones, especially at the EU-level rather than at the country-level. However, the wider land system context and demands for multiple services are not fully considered in these studies, and the effects of potential future conditions are not assessed. We attempt to provide a more comprehensive view by modelling a representative range of land uses, ecosystem services and future scenarios across the EU. The impacts we find are, in practice, barely observable in total supply levels, largely hidden in land cover summaries, but progressively clearer as we look further into the details of land management and ecosystem service provision. This demonstrates the need to use detailed and integrated land system models to investigate the complex reality of possible impacts, which would be missed in more traditional land cover models (Verburg et al., 2019).

By the same token, our specific findings are dependent on our assumptions and approaches. On the network side, we do not try to optimize design but adopt a spatially 'rational' method that respects broad land use categories (protected/not protected/urban areas). In this study, network connectivity improvement is influenced by design criteria such as the distances among existing PAs, size and number of sites, but not by protection needs from a biodiversity and habitats perspective. Therefore, countries with many and/or closer PAs (such as Germany, The Netherland or Belgium) resulted to have largest potential improvement in terms of corridors. On the other hand, parts of Europe with particularly few or isolated PAs are not included in the network we assess, even though they might have substantial ecological value. We have not also considered the small-scale effects of other land use connectivity on ecosystem services. Alternative network designs could be explored, including different criteria, optimizing new corridors across countries or to maximize benefits, or balancing trade-offs in terms of specific services. This could be particularly relevant for addressing more feasibility considerations, that are here associated with built-up land use categories, but need further case-specific investigation in an implementation phase. Here, the analysis is testing the impacts of potential configuration, but it is not specifically meant for a design and implementation purpose. Similarly, CRAFTY-EU does not consider how the EU land system could be optimised around a PA network (if such a thing were possible). As an agent-based model, it allows us to consider various socio-economic characteristics of the land system and scenarios, but its results are dependent on a set of behavioural assumptions (set out in Brown et al., 2021) rather than a single objective function. Exploring network effects under different modelling approaches for social and ecological components of the land system would allow us to draw firmer conclusions.

Nevertheless, in addition to the specific results and methodology perspectives, this analysis offers some insights for policies, landscape management and decision-making. Working at a large, continental scale showed the relevance of cross-border connections to reach protection goals and to effectively build the PA network, making trans-national cooperation fundamental as advocated by the EU Biodiversity Strategy 2030 (EC, 2020a). Large scale connectivity can also inform and drive actions at smaller scales: to integrate and better plan regional and local network management to contribute to European targets, and to connect and upscale local projects and goals to the regional and international context. In this perspective, protection levels and forms of management can influence outcomes across scales. In the analysis presented here, strict protection of new corridors better matched the policy goals, and can also be expected to improve service provision, material and species flows within the network. New corridors generally linked areas with less strict protection, especially in central Europe, and the network potentially makes important contributions to nature conservation in those areas. Conversely, network improvement is limited around larger strictly protected areas. In the policy context, it would be relevant to investigate the effects of protection strictness on biodiversity, ecosystem services and climate change mitigation and adaptation. Finally, it is clearly necessary for policy to account for possible future conditions in which a PA network will operate, and so to maximise its contribution to the long-term sustainability of the EU land system.

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CHAPTER 4: URBAN SCALE⁵

Connected urban green spaces for pluvial flood risk reduction in the Metropolitan Area of Milan

Introduction

The Sixth Assessment Report of IPCC (Intergovernmental Panel on Climate Change) identifies cities and urban environments as hotspots of impacts and risks associated with climate change, but it also recognises the important role they can play to fight the climate crisis (IPCC, 2022).

Nowadays, a half of world population is living in cities, in Europe urban population is even higher (63.5%) while in Italy around 56% (ISTAT, 2020). Urbanisation is a major cause of fragmentation and degradation of natural ecosystems, potentially exacerbating the economic, social, and environmental impacts of climate change (UNEP and UN-Habitat, 2021). Under future climate conditions, urban areas will very likely be even more affected by extreme weather events and progressing urbanisation can lead to an increase of casualties and economic losses and damages (IPCC, 2022; Spano et al., 2021b).

Hydrological and meteorological hazards (e.g. floods, mass movement and storms) are accountable for the largest economic losses from weather- and climate-related events in Europe (EEA, 2022). Italy is among the European countries with the highest flood risk in economic terms, with damages exceeding 38 billion Euros over the period 1980-2020 (Mysiak et al., 2022). Those impacts are not equally distributed: Lombardy, for instance, resulted to be the region with the highest economic damages (Carrera et al., 2015) and is among the five Italian regions with the highest exposure to flood hazard (Lastoria et al., 2021). In a +2 °C warmer world, the annual flood damages in Italy are expected to exceed 3 billion Euro, and almost 40,000 people affected every year, if no adaptation actions are taken (Dottori et al., 2020).

Pluvial flood (i.e. the overland accumulation of rainwater that does not infiltrate the ground or is not captured by the drainage systems) risk is particularly pronounced in urban environments. Urbanisation and soil sealing contribute to increasing pluvial flood risks due to lower infiltration rates and higher surface runoff values (EEA, 2017).

Rethinking cities in a more sustainable and integrated way offers a key opportunity for climate change adaptation and mitigation. Green and energy-efficient buildings (Cirrincione et al., 2021; Ercolani et al., 2018), sustainable transport systems (Łukasziewicz et al., 2021; Sharifi, 2021), and urban green spaces (EEA, 2021; Misiune and Kazys, 2022; Pamukcu-Albers et al., 2021) can provide a viable contribution to climate- and weather-related risk reduction. These so-called nature-based solutions (NBS), i.e., actions inspired and

⁵ This chapter is derived from Staccione, A., Essenfelder, A.H., Bagli, S. and Mysiak, J.: “Connected urban green spaces for pluvial flood risk reduction in the Metropolitan area of Milan”, submitted for consideration in the Sustainable Cities and Society.

supported by nature that simultaneously provide environmental, social and economic benefits, can help building resilience to climate change (EC, 2015).

In this working-with-nature framework, green infrastructures (GI) play a prominent role, especially in the urban environment. GI are defined as “*strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services*” (EC, 2013a). They help to safeguard urban nature and biodiversity, provide multiple services to reduce climate risks and improve well-being, such as carbon sequestration, food and water, increased infiltration capacity of the soil, recreational and social opportunities. GI often bring back vegetation and green cover in cities that can contribute to flood regulation by increasing the soil water retention capacity and reducing the storm-water runoff and peak flow (EC, 2013b).

To increase the flood regulation capacity, GI should be also strategically distributed and connected across an urban space. Building a green urban network and improve connectivity and proximity of green areas is fundamental to maintain healthy and well-functioning ecosystems that can support multiple ecological functions and delivery the expected services (Mitchell et al., 2015; Monteiro et al., 2020). This is also in line with the emerging ‘15-minutes City’ approach for a more sustainable and resilient urban development, already applied in several cities as Paris, Barcelona and Melbourne, that aim to include all the daily services for citizens in a walking or cycling radius of around 15 minutes (Moreno et al., 2021). Closer green spaces would increase human health and capability to deal with climate change, especially in a post-pandemic context (EEA, 2020).

In this paper, we analyse the effects of GI on pluvial flood risk in an urban environment. We elaborate scenarios of GI network improvements in the city of Milan (Italy) and analyse the performance in terms of direct economic damages and population exposed. The study investigates the existing GI network and defines potential scenarios of additional green elements, meant to increase GI connectivity, accessibility, and flood regulation potential. The paper is structured as follows: we first present the case study and methods to define the current network conditions, to define scenarios of green network improvement and to assess the effects of the green network. Results are then presented following the key steps of the analysis. Finally, we discuss the main findings and implications of the study.

Methods

Case study: the metropolitan area of Milan

The Metropolitan City of Milan is the administrative centre of Lombardy Region (Figure 22). It is the second-largest city in Italy, highly developed with strong economic and industrial sectors, and densely populated, being home to 3.3 million residents.

Milan is located in the Padan Plain, an alluvial plain generated by the Po River and its major tributaries, and is crossed by Lambro, Seveso and Olona rivers. Due to its orographic and hydrographic conformation, the city is exposed to a significant flood risk, enough to be one of the Italian cities with the highest number of disaster events in Italy, especially linked to urban floods (Spano et al., 2021a). The 4% of municipal land resulted to be subjected to High Probability Flood Hazard (HPH) and 10.9% of land subjected to Low Probability Flood Hazard (LPH); with 1.5% of population living in HPH areas and 9% of population living in LPH areas (Lastoria et al., 2021). In the period 2010-2020, the city experienced 29 disaster events linked to intense precipitation, causing 20 river floods, 19 days of stop for

transportation systems, some electricity black-out events, with severe economic and social impacts (Zanchini et al., 2020). In the past decades, the climate in Milan has been characterised by increasing temperature, increasing number of tropical nights and decreasing of total precipitation (ISTAT, 2022). The climate projections for 2100 are following the same trends of temperature and precipitation, but with increasing frequency and intensity of extreme rain events (Fischer and Knutti, 2016; IPCC, 2021; Myhre et al., 2019; Spano et al., 2021a). This will increase, at the same time, the risk of urban pluvial floods and heat waves (Spano et al., 2021a).

Milan has established a series of plans and strategies to address climate change. Urban green spaces and infrastructures are among the key actions identified. As part of the Covenant of Mayor for Climate and Energy, C40 Cities Climate and Leadership Group and 100 Resilient Cities Network initiatives, the city aims to become more sustainable and resilient through urban green regeneration. The Urban Development Plan for 2030 (Comune di Milano, 2019) and the Air and Climate Plan (Comune di Milano, 2020) address heat waves and flood risks through a strong implementation of NBS to increase water infiltration and limit the soil sealing. To this end, the city is investing in several projects to plant 3 million of trees and increase the canopy coverage of 5% by 2030, support the installation of green roofs and walls in private and commercial buildings, reopen and greening the channel network, create permeable surface, green areas, vegetated rails and bus stops.

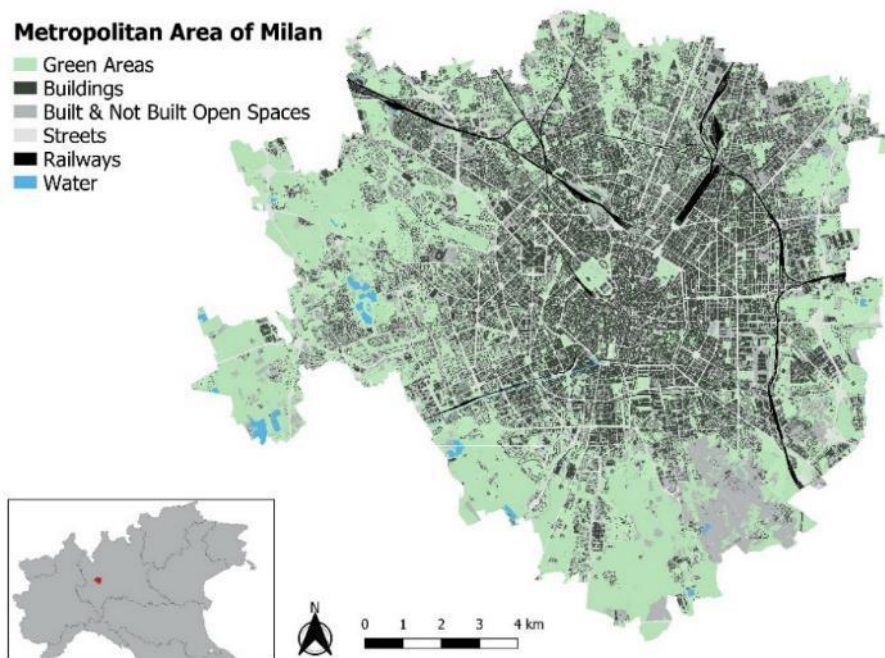


Figure 22 – Metropolitan Area of Milan. The map shows the main classes derived from ESM (Ferri et al., 2017), particularly the green areas used in the analysis.

Urban green infrastructure network analysis

For the analysis of existing urban green infrastructure network, we applied the framework developed in chapter 1 (Staccione et al., 2022). As a first step, we defined the green elements to be included in the network. We used all the existing green spaces identified in the European Settlement Map (resolution 2.5m – Figure 22), reclassified on a regular grid of 100m (Ferri et al., 2017). The cells with more than 25% of green coverage are considered

as part of the network. As a next step, the resulting grid is used as input to perform the morphological spatial pattern analysis to identify the GI network elements in terms of core areas (network nodes) and connectors (network links) (Soille and Vogt, 2009; Vogt et al., 2009). Finally, the definition of core areas and connectors makes it possible to analyse the connectivity of the network. We used a landscape connectivity index, the Integrate Index of Connectivity (IIC), based on presence/absence of connections, to provide an insight on existing conditions (Pascual-Hortal and Saura, 2006). An interesting feature of IIC is the ability to rank the contribution and importance of core areas to the overall network connectivity (Pascual-Hortal and Saura, 2006; Saura and Rubio, 2010).

Urban green infrastructure improvement scenarios

The grid of the existing GI network is used to define various scenarios of potential flood risk reduction. We hypothesised three scenarios of green conversion: i) Green Buildings (GB), which considers the establishment of green roofs; ii) Green Spaces (GS), which involves the conversion of open, ground spaces to green spaces; and iii) Green City (GC), which combines both GB and GS. For each green conversion scenario, we investigated four different incremental percentage scenarios of green conversion: 25%, 50%, 75%, and 100% of all potential green areas.

The conversion of a certain area to green implies a change in the permeability of that area. Permeability, a parameter that ranges from 0 (impermeable) to 1 (completely permeable), is defined according to the potential green area coverage in each cell, which is in turn a function of the share of green roof (GB), open green spaces (GS), or both (GC). To define the areas converted to green, we identified potentially relevant areas in terms of improved connectivity of the green network and of potential reduction of pluvial flood risks. To measure the potential improvement in connectivity, we first used walking distance (5 to 10 mins) from existing green areas, in line also with the goal of Milan's city administration to improve proximity and accessibility to different services and green spaces (Comune di Milano, 2019). Then, the identified areas were further characterised in terms of potential flood risk reduction (measured as direct economic damage and population exposed) and potential land use conversion to a green area (measured as the percentage of the cell that can be converted to a green area). We selected the following criteria to help identify the priority areas for GI interventions: i) the cumulative flood direct damages to buildings, obtained from Essenfelder et al. (2022); ii) the residential population living in a certain area, obtained from Schiavina et al. (2019) and SISI (2021); iii) the share of existing open spaces that can be turned to green, obtained from Ferri et al. (2017); and iv) the impact of potential conversion to green roofs, defined as a function of sealed areas in the surrounding area (i.e. lower is the permeability of the area, higher is the expected impact) and obtained from Comune di Milano (2016). All the above-mentioned criteria were then normalised by feature-scaling, with resulting values ranging between 0 and 1. We used feature-scaling normalisation as it is a method that provides feature independent results in the same range across all the considered criteria, thus not penalising or biasing one criterion over the other.

Finally, we assumed not full compensability between the criteria and considered a weightless simple multiplicative aggregation method to rank the areas where a higher potential for minimising direct damages to buildings and to population exposed to floods exist. Additionally, the ranking of the areas (i.e. cells) is used to identify the priority-areas for the total percentages of green conversion in each scenario by selecting the top ranked

cells up to the total area of the green conversion scenario (i.e. ordering the resulting aggregation metrics and selecting the cells from the highest values to the lowest). The aggregation functions used to rank the cells are described in Table 13.

| | Minimise Flood Damage | Minimise Population Exposed |
|------------------------|---|---|
| Green Buildings | Damage × Green Roof Area × Green Roof Impact | Population × Green Roof Area × Green Roof Impact |
| Green Spaces | Damage × Green Space Area | Population × Green Space Area |
| Green City | Damage × Green Roof Area × Green Roof Impact × Green Space Area | Population × Green Roof Area × Green Roof Impact × Green Space Area |

Table 13 - Ranking functions for each scenario. Cells have been ranked from higher to lower values.

Urban green infrastructure assessment

To assess the effects of the additional green infrastructures, we followed a methodology that combines a pluvial flood hazard mapping model and a risk-centred damage function. We used the scenarios of green conversion as input for the Safer_RAIN model (Samela et al., 2020). Safer_RAIN is a static filling and spilling pluvial hazard model which identifies pluvial flood prone areas on the basis of surface depressions that could store precipitation water volumes. The model generate pluvial flood hazard maps over urban areas by accounting for spatially distributed rainfall input and for infiltration processes, building upon pixel-based Green-Ampt model (Green and Ampt, 1911). We considered rain events of 1 hour with different rain intensities, to assess changes in water depth by changing soil permeability in the different scenarios of green conversion. Rainfall intensities are defined in accordance with the estimated depth-frequency values of extreme precipitation events (Table 14).

| Return Period | Hourly rainfall Intensity [mm] |
|----------------------|---------------------------------------|
| RP 5 | 33.36 |
| RP 10 | 38.52 |
| RP 25 | 45.04 |
| RP 50 | 49.88 |
| RP 100 | 54.68 |

Table 14 - Rain events for the metropolitan area of Milan (Essenfelder et al., 2022).

Then, we used the direct damage estimation function to evaluate the potential reduction of damages to buildings for each scenario, compared to the current situation. The damage estimation is based a depth-damage function linking the hazard magnitude to the value of exposed assets (Huizinga et al., 2017). The hazard is defined through the flood extension and water depth outputs obtained from Safer_RAIN, while the exposure is described by reconstruction costs of buildings. Building reconstruction costs are extracted from country-specific cadastral estimates per type of building, i.e. residential, commercial and industrial (EC-Harris, 2010). Buildings data have been retrieved from OpenStreetMaps (OSM, 2021). Damage results are expressed as percentage reduction and Expected Annual Damage, computed using the trapezoidal method (Olsen et al., 2015). To account for the presence of stormwater drainage network systems in the metropolitan area of Milan, we assume a maximum drainage capacity corresponding to a precipitation event with a return period of five years (RP 5, Skougaard Kaspersen et al., 2017). For each rain event, we compared the

expected damage at the current green condition with the potential green coverage scenarios.

Similarly, we assessed the population exposed to pluvial floods. We defined six classes of water depth: 0-0.05; 0.05-0.1; 0.1-0.25; 0.25-0.5; 0.5-1; >1m. For each scenario of green conversion and rain intensity, we counted the population living in the different classes of flooded areas. Results are reported as percentage reduction and Expected Annual Exposed Population

Results

Milan Green Infrastructure Network

The existing GI network in the city of Milan is shown in Figure 23. The city has a significant presence of green areas, but mainly concentrated in the peripheral zones of the city. Here, the network is well developed and has important core areas supporting the overall connectivity. The inner part of the city, on the other hand, has few or no core green areas, that are disconnected and contribute to a low connectivity value (IIC = 0.1).

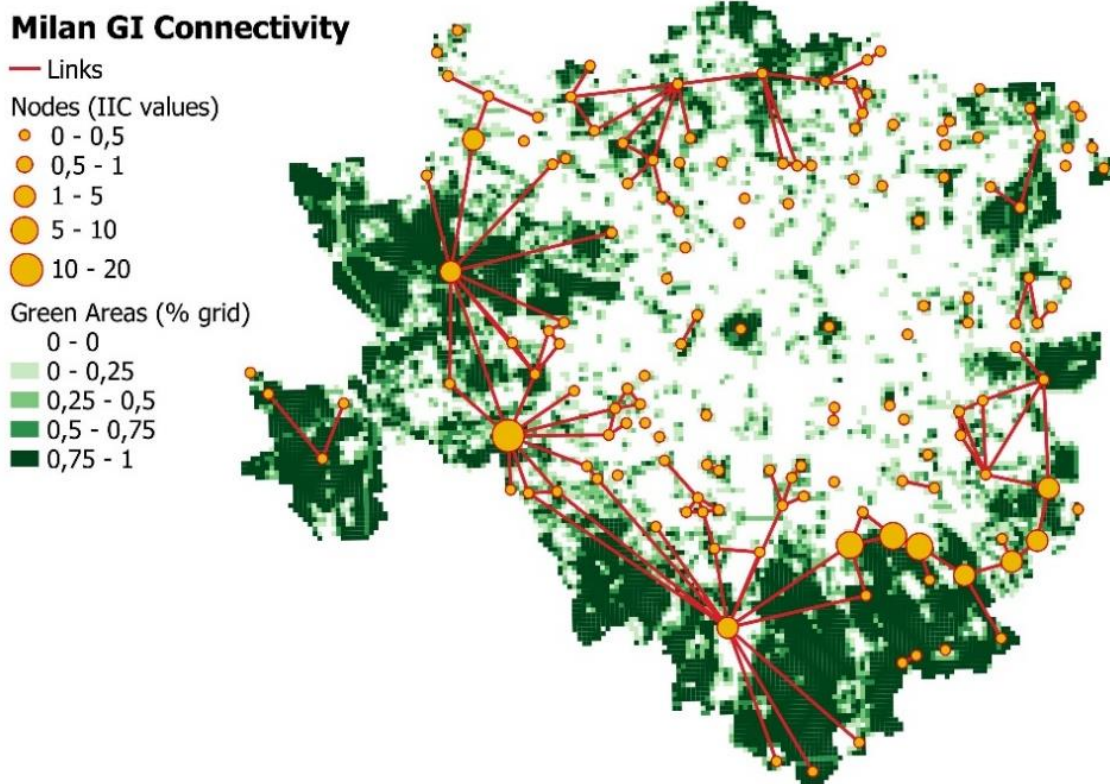


Figure 23 - Existing GI Network in the City of Milan. The lines (connections) and dots (core areas) are the graphical representation of the network. The size of dots indicates the importance of the area to the overall connectivity of the network (IIC values). The green grid represents the ESM green areas reclassified on a grid of 100m. Green shades correspond to the share of green areas in each cell.

Greening Scenarios

We identified around 6350 suitable cells that could guarantee accessibility to a green area every 5-10 minutes of walk. These are mainly distributed in inner part of the city, in accordance with the highlighted needs, and are differently characterised by the evaluation criteria (Figure 24). The cells contributing more to reducing flood damages are in the central, northern, and western part of the city. Population is mostly distributed around the

city centre. Potential open spaces and roofs that are convertible to green are predominantly located in the more peripheral areas. However, green roofs would have higher impacts in the central part of the city.

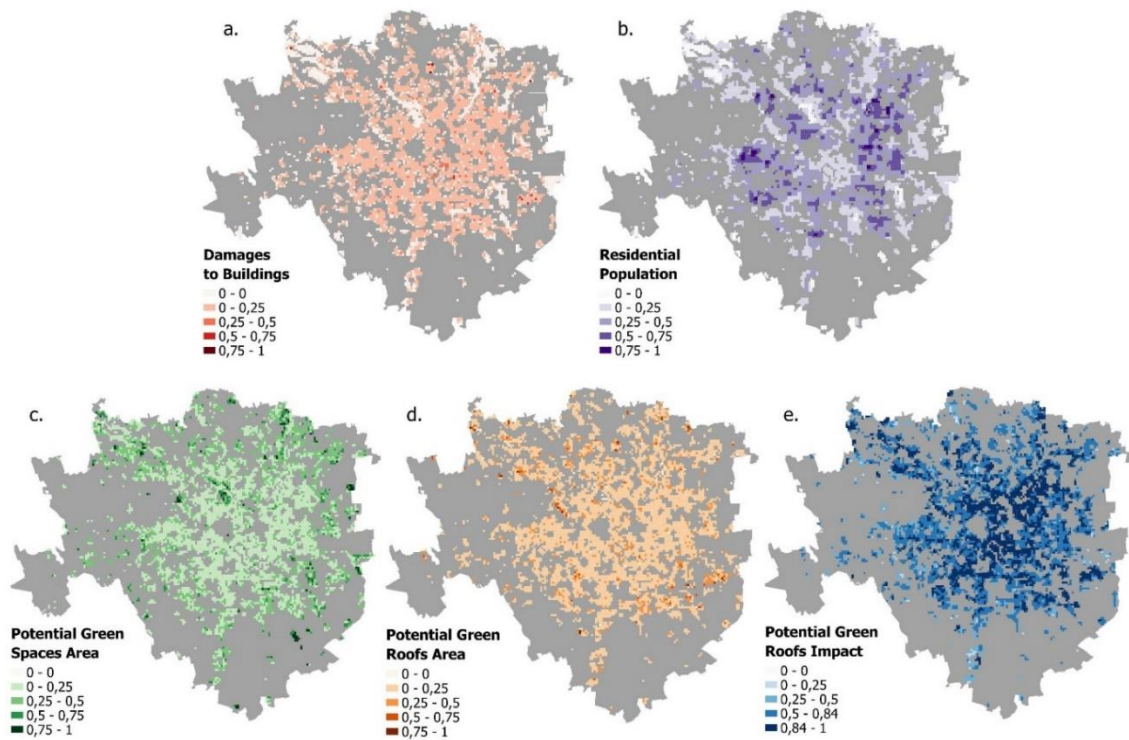


Figure 24 – Characterisation of the suitable areas for green conversion according to the defined evaluation criteria: a) damage to buildings; b) residential population; c) potential green spaces area; d) potential green roofs area; e) potential green roofs impact.

The top 25% of potential areas prioritised for green conversion in all the scenarios are reported in Figure 25. By combining the criteria, we obtain different ranking of areas according to their contribution to minimize the damage and the population exposed. New green areas result to be distributed throughout the city, potentially acting as green corridors between central and peripheral green areas. They provide an increase in permeability, based on the share of potential new green areas per cell, that is higher in the green city scenarios with respect to the solely green spaces and green buildings' conversion. Major improvements are visible in areas closer to existing green spaces. The maps of all the scenarios of conversion are reported in the Annex 4.1.



Figure 25 – Top 25% of green conversion in all the scenario: a-c) green buildings, green spaces, and green city scenarios to minimise damage; d-e) green buildings, green spaces, and green city scenarios to minimise population exposed. Grey cells represent the existing green network.

Green Network Assessment: damage and population exposed

For each scenario of green conversion, we observe a progressive reduction of the expected damage to buildings at the increasing of green coverage (Figure 26). Generally, results show higher effects in case of lower rain intensities, with similar effects for both the tested configurations, i.e. minimizing the damage to buildings and minimizing the population exposed. The two configurations show some differences at the lower levels of green conversion, being almost equivalent in the 100% of potential greening, for all the types of conversion. The Green City scenarios result to have the higher damage reduction for all rain intensities. The percentage reduction of damage ranges from almost 60% in RP100 up to 100% in RP10. Green Spaces scenarios reach a damage reduction of around 35% in the most extreme scenario, while Green Buildings scenarios provide the lower impacts for extreme rainfall events (up to 20%). Nevertheless, both GS and GB show important damage reduction for lower rain intensities.

The expected annual damage to buildings is significantly reduced. Figure 27 shows a summary of EAD estimated values referred to the minimization of damage configuration. At the current conditions, the EAD is around 18.6M€. In GC scenarios, the EAD is halved with the 25% of additional green areas. At the same percentage of conversion, the EAD is reduced by a quarter in GS and in GB. Similar values resulted for the minimization of population configuration (see Annex 4.2). These results show how the combination of measures, both green roofs and green open areas, better contribute to flood risk reduction by providing a major permeability of the soil (as we observed in Figure 25).

% Reduction of Damage to Buildings

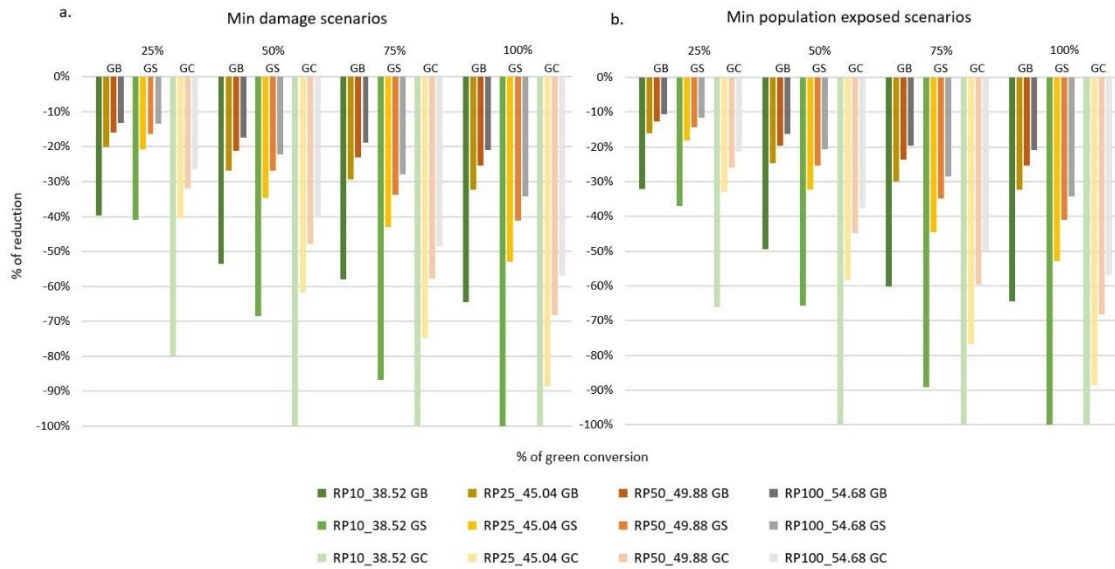


Figure 26 – Percentage reduction of damage to buildings for each scenario of conversion compared to the baseline: a) reduction associated with the minimization of damage scenarios; b) reduction associated with the minimization of population exposed scenarios.

Expected Annual Damage – min damage scenarios

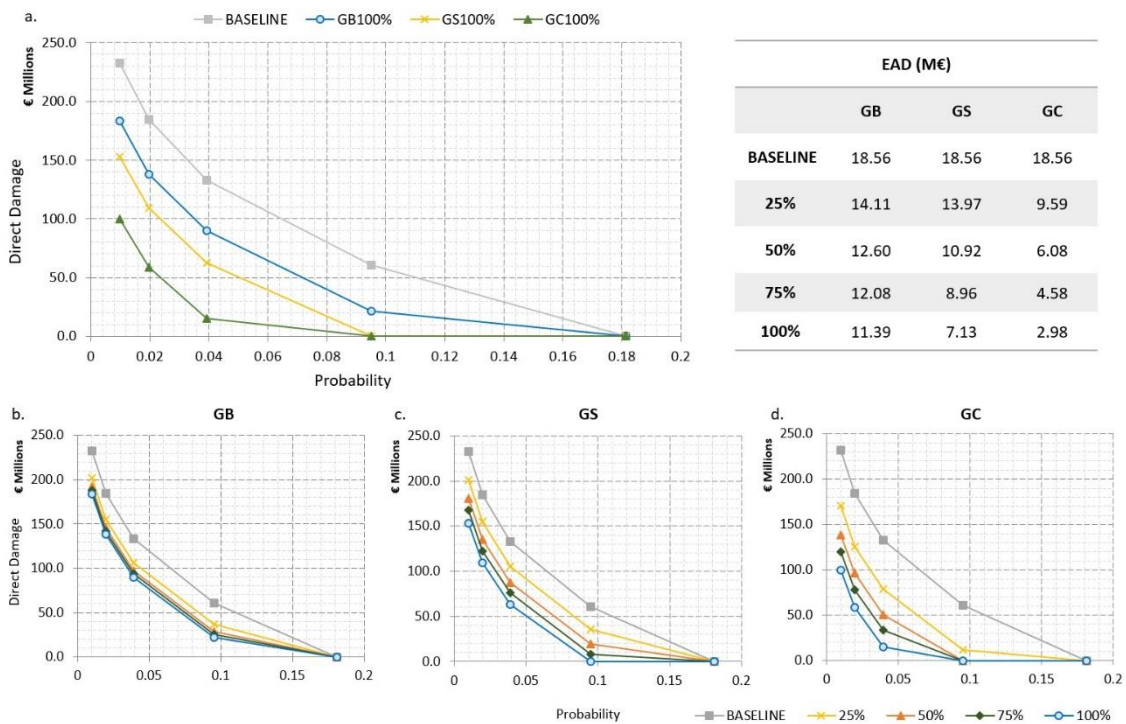


Figure 27– Estimated expected annual damage values and curves. A) comparison of EAD for 100% of green in all scenarios; b) EAD estimated for Green Buildings scenarios; c) EAD estimated for Green Spaces scenarios; d) EAD for Green City scenarios.

Similar trends resulted for the population exposed. Figure 28 reports the results for the population exposed to pluvial floods, showing the total population exposed to water depth >5 cm and that exposed to extreme class of water depth >100 cm. With the increase of green coverage, less people are generally affected by pluvial floods for all rain intensities. In case

of Green City scenarios, the percentage reduction of population exposed ranges from 8% to 45% in RP100 up to 100% in RP10 for water depth >5 cm. For people exposed to extreme pluvial floods, in Green City scenarios, we can observe a reduction of 100% for lower rain intensities, up to 50% in RP100 events. Percentage reduction ranges from 11% to around 18% in Green Buildings scenarios, and from 17% to 34% in Green Spaces scenarios. These trends can be explained by the fact that green areas progressively reduce the water depth in the city, and so population living in a certain class of water depth tend to move to lower classes of exposure. This is happening again for each rainfall event, with higher impacts in case of low-intermediate rain intensities. Comparing the effects associated with the two minimisation goals, we found higher reduction in the lower levels of green conversion in the configuration to minimise population exposed and comparable results in the 100% of potential greening.

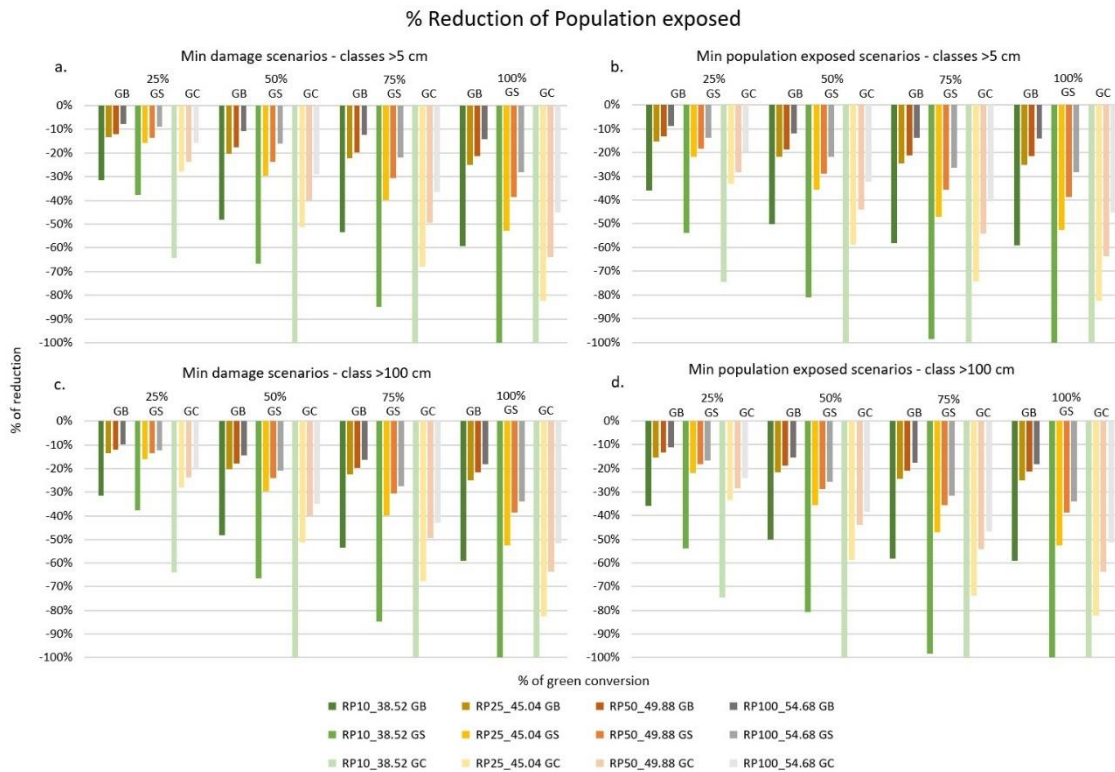


Figure 28 - Percentage reduction of population exposed for each scenario of conversion: a-b) reduction of population exposed to classes >5 cm of water depth associated with the minimization of damage scenarios; c-d) reduction of population exposed to extreme class >100 cm of water depth associated with the minimization of population exposed scenarios.

The expected annual population exposed confirmed a notable reduction at the increasing of green coverage. At the current conditions, the total EAPE to water depth >5cm counts almost 2500 persons, and around 500 persons exposed to extreme class of water depth >100 cm. In GC scenarios, the 25% of additional green coverage contribute to reduce the population exposed of around 40-42% for both classes of water depth >5 cm (Figure 29) and class >100 cm (Figure 30). At the same percentage of conversion, the EAPE is reduced by 18-20% GS and 28-30% in GB. Similar results are obtained for the EAPE in the minimization of damage configuration (Annex 4.3).

Expected Annual Population Exposed (>5 cm) – min population exposed scenarios

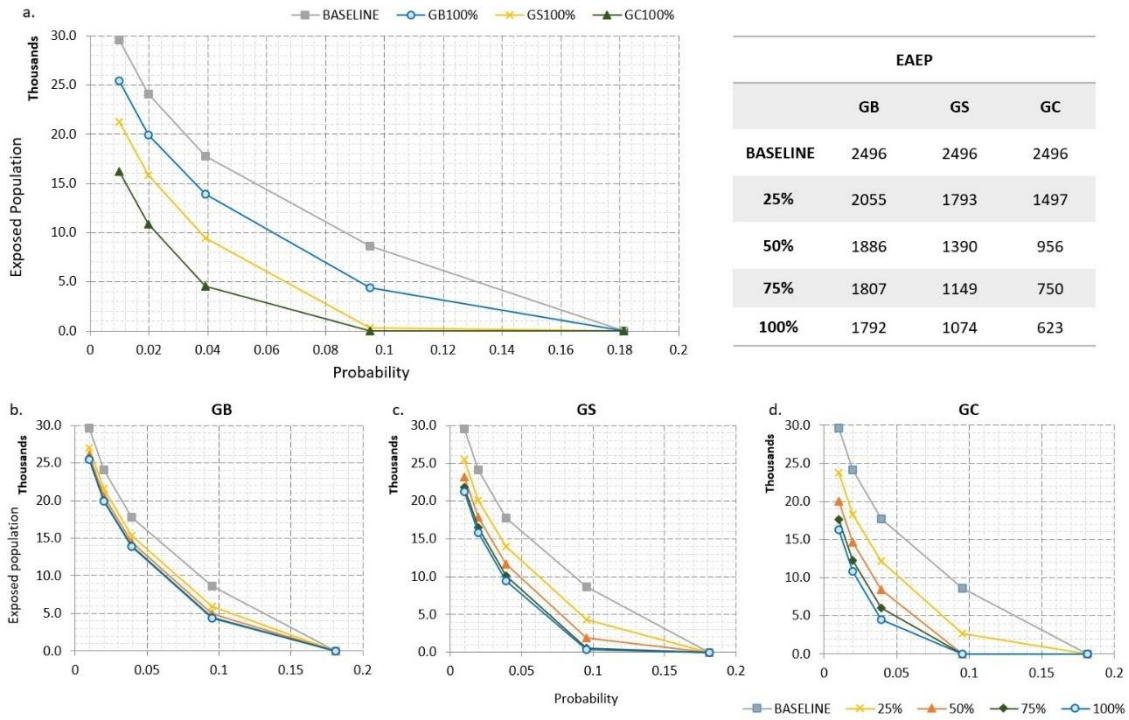


Figure 29 - Estimated expected annual population exposed values and curves for classes of water depth >5 cm. A) comparison of EAPE for 100% of green in all scenarios; b) EAPE estimated for Green Buildings scenarios; c) EAPE estimated for Green Spaces scenarios; d) EAPE for Green City scenarios.

Expected Annual Population Exposed (>100 cm) – min population exposed scenarios

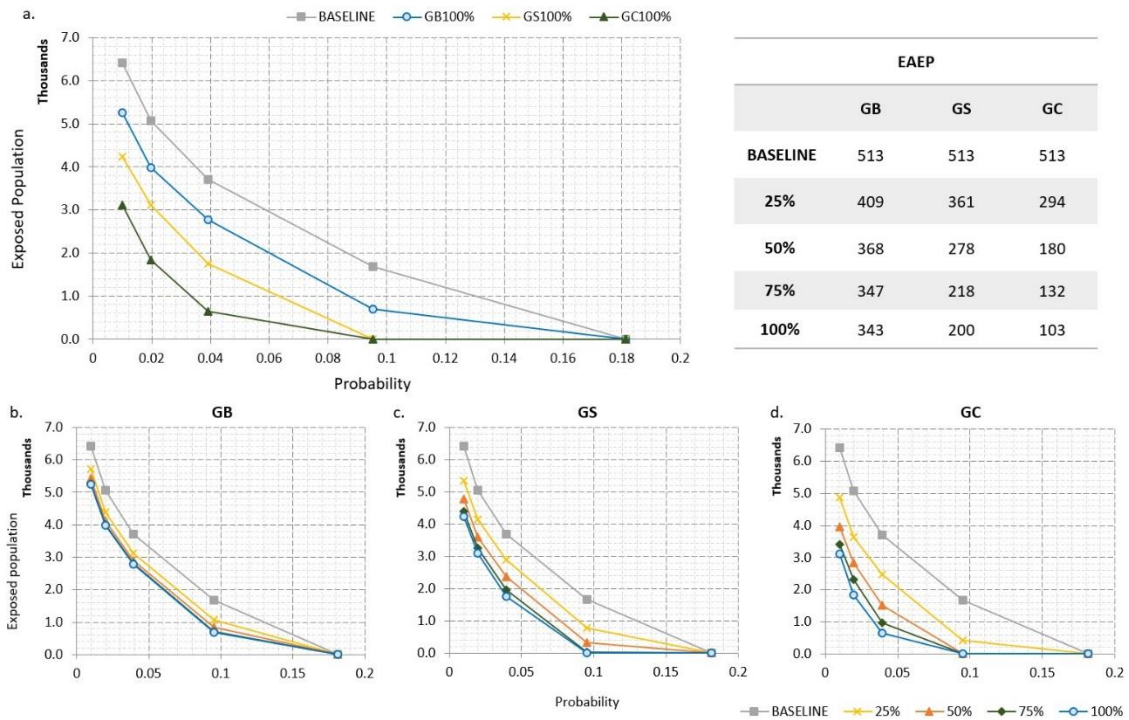


Figure 30 - Estimated expected annual population exposed values and curves for class of water depth >100 cm. A) comparison of EAPE for 100% of green in all scenarios; b) EAPE estimated for Green Buildings scenarios; c) EAPE estimated for Green Spaces scenarios; d) EAPE for Green City scenarios.

The spatial distribution of damage and population exposed reduction per unit of area is shown in Figure 31. We reported the 25% of conversion in the Green City scenarios for RP100 rainfall events, showing the effects associated with the two minimization goals analysed. The highest ranked areas for percentage reduction of impacts are similarly distributed across the city in both rainfall events. Areas with higher reduction of population exposed are located mostly in the north or in the very south of the studied area. Areas with higher reduction potential in terms of direct economic damages are distributed all around the city centre. Clusters of higher economic impacts are recognizable in the north-east, south-east and south-west. In general, the higher ranked areas are mostly concentrated where the surround green coverage is higher.

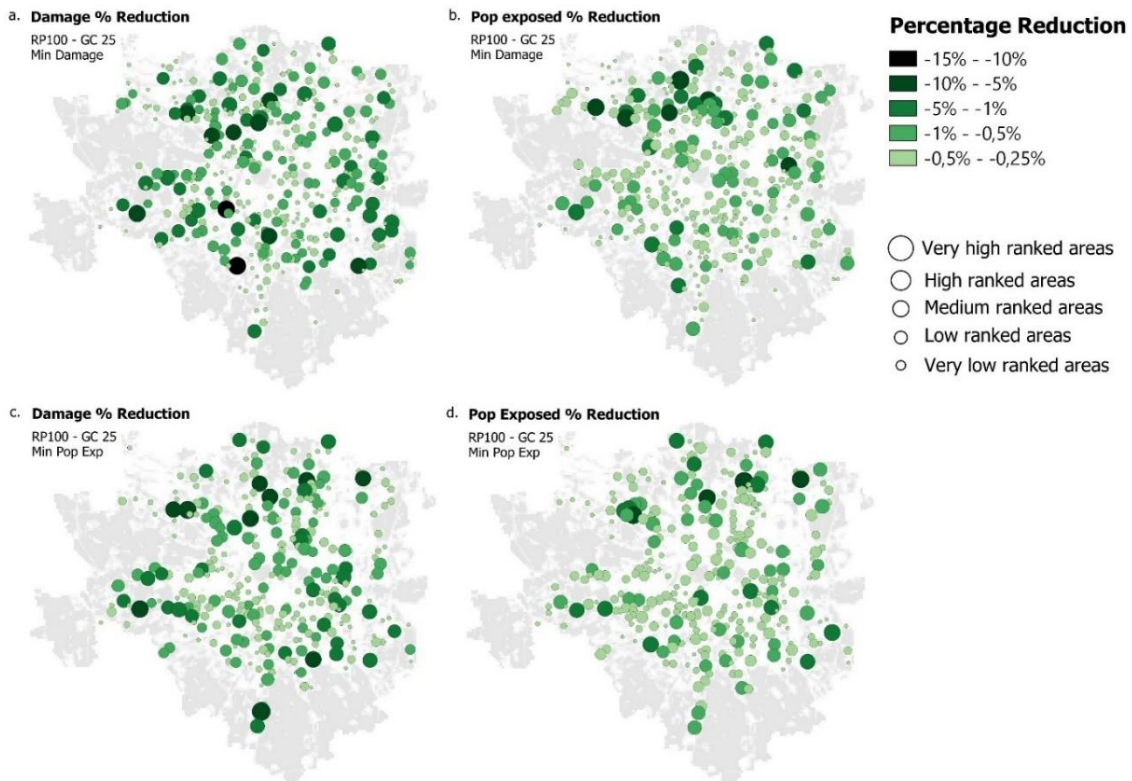


Figure 31 – Spatial representation of damage and population exposed reduction per unit of area in the 25% Green City scenario for a rainfall event RP100: a-b) reduction associated with the minimization of damage scenarios; c-d) reduction associated with the minimization of population exposed scenarios. Population exposed here counts for all classes >5cm.

Discussion

Our results show many opportunities for implementing an urban green network in the city of Milan. The scenarios analysis identified several options for green conversions also across the city centre, both in terms of green buildings and open green spaces. All the different scenarios of green conversion investigated provided positive impacts for pluvial flood mitigation, reducing both direct damages to building and population exposed.

Generally, GI showed a slightly better response to lower rain intensities, but with significant contribution also in case of more extreme rainfall events. In addition to rain intensity, flood risk also depends on the soil infiltration capacity, which is a function of soil characteristics and properties that can limit the amount of water retained in and passing by the soil layers (Ren et al., 2020). Higher reduction impacts are also associated with larger extent of green coverage and with different types of conversion combined together. This suggests that

multiple and diverse interventions, spatially distributed and connected across the space, should be considered to have more benefits. They can include different NBS options or the integration of green and more traditional interventions. Green conversion should be specifically designed according to the context, implementing, for example, urban parks, rain gardens, green roofs and walls, vegetated alleys, or green rail paths. A total green conversion of an area is often not feasible, and NBS should be situated in conjunction with the urban drainage system and more engineered solutions, to increase the potential water retention capacity in case of the most extreme rainfall events. This is in line with recent reviews and studies, finding that the potential limited effectiveness to cope with extreme pluvial flooding can be compensated by the joint implementation and the use of diverse types of both green and grey solutions across the city, that differently contribute to mitigate flood risk (Costa et al., 2021; Huang et al., 2020; Majidi et al., 2019)

The spatial ranking of areas with higher positive impacts can help the administration to prioritise intervention of green conversion according to the goal pursued, i.e. minimize the economic damages, the population affected or both. The priority areas are located in the districts characterised also by higher social and material vulnerability, especially in the north-west (Istat, 2020). This can be an additional driver to act in these areas, where population has also possibly lower capacity to recover after a disaster, i.e. with lower economic capacity, poorer labour conditions, more fragile social and housing conditions, elderly population.

The analysis can be further extended by additional scenarios of green conversion or different city resilience goals. Here we considered the conversion of a share area per cell, including the greening of buildings and open spaces. This makes it possible to assess potential for pluvial flood risk reduction and serve as starting point for detailed planning of urban regeneration projects. The analysis can be further extended by other greening solutions or vulnerability traits. Further analysis could also address rain events in climate change scenarios or different types of hazards, such as heat waves to support a better understanding and quantification of urban green also in future and diverse conditions. Our study is also useful for identifying priorities for investments in nature-based solutions and urban ecosystem restoration. Urban green network can be connected to and integrated within a regional ecological network, contributing so to more sustainable interactions between nature and society, supportive of human, ecosystem and planetary health (IPCC, 2022). Multifunctional urban green infrastructure can contribute to thermal comfort, air quality, carbon sequestration, and multiple health, social and recreational benefits in addition to risk mitigation. Robust evidence underpinning the damage reduction could boost the development of insurance and investments schemes which help to address the finance gaps for nature-based solutions.

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CONCLUSIONS

The value of working with nature is increasingly recognized, but it needs to be carefully managed. The thesis explored the benefits of using a network approach to design green infrastructures and nature-based interventions for climate change adaptation and disaster risk reduction. The different case studies showed how considering nature connectivity as a core principle in landscape management can inform climate change adaptation actions and support a transition towards a more resilient environment. This hopefully contributes to build a better knowledge and understanding of the value of nature-based solutions, also in quantitative terms, that can help the definition of policies and plans at different levels.

From a methodological perspective, the proposed framework resulted to be a flexible and multidisciplinary tool to investigate and guide green interventions at different scales and in different contexts. It represents a base methodology to have a first overview and provide indications in decision-making processes. The framework can be then adjusted to perform more specific and contextualised analysis. Here, for the analysis of the existing networks condition, we applied the same procedure, although considering different ecosystems and green elements (protected areas, vegetated riparian zones, natural water retention ponds, urban green spaces and green roofs). But in the different chapters, we experimented some modifications in the definition of potential network scenarios of implementation. In chapter 2, the network improvement definition was driven by a suitability analysis of new sites for ponds according to their construction characteristics and connectivity contributions. At the European scale, the proposed network scenario was based on policy target privileging additional corridors. Finally, at the city level, the proposed configurations to build an urban green network considered the most critical areas in terms of pluvial flood risks and potential of green conversion, improving green spaces accessibility at the same time. The analyses also showed the possibility of integrating the network approach in combination with different types of models.

Studying different scales, the thesis provides a wider view about the need of integrating policies and planning from local to international level and vice versa in the context of nature-based solutions. The relevance of a closer collaboration among different administration levels and of international and regional cooperation to protect nature and have more effective adaptation strategies emerged at each level. Connectivity does not follow administrative boundaries. Chapter 1 and 2 showed the contrast between regional and river basins limits, and the third chapter the different application of European and national governance and strategies. At the European scale, this result to be particularly relevant when considering the future climatic (RCPs) and socio-economic (SSPs) conditions, that have a strong influence on land use and ecosystem services changes. Although connecting protected areas contributed to mitigate the negative effects, results presented lower benefits in scenarios dominated by nationalism and lack of international cooperation (RCP4.5-SSP3).

The thesis also highlighted the multifunctional role of nature-based solutions and green infrastructures. They have been applied to address different issues, from water scarcity in agriculture, to biodiversity protection, to extreme weather events. The results showed the positive benefits associated to a network of green infrastructures in all the cases, both at the

current and future climate change conditions. Additionally, when designed for a specific purpose, they do not undermine but indeed favour other services and co-benefits, such as the improvement of ecological functions and biodiversity (chapter 2), the provision of primary resources (chapter 3), the creation of recreational spaces and more liveable cities (chapter 4).

However, the use of diverse and combined measures is important. As mentioned in the introduction, connected, diverse and redundant features better contribute to resilience. Additionally, nature can be influenced by climate and environmental change, that can limit their effectiveness in severe conditions. As resulted in the urban case study, the contribution of green spaces is lower in case of very intense rainfall events or could need a more extended implementation in terms of area, that can be unfeasible in a city. Therefore, results suggested that policies and strategies should consider the integration with other more engineered solutions and soft measures, focusing on population preparedness and implementation of early warning systems. As well, when considering green interventions, the implementation of different types of nature-based solutions can be more beneficial.

The demonstrated benefits and co-benefits represent a value added to apply green interventions, although they could have higher costs of implementation. Investments for nature-based solutions are widely supported, especially in Europe, by policies, funds and initiatives. However, these opportunities cannot be always sufficient and easy to access. The second chapter showed how the 'extra' economic costs of nature-based solutions can be compensated by alternative and innovative financial scheme that allow to share costs and gains within the community. To this end, is fundamental the engagement of stakeholders, both from public and private sectors, and citizens. They need to be aware about risks associated with climate change, the potential measures, the benefits and costs associated to their implementation. This could create a wider consensus for their use and possibly promote investments and willingness to pay mechanisms in this sector, overcoming the main barriers to mainstream their use. Additionally, the last chapter highlighted the value of green infrastructure to mitigate the economic damages associate with extreme rainfall events. This can help to increase citizen and public administration awareness about the importance of preventing risks and investing in measures that can help to save both people and money. In this perspective, the thesis can be the basis for future research opportunities related to economic benefits and costs of nature-based solutions. The quantification of direct and indirect economic costs and values associated with green network can contribute to a better estimation of social and insurance values produced by ecosystems for climate risks management. This topic is relevant in the international agenda, both for policy and research, with particular focus on financial and insurance schemes to invest in green infrastructure, resources management and quality, climate-proof cities development.

SUPPLEMENTARY MATERIALS

Annex Chapter 1

1.1 Distance thresholds for building network scenarios

Annex 1.1 includes additional information used in the Building Scenarios sections, reporting graphical example of improvement and reduction of the network.

Table A1 report the distribution of the distance values between nodes in the existing network, used to set the distance scenarios.

| Existing GI Network | Min | 1 st Qu | Median | Mean | 3 rd Qu | Max |
|---------------------|-------|--------------------|---------|---------|--------------------|----------|
| Distance (m) | 54.99 | 880.62 | 1919.89 | 3065.48 | 4062.70 | 27318.91 |

Table A1 – Distribution of distances between nodes within the existing GI network.

Table A2 reports the maximum distance and the buffer values used in the analysis for the identification of new nodes potential sites.

| GI Network Scenarios | 1km | 2km | 4km |
|----------------------|-----|------|------|
| Maximum distance (m) | 500 | 1000 | 2000 |
| Buffer (m) | 600 | 1100 | 2200 |

Table A2 – Maximum distance values used to define suitable area for new nodes establishment according to the three different distance scenario.

1.2 Connectivity analysis

Here we report the graphical representation of the node rank according to IIC and its fraction (IIC_{intra} and IIC_{flux}).

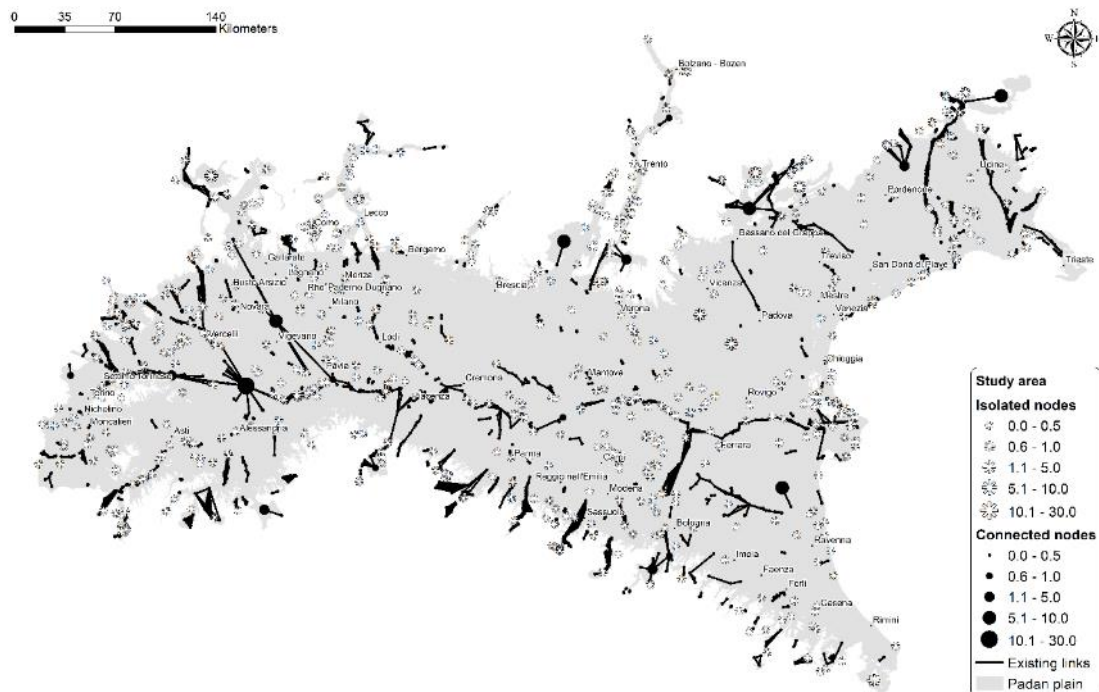


Figure A1 – IIC rank of the network. The node size represents the node importance.

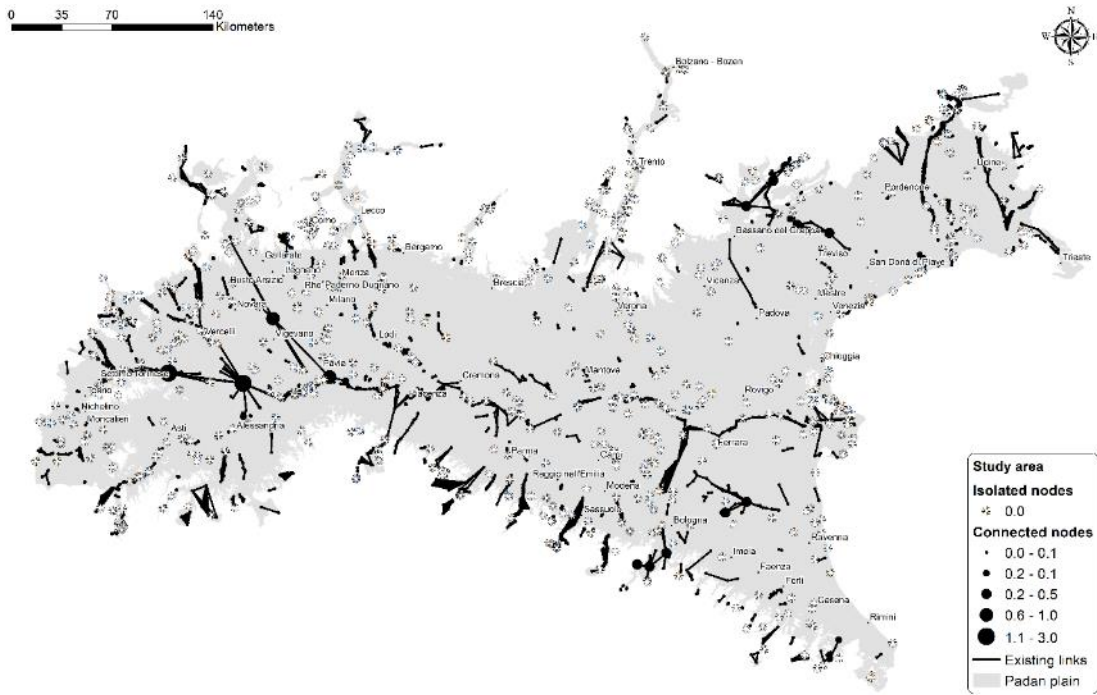


Figure A2 - IICflux rank of the network. The node size represents the node importance.

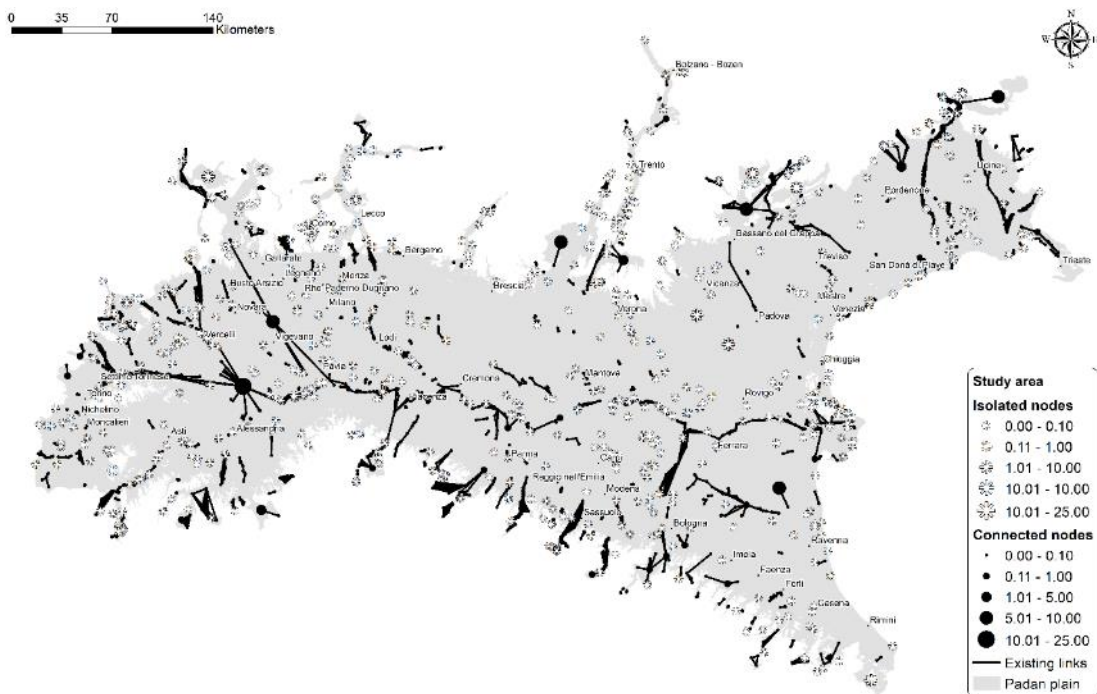


Figure A3 - IICintra rank of the network. The node size represents the node importance.

1.3 Network scenarios

Reduction scenario

Figures A4-A6 show a zoom in the graph network representation to highlights the addition of nodes and links in the different scenarios.

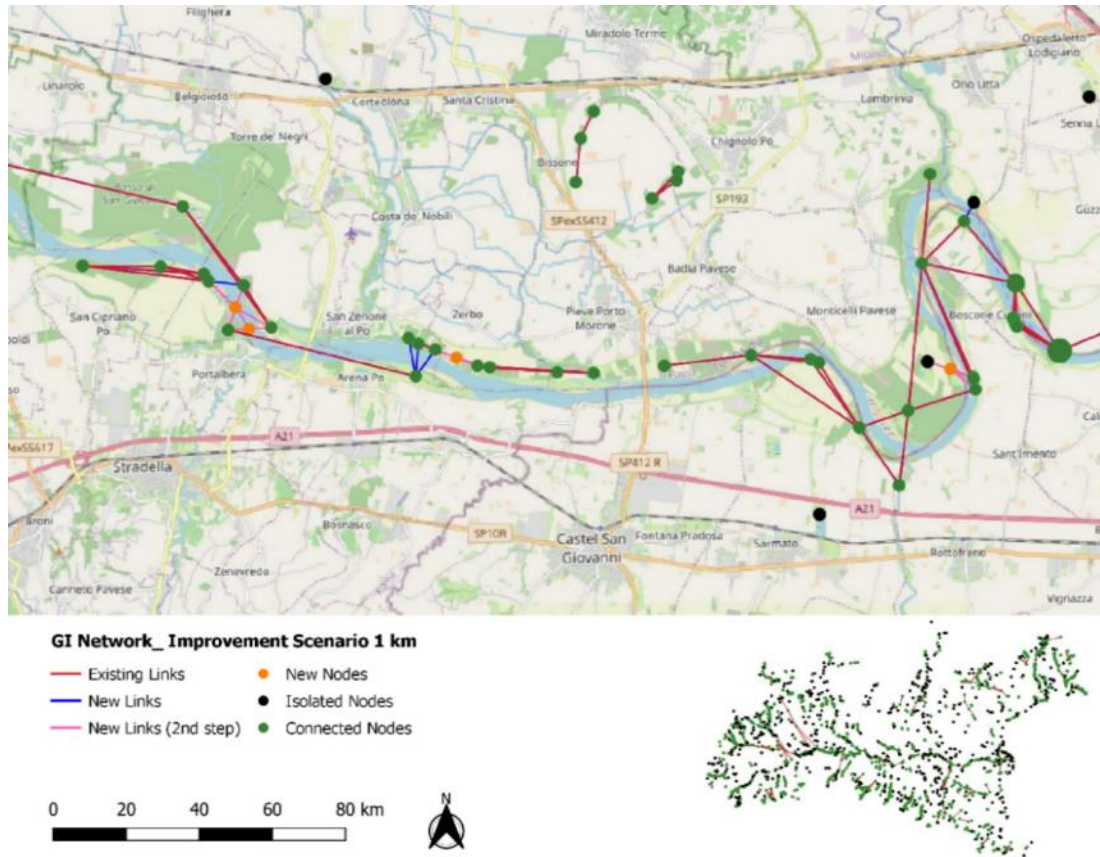


Figure A4 – Example of GI network improvement adding nodes and links for 1 km distance scenario. Different colour of links and nodes indicates the successively improving steps.

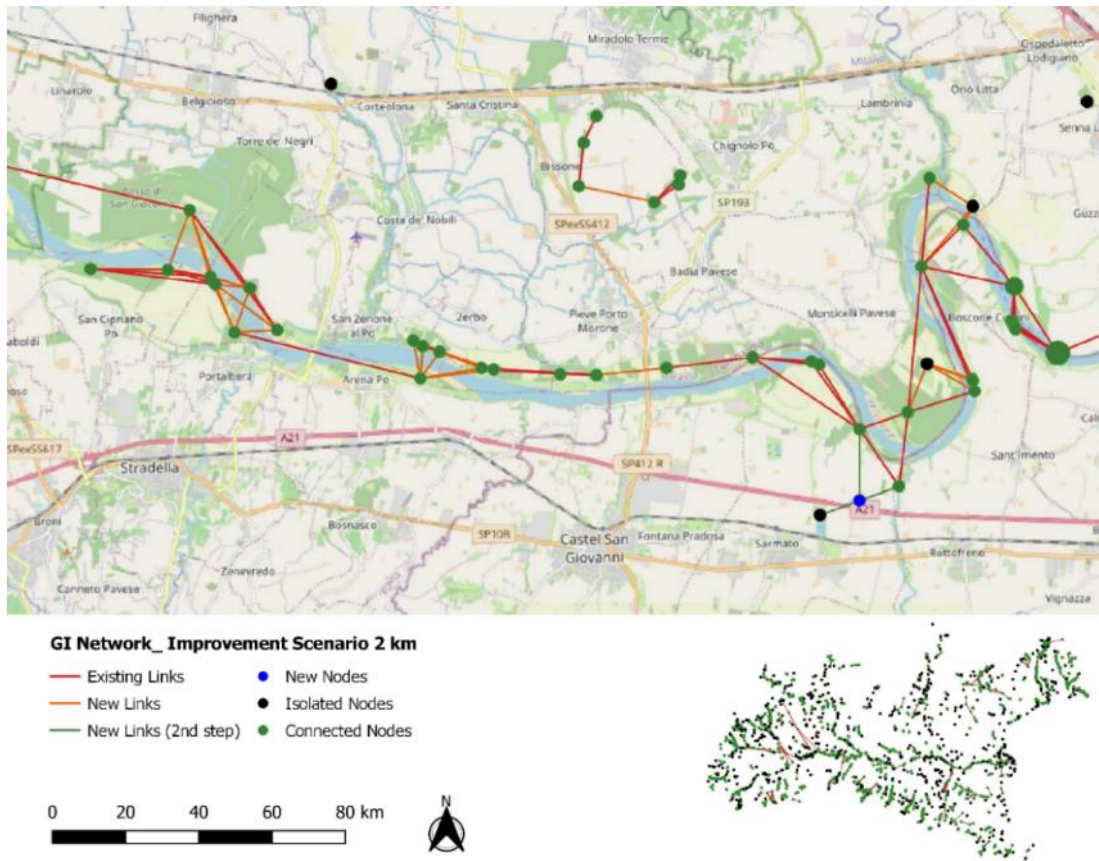


Figure A5 - Example of GI network improvement adding nodes and links for 2 km distance scenario. Different colour of links and nodes indicates the successively improving steps.

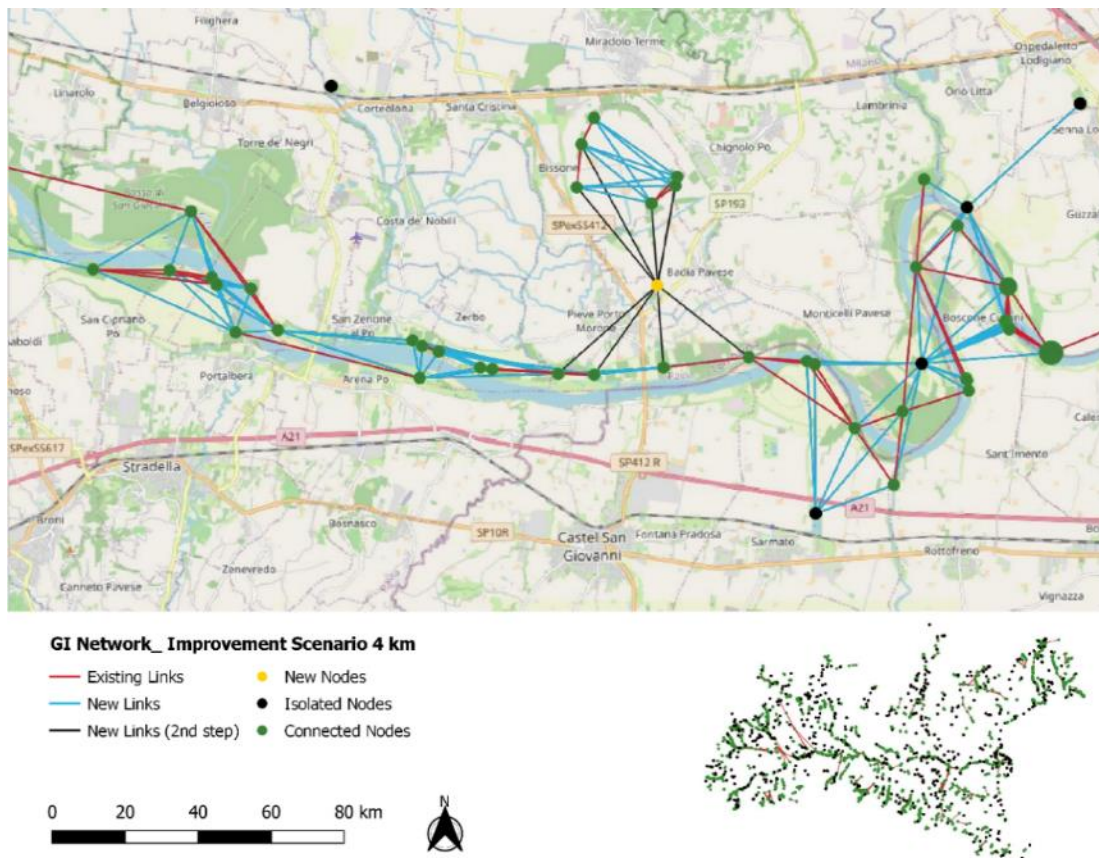


Figure A6 - Example of GI network improvement adding nodes and links for 4 km distance scenario. Different colour of links and nodes indicates the successively improving steps.

Reduction scenario

Figure A7 represents the cumulative value of *IICconnector* fractions, showing how the additional contribution of nodes reach a steady state with no significant improvement. This happens around adding one by one 90 nodes, with *IICconnector* value down to 0.001. This value has been used as threshold to define cut-nodes in the reduction scenario.

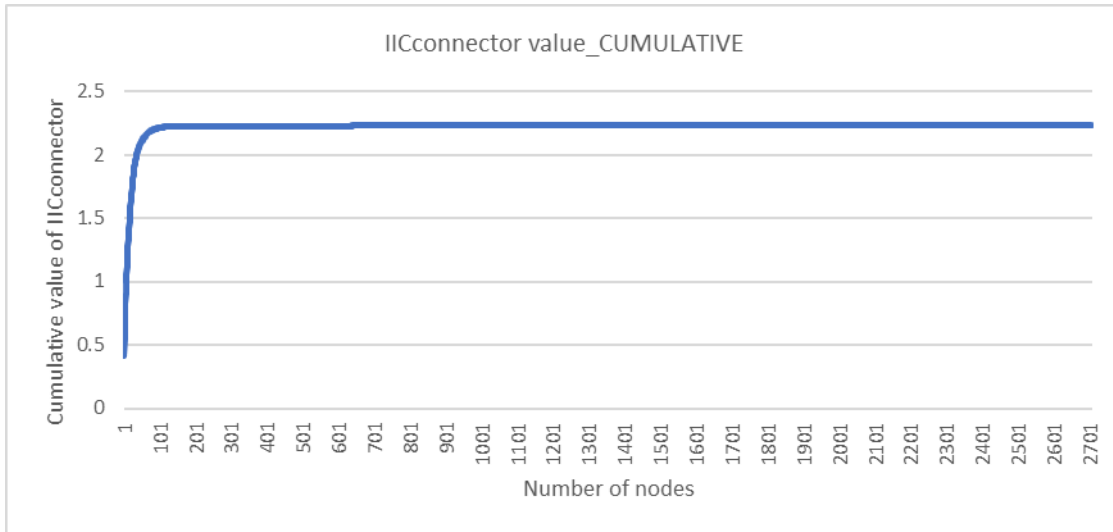


Figure A7 – Cumulative value of *IICconnector*.

Figure A8 shows a zoom in the graph network representation to highlights the removal of nodes and links.

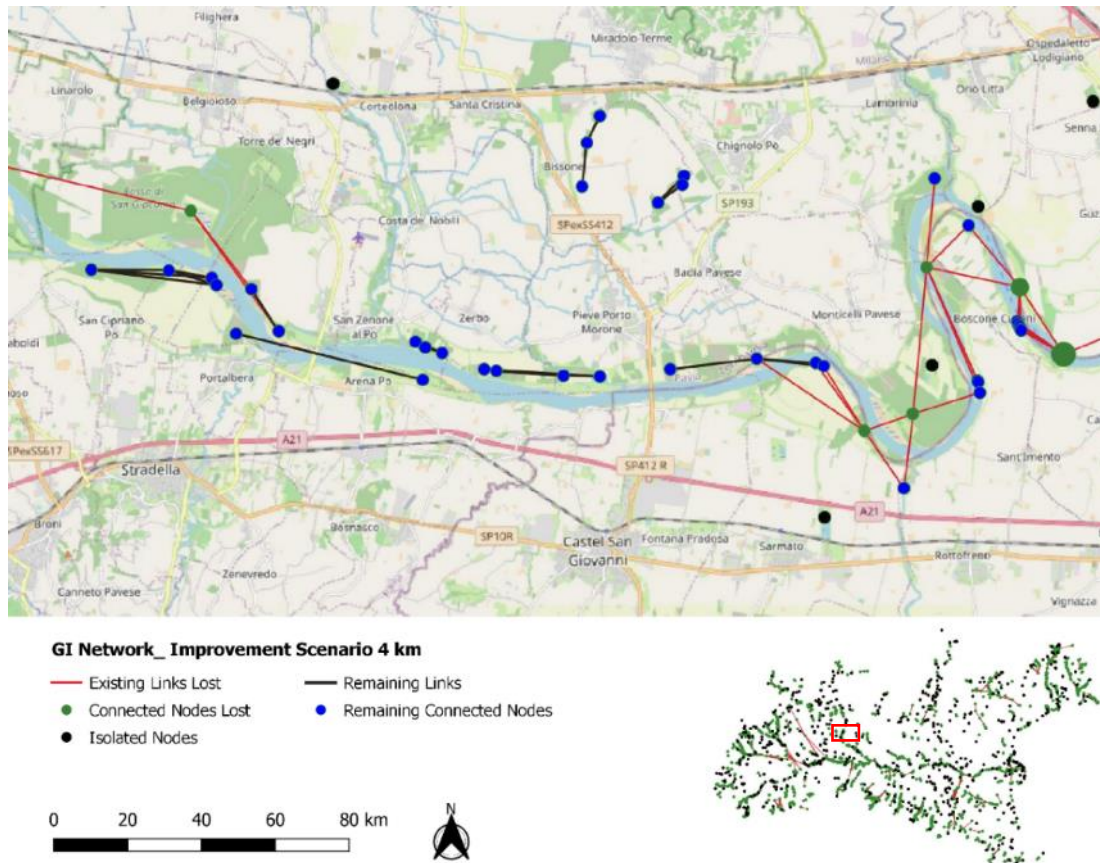


Figure A8 - Example of GI network reduction removing nodes and links. Different colour of links and nodes indicates the remaining and lost nodes and links.

Annex Chapter 2

2.1 Dimensions and volumes for retention ponds

Table A reports dimensions and volumes for four conventional sizes of circular water retention ponds.

| R | r | h | Pond effective volume |
|-----|-----|-----|-----------------------|
| [m] | [m] | [m] | [m ³] |
| 36 | 20 | 4 | 10120 |
| 66 | 46 | 5 | 49784 |
| 89 | 69 | 5 | 98557 |
| 105 | 73 | 8 | 201221 |

Table A3 - Dimensions and volumes for different sized water retention ponds.

2.3 IICconnector cumulative values for suitability threshold

The following graph represents the cumulative values of *IICconnector* index. This is used to define the threshold to select new suitable area for ponds implementation. Only the area with a significant increment of connectivity have been included in the selection. The threshold has been defined at *IICconnector* > 0.001, corresponding to 35 new areas and equal to a cumulative volume of 5.3 Mm³.

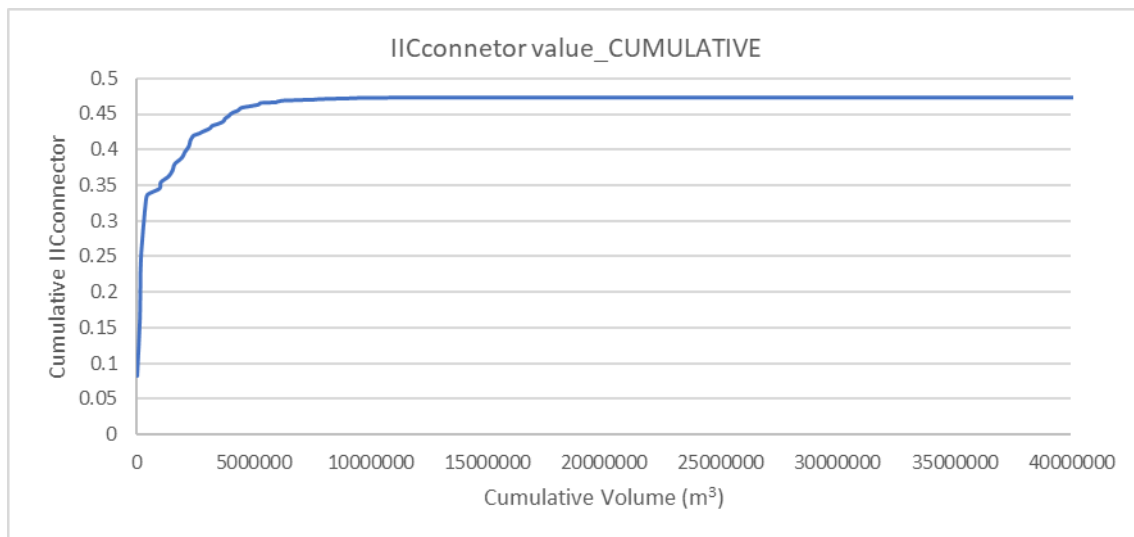


Figure A9 - *IICconnector* cumulative value graph, showing the connectivity influence of nodes used to define the suitability threshold.

2.4 Present scenario water balance results

The following tables show the synthetic indexes identified as measures of withdrawals pressures in current scenario. Chosen indexes, obtained as output of the river water balance for Lamone sub-catchments, are the following:

- Water availability: water volume still available, net of existing uses (WA in Figure 9 in the paper)
- Environmental indicator: number of days with flow lower than MEF (X' in Figure 9 in the paper)
- Seasonal WEI+: water exploitation index modified to consider volumes returned to the river (Cassani et al., 2009)

$$sWEI+ = \frac{\text{astractions} - \text{returns}}{\text{renewable water resources}}$$

Water availability is calculated in Mm³, time of no withdrawal in days and sWEI+ is referred to stress level thresholds as reported in next table.

| WEI+ threshold | stress level |
|-----------------------|---------------------------|
| WEI+ ≤ 35% | stress level: zero or low |
| 35% < WEI+ ≤ 65% | stress level: moderate |
| 65% < WEI+ ≤ 85% | stress level: medium |
| 80% < WEI+ ≤ 90% | stress level: high |
| WEI+ > 90% | stress level: very high |

Table A4 - sWEI+ index thresholds.

Next tables report synthetic indexes as measures both in summer period and in winter period, for every Lamone sub-catchment reported in Figure 7 in the paper.

| | | summer period | | | winter periods | | |
|-----------------|------------------------------|-------------------------|-----------------------|-------------------|-------------------------|-----------------------|------------------|
| | | Water availability | time of no withdrawal | sWEI+ | Water availability | time of no withdrawal | sWEI+ |
| basin ID | sub-catchment | [Mm³] | [d] | | [Mm³] | [d] | |
| 1 | Lamone Marradi | 2.925 | 69 | 26% - zero or low | 35.881 | 20 | 5% - zero or low |
| 2 | Lamone after S Martino | 4.905 | 70 | 20% - zero or low | 53.780 | 20 | 3% - zero or low |
| 3 | Tramazzo inflow into Marzeno | 3.873 | 52 | 6% - zero or low | 25.237 | 21 | 1% - zero or low |
| 4 | Acerreta inflow into Marzeno | 3.052 | 59 | 6% - zero or low | 20.148 | 25 | 0% - zero or low |
| 5 | Marzeno after Modigliana | 4.032 | 79 | 10% - zero or low | 39.536 | 19 | 0% - zero or low |
| 6 | Lamone S.Casale | 6.433 | 70 | 17% - zero or low | 68.340 | 20 | 3% - zero or low |
| 7 | Lamone Sarna | 6.127 | 65 | 28% - zero or low | 78.908 | 21 | 2% - zero or low |
| 8 | Marzeno into Rivalta | 1.311 | 80 | 56% - moderate | 45.863 | 22 | 3% - zero or low |
| 9 | Lamone Errano weir | 5.467 | 103 | 33% - zero or low | 79.102 | 21 | 3% - zero or low |
| 10 | Marzeno inflow into Lamone | 0.627 | 78 | 65% - moderate | 51.488 | 25 | 4% - zero or low |
| 11 | Lamone inflow into Marzeno | 1.179 | 90 | 66% - medium | 73.057 | 20 | 8% - zero or low |
| 12 | Lamone Reda | 3.628 | 20 | 59% - moderate | 130.649 | 4 | 5% - zero or low |

Table A5 - River Water Balance for Lamone sub-catchments in summer period.

2.5 Regional natural FDCs

As described in Cassani et al. (2009) two dimensionless curves have been identified for the Lamone sub-catchment reported in Figure A10 and A6.

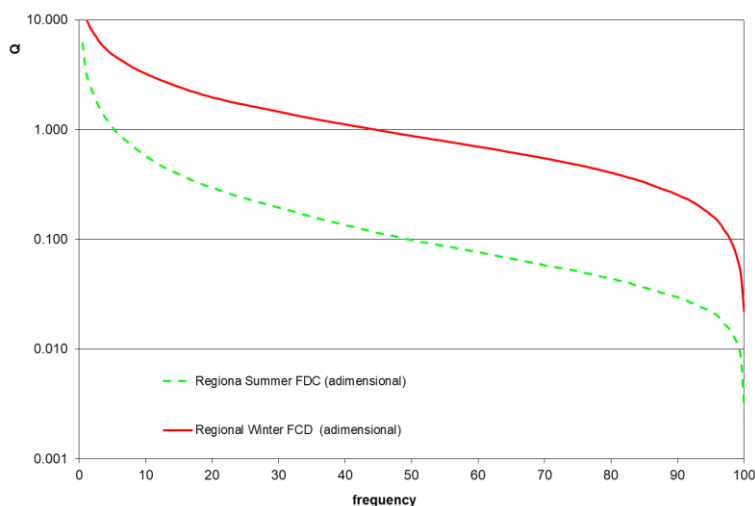


Figure A10 – Dimensionless regional FDCs from Cassani et al. (2009).

| duration | Summer | Winter |
|----------|--------|--------|
| 0.005 | 6.120 | 13.592 |
| 0.05 | 1.050 | 4.822 |
| 0.1 | 0.573 | 3.229 |
| 0.15 | 0.392 | 2.443 |
| 0.2 | 0.296 | 1.963 |
| 0.25 | 0.235 | 1.679 |
| 0.3 | 0.195 | 1.457 |
| 0.35 | 0.160 | 1.262 |
| 0.4 | 0.135 | 1.113 |
| 0.45 | 0.114 | 0.988 |
| 0.5 | 0.098 | 0.875 |
| 0.55 | 0.087 | 0.783 |
| 0.6 | 0.076 | 0.699 |
| 0.65 | 0.067 | 0.619 |
| 0.7 | 0.058 | 0.546 |
| 0.75 | 0.051 | 0.476 |
| 0.8 | 0.044 | 0.404 |
| 0.85 | 0.036 | 0.331 |
| 0.9 | 0.030 | 0.254 |
| 0.95 | 0.022 | 0.167 |
| 1 | 0.003 | 0.022 |

Table A6 - Dimensionless regional FDCs from Cassani et al. (2009), tabular output.

The two dimensionless curves shall be multiplied by the average annual flow Q_{av} typical for each sub-catchment, that has been derived from Regione Emilia-Romagna (2015), to obtain the natural FDCs. Q_{av} is reported in Table A7.

| Annula flow | | Qav |
|-------------|------------------------------|--------|
| basin ID | sub-catchment | [m3/s] |
| 1 | Lamone Marradi | 1.641 |
| 2 | Lamone after S Martino | 2.414 |
| 3 | Tramazzo inflow into Marzeno | 1.122 |
| 4 | Acerreta inflow into Marzeno | 0.90 |
| 5 | Marzeno after Modigliana | 1.718 |
| 6 | Lamone S.Casale | 3.042 |
| 7 | Lamone Sarna | 3.505 |
| 8 | Marzeno into Rivalta | 2.089 |
| 9 | Lamone Errano weir | 3.53 |
| 10 | Marzeno inflow into Lamone | 2.37 |
| 11 | Lamone inflow into Marzeno | 3.446 |
| 12 | Lamone Reda | 5.72 |

Table A7 - Average annual flow Q_{av} for each sub-catchment (Regione Emilia-Romagna, 2015).

2.6 Water balance data

The following tables show data used for water balance estimation, with scheme described in paper, showing withdrawals and intakes for each sub-catchment for two seasons: summer period, from May to September, and winter period, from October to April.

Withdrawal data have been subdivided into three types of water use (domestic, agricultural (including livestock) and industrial deriving information from:

- Regional permission databases are updated to 2016.
- Estimation of water consumption for different usages and infiltration in the riverbed (the amount is considered inside the agricultural usage in Table A10 *Table A*) from Regional Protection Agency for the updated river district balance (Regione Emilia-Romagna, 2015) and for the previous iteration (EEA, 2019c).
- Local wastewater treatments plans discharges provided by local multiutility upon request by GECOsistema.

| withdrawals | | domestic | | agricultural (including livestock) | | industrial | | infiltration | |
|-------------|------------------------------|--------------------|--------------------|---------------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| | | summer | winter | summer | winter | summer | winter | summer | winter |
| basin ID | sub-catchment | [Mm ³] | [Mm ³] | [Mm ³] | [Mm ³] | [Mm ³] | [Mm ³] | [Mm ³] | [Mm ³] |
| 1 | Lamone Marradi | 1.574 | 2.191 | 0.063 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | Lamone after S Martino | 0.000 | 0.000 | 0.160 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3 | Tramazzo inflow into Marzeno | 0.202 | 0.280 | 0.149 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | Acerreta inflow into Marzeno | 0.000 | 0.000 | 0.245 | 0.004 | 0.002 | 0.003 | 0.000 | 0.000 |
| 5 | Marzeno after Modigliana | 0.000 | 0.000 | 0.260 | 0.000 | 0.179 | 0.248 | 0.000 | 0.000 |
| 6 | Lamone S.Casale | 0.000 | 0.000 | 0.217 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 |
| 7 | Lamone Sarna | 0.000 | 0.000 | 1.809 | 0.007 | 0.003 | 0.004 | 0.000 | 0.000 |
| 8 | Marzeno into Rivalta | 0.000 | 0.000 | 2.775 | 0.001 | 0.007 | 0.010 | 0.895 | 1.800 |
| 9 | Lamone Errano weir | 0.000 | 0.000 | 0.491 | 0.000 | 0.000 | 0.000 | 0.224 | 0.354 |
| 10 | Marzeno inflow into Lamone | 0.000 | 0.000 | 1.104 | 0.026 | 0.000 | 0.000 | 0.355 | 0.713 |
| 11 | Lamone inflow into Marzeno | 0.000 | 0.000 | 3.200 | 2.883 | 0.000 | 0.000 | 0.928 | 1.465 |
| 12 | Lamone Reda | 0.000 | 0.000 | 0.269 | 0.000 | 0.000 | 0.000 | 0.545 | 0.861 |

Table A8 - Withdrawals estimated for River water balance for each sub-catchment.

| intakes | | summer | winter |
|----------|------------------------------|--------------------|--------------------|
| basin ID | sub-catchment | [Mm ³] | [Mm ³] |
| 1 | Lamone Marradi | 0.037 | 0.084 |
| 2 | Lamone after S Martino | 0.000 | 0.000 |
| 3 | Tramazzo inflow into Marzeno | 0.044 | 0.061 |
| 4 | Acerreta inflow into Marzeno | 0.000 | 0.000 |
| 5 | Marzeno after Modigliana | 0.342 | 0.474 |
| 6 | Lamone S.Casale | 0.009 | 0.013 |
| 7 | Lamone Sarna | 0.129 | 0.179 |
| 8 | Marzeno into Rivalta | 0.000 | 0.000 |
| 9 | Lamone Errano weir | 0.000 | 0.000 |
| 10 | Marzeno inflow into Lamone | 0.000 | 0.000 |
| 11 | Lamone inflow into Marzeno | 0.000 | 0.000 |
| 12 | Lamone Reda | 2.421 | 3.354 |

Table A9 - Intakes estimated for River water balance for each sub-catchment.

2.7 Climate impact indicators- E-Hype model

Information about climate impact indicators is taken from Hypeweb portal (<https://hypeweb.smhi.se/>) and reported below. Time series of the variable of interest (in this case daily river discharge) are provided at a sub catchment level; the Lamone catchment is described by 3 Hype sub-basins (Figure A.10).

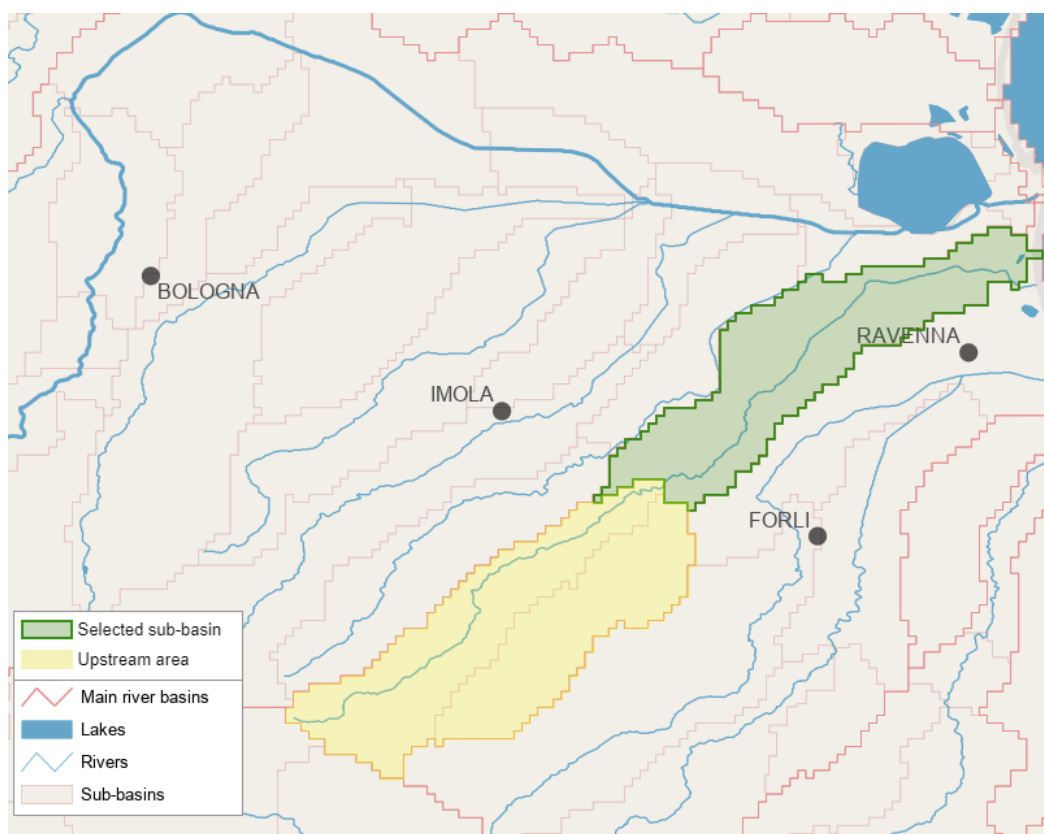


Figure A11 –Lamone catchment and sub-cathments available in the Hypeweb portal (source <https://hypeweb.smhi.se/>)

The climate impact indicators are based on hydrological impact modelling using the hydrological model E-HYPEv3.1.2. The hydrological modelling is now available from Hypeweb portal (<https://hypeweb.smhi.se/>) with an ensemble of bias-corrected climate model data provided by the EU FP7 project IMPACT2C (grant agreement 282746). More information on the climate-model ensemble used (for instance model selection procedures, uncertainties, adjustments) can be found here:

http://impact2c.hzg.de/imperia/md/content/csc/projekte/impact2c_d5.1_fin.pdf

Within the project IMPACT2C, the original RCM output data has been spatially interpolated, adjusted to the standard Gregorian calendar and has partly been biascorrected. More details can be found here:

http://impact2c.hzg.de/imperia/md/content/csc/projekte/impact2c_d4.1.pdf

The dataset covers the ensemble members given in Table A12. The ensemble comprises three Representative Concentration Pathways (RCP) to cover a range of policy scenarios: a mitigation scenario (RCP2.6), a stabilization scenario (RCP4.5) and a high greenhouse gas scenario (RCP8.5). The indicators at single catchment resolution are provided for an ensemble using one hydrological model (E-HYPEv3.1.2).

The full ensemble of time series from the model runs is stored at SMHI and the original daily time-series of some essential climate variables have been downloaded initially from the portal of the project "SWICCA" (<https://swicca.eu/>), now closed; those data are still available and updated from Hypeweb portal (<https://hypeweb.smhi.se/>).

Combinations of climate data scenarios are reported in Table A12.

| Hydrological model | Model input / forcing | | | Period | Institute |
|--------------------|-----------------------|------------|----------|-----------|-----------|
| | RCP | GCM | RCM | | |
| E-HYPE 2.1 | 2.6 | EC-EARTH | RCA4 | 1970-2100 | SMHI |
| | | MPI-ESM-LR | REMO2009 | 1951-2100 | CSC |
| | 4.5 | EC-EARTH | RCA4 | 1970-2100 | SMHI |
| | | EC-EARTH | RACMO22E | 1951-2100 | KNMI |
| | | HadGEM2-ES | RCA4 | 1970-2098 | SMHI |
| | | MPI-ESM-LR | REMO2009 | 1951-2100 | CSC |
| | | CM5A | WRF33 | 1971-2100 | IPSL |
| | 8.5 | EC-EARTH | RCA4 | 1970-2100 | SMHI |
| | | EC-EARTH | RACMO22E | 1951-2100 | KNMI |
| | | HadGEM2-ES | RCA4 | 1970-2098 | SMHI |
| | | MPI-ESM-LR | REMO2009 | 1951-2100 | CSC |

Table A10 - Table of all available ensemble members for the indicators. The abbreviations in Model input/forcing stand for various elements of the modeling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM).

Ratio between CC FDCs and actual reference period FDCs (years 1991-2011), for every duration provides a correction CC factor. This factor is then applied to most accurate FDCs from regional analysis (Cassani et al., 2009) to define the actual reference scenario, allowing simulation of C.C. effects. This so-called *delta change* method is quite common when downscaling climate projections, usually available at coarse resolution, to local scale data, see also (Trzaska and Schnarr, 2014).

In practice modified flow is obtained by multiplying the original flow Q, for a give duration, by the CC factor, derived as previously described from E-HYPE modelled curves. CC factors

are reported in the following tables (upper and lower values omitted due to inconsistent results at the extreme of the curves).

The 3 E-hype basins roughly correspond to the sub catchment of interest according to the following list: 9740041- All Marzeno sub-cathments; 9744931- Lamone Reda; 9780149- All remaining.

Sub-catchment Lamone Reda

| duration | summer | | | | | | | | | | | winter | | | | | | | | | | |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| | CSC_REMO2009_MPI-ESM-IR_rcp26 | CSC_REMO2009_MPI-ESM-IR_rcp45 | CSC_REMO2009_MPI-ESM-IR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-IR_rcp26 | CSC_REMO2009_MPI-ESM-IR_rcp45 | CSC_REMO2009_MPI-ESM-IR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
| 0.05 | -0.21 | -0.34 | -0.09 | 0.33 | -0.19 | 0.18 | -0.07 | 0.07 | 0.15 | 0.03 | 0.07 | -0.01 | 0.26 | 0.17 | 0.26 | 0.19 | 0.17 | 0.01 | 0.01 | 0.11 | -0.02 | 0.00 |
| 0.1 | -0.25 | -0.26 | -0.09 | 0.36 | -0.09 | 0.21 | -0.12 | 0.01 | 0.04 | 0.08 | -0.03 | 0.05 | 0.23 | 0.17 | 0.29 | 0.17 | 0.21 | -0.04 | 0.04 | 0.06 | 0.06 | -0.01 |
| 0.15 | -0.31 | -0.22 | -0.13 | 0.36 | 0.02 | 0.36 | -0.15 | -0.06 | 0.09 | 0.03 | -0.07 | 0.04 | 0.21 | 0.16 | 0.28 | 0.17 | 0.17 | -0.04 | 0.02 | 0.02 | 0.07 | -0.05 |
| 0.2 | -0.24 | -0.14 | -0.03 | 0.42 | 0.09 | 0.47 | -0.17 | -0.14 | 0.02 | 0.04 | -0.05 | 0.03 | 0.18 | 0.14 | 0.29 | 0.17 | 0.14 | -0.04 | 0.03 | 0.04 | 0.06 | -0.09 |
| 0.25 | -0.21 | -0.08 | 0.03 | 0.39 | 0.10 | 0.45 | -0.17 | -0.14 | 0.05 | -0.02 | -0.04 | 0.03 | 0.18 | 0.12 | 0.27 | 0.14 | 0.13 | -0.03 | 0.05 | 0.04 | 0.05 | -0.07 |
| 0.3 | -0.19 | -0.07 | 0.05 | 0.34 | 0.11 | 0.46 | -0.20 | -0.14 | 0.02 | -0.06 | -0.02 | 0.02 | 0.16 | 0.09 | 0.26 | 0.14 | 0.13 | -0.02 | 0.07 | 0.03 | 0.03 | -0.08 |
| 0.35 | -0.19 | -0.06 | 0.08 | 0.29 | 0.15 | 0.46 | -0.22 | -0.13 | 0.00 | -0.07 | 0.02 | -0.01 | 0.16 | 0.09 | 0.23 | 0.12 | 0.13 | -0.02 | 0.09 | 0.02 | 0.02 | -0.08 |
| 0.4 | -0.20 | -0.05 | 0.10 | 0.29 | 0.17 | 0.46 | -0.23 | -0.10 | 0.00 | -0.06 | 0.03 | -0.03 | 0.14 | 0.06 | 0.21 | 0.13 | 0.12 | -0.01 | 0.10 | 0.01 | 0.02 | -0.08 |
| 0.45 | -0.19 | -0.07 | 0.09 | 0.31 | 0.19 | 0.45 | -0.24 | -0.10 | 0.00 | -0.07 | 0.03 | -0.04 | 0.13 | 0.04 | 0.21 | 0.13 | 0.13 | 0.00 | 0.12 | 0.02 | 0.02 | -0.09 |
| 0.5 | -0.17 | -0.08 | 0.07 | 0.29 | 0.22 | 0.44 | -0.25 | -0.10 | 0.00 | -0.06 | 0.00 | -0.05 | 0.14 | 0.04 | 0.21 | 0.15 | 0.12 | 0.00 | 0.11 | 0.01 | 0.01 | -0.09 |
| 0.55 | -0.17 | -0.06 | 0.06 | 0.28 | 0.25 | 0.41 | -0.27 | -0.10 | 0.00 | -0.05 | 0.01 | -0.05 | 0.17 | 0.04 | 0.24 | 0.15 | 0.12 | -0.01 | 0.12 | 0.02 | 0.01 | -0.11 |
| 0.6 | -0.17 | -0.06 | 0.05 | 0.25 | 0.26 | 0.37 | -0.28 | -0.08 | 0.00 | -0.06 | -0.02 | -0.06 | 0.19 | 0.04 | 0.24 | 0.18 | 0.15 | -0.01 | 0.13 | 0.01 | 0.01 | -0.13 |
| 0.65 | -0.17 | -0.07 | 0.02 | 0.20 | 0.22 | 0.37 | -0.28 | -0.06 | -0.01 | -0.09 | -0.04 | -0.07 | 0.20 | 0.01 | 0.24 | 0.19 | 0.16 | -0.01 | 0.15 | 0.00 | 0.00 | -0.14 |
| 0.7 | -0.15 | -0.08 | -0.01 | 0.09 | 0.16 | 0.38 | -0.31 | -0.03 | -0.01 | -0.06 | -0.04 | -0.07 | 0.24 | 0.00 | 0.29 | 0.20 | 0.16 | 0.00 | 0.17 | 0.00 | -0.01 | -0.17 |
| 0.75 | -0.13 | -0.06 | -0.05 | 0.02 | 0.16 | 0.39 | -0.35 | 0.01 | -0.04 | -0.06 | -0.07 | -0.06 | 0.27 | 0.01 | 0.31 | 0.18 | 0.13 | -0.02 | 0.19 | -0.04 | 0.00 | -0.15 |
| 0.8 | -0.15 | 0.00 | -0.12 | -0.03 | 0.16 | 0.34 | -0.37 | 0.04 | -0.09 | -0.03 | -0.06 | -0.03 | 0.29 | 0.05 | 0.34 | 0.15 | 0.09 | -0.07 | 0.18 | -0.08 | 0.04 | -0.16 |
| 0.85 | -0.17 | 0.03 | -0.17 | 0.00 | 0.12 | 0.30 | -0.38 | 0.08 | -0.17 | 0.04 | -0.09 | -0.02 | 0.30 | 0.01 | 0.38 | 0.14 | 0.11 | -0.12 | 0.11 | -0.08 | 0.09 | -0.23 |
| 0.9 | -0.14 | 0.12 | -0.23 | 0.07 | 0.06 | 0.32 | -0.42 | 0.09 | -0.27 | 0.08 | -0.24 | -0.04 | 0.31 | 0.01 | 0.47 | 0.12 | 0.14 | 0.03 | 0.12 | -0.03 | 0.20 | -0.20 |
| 0.95 | -0.30 | 0.02 | -0.26 | 0.10 | -0.09 | 0.60 | -0.38 | -0.03 | -0.42 | 0.12 | -0.45 | -0.14 | 0.00 | -0.10 | 0.49 | 0.03 | 0.16 | 0.14 | 0.17 | 0.06 | 0.08 | -0.20 |

Table A11 – CC correction factors for 2020 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM)- group E-Hype catchment 9744931

| duration | summer | | | | | | | | | | | winter | | | | | | | | | | |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| | CSC_REMO2009_MPI-ESM-IR_rcp26 | CSC_REMO2009_MPI-ESM-IR_rcp45 | CSC_REMO2009_MPI-ESM-IR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-IR_rcp26 | CSC_REMO2009_MPI-ESM-IR_rcp45 | CSC_REMO2009_MPI-ESM-IR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
| 0.05 | -0.04 | -0.28 | -0.17 | 0.87 | -0.14 | 0.10 | 0.00 | 0.12 | -0.07 | 0.11 | 0.29 | -0.08 | 0.20 | 0.28 | 0.31 | 0.16 | 0.30 | 0.05 | 0.06 | 0.42 | -0.17 | 0.17 |
| 0.1 | -0.07 | -0.35 | -0.26 | 0.89 | -0.13 | 0.08 | -0.02 | -0.04 | -0.16 | -0.01 | 0.08 | -0.04 | 0.26 | 0.29 | 0.36 | 0.14 | 0.33 | 0.05 | 0.02 | 0.29 | -0.15 | 0.17 |
| 0.15 | -0.14 | -0.33 | -0.25 | 0.74 | -0.06 | 0.22 | -0.10 | -0.12 | -0.07 | -0.10 | -0.01 | -0.07 | 0.24 | 0.30 | 0.34 | 0.12 | 0.30 | 0.05 | 0.01 | 0.25 | -0.17 | 0.15 |
| 0.2 | -0.13 | -0.20 | -0.14 | 0.67 | 0.03 | 0.37 | -0.07 | -0.13 | -0.04 | -0.11 | 0.01 | -0.08 | 0.22 | 0.27 | 0.31 | 0.13 | 0.27 | 0.05 | 0.02 | 0.21 | -0.17 | 0.11 |
| 0.25 | -0.11 | -0.13 | -0.04 | 0.58 | 0.07 | 0.39 | -0.04 | -0.10 | 0.01 | -0.15 | 0.03 | -0.08 | 0.21 | 0.24 | 0.30 | 0.13 | 0.23 | 0.05 | 0.03 | 0.20 | -0.16 | 0.08 |
| 0.3 | -0.11 | -0.10 | -0.03 | 0.58 | 0.08 | 0.43 | -0.06 | -0.11 | 0.03 | -0.16 | 0.07 | -0.07 | 0.21 | 0.19 | 0.29 | 0.13 | 0.21 | 0.06 | 0.03 | 0.16 | -0.17 | 0.04 |
| 0.35 | -0.13 | -0.05 | 0.00 | 0.55 | 0.11 | 0.44 | -0.08 | -0.13 | 0.04 | -0.17 | 0.09 | -0.10 | 0.22 | 0.19 | 0.26 | 0.13 | 0.19 | 0.07 | 0.03 | 0.14 | -0.20 | 0.01 |
| 0.4 | -0.14 | -0.01 | 0.02 | 0.49 | 0.12 | 0.46 | -0.09 | -0.13 | 0.03 | -0.16 | 0.09 | -0.11 | 0.21 | 0.16 | 0.28 | 0.15 | 0.19 | 0.06 | 0.02 | 0.12 | -0.22 | -0.01 |
| 0.45 | -0.14 | 0.00 | 0.02 | 0.47 | 0.15 | 0.48 | -0.11 | -0.14 | 0.02 | -0.17 | 0.09 | -0.13 | 0.19 | 0.14 | 0.29 | 0.16 | 0.19 | 0.07 | 0.03 | 0.11 | -0.23 | -0.03 |
| 0.5 | -0.13 | 0.02 | 0.02 | 0.42 | 0.17 | 0.49 | -0.11 | -0.15 | 0.00 | -0.19 | 0.07 | -0.14 | 0.20 | 0.16 | 0.31 | 0.16 | 0.17 | 0.08 | 0.03 | 0.09 | -0.24 | -0.02 |
| 0.55 | -0.14 | 0.04 | 0.02 | 0.39 | 0.21 | 0.49 | -0.12 | -0.16 | -0.03 | -0.21 | 0.09 | -0.14 | 0.24 | 0.17 | 0.33 | 0.17 | 0.18 | 0.06 | 0.04 | 0.09 | -0.25 | -0.03 |
| 0.6 | -0.16 | 0.07 | 0.02 | 0.39 | 0.24 | 0.51 | -0.13 | -0.16 | -0.04 | -0.24 | 0.07 | -0.14 | 0.26 | 0.20 | 0.33 | 0.19 | 0.22 | 0.06 | 0.05 | 0.07 | -0.25 | -0.03 |
| 0.65 | -0.18 | 0.09 | 0.02 | 0.40 | 0.26 | 0.56 | -0.14 | -0.15 | -0.06 | -0.26 | 0.10 | -0.13 | 0.26 | 0.22 | 0.34 | 0.20 | 0.24 | 0.04 | 0.07 | 0.07 | -0.28 | -0.01 |
| 0.7 | -0.18 | 0.10 | 0.01 | 0.40 | 0.25 | 0.62 | -0.16 | -0.14 | -0.10 | -0.29 | 0.12 | -0.14 | 0.30 | 0.26 | 0.39 | 0.17 | 0.23 | 0.05 | 0.10 | 0.07 | -0.30 | -0.03 |
| 0.75 | -0.20 | 0.14 | 0.01 | 0.44 | 0.31 | 0.70 | -0.17 | -0.12 | -0.13 | -0.33 | 0.09 | -0.14 | 0.37 | 0.35 | 0.46 | 0.11 | 0.21 | 0.06 | 0.10 | 0.03 | -0.32 | -0.04 |
| 0.8 | -0.19 | 0.24 | 0.05 | 0.49 | 0.36 | 0.72 | -0.20 | -0.09 | -0.15 | -0.34 | 0.11 | -0.14 | 0.39 | 0.41 | 0.49 | 0.01 | 0.17 | 0.06 | 0.06 | -0.01 | -0.32 | -0.11 |
| 0.85 | -0.10 | 0.35 | 0.13 | 0.67 | 0.39 | 0.77 | -0.19 | -0.08 | -0.16 | -0.30 | 0.12 | -0.18 | 0.37 | 0.35 | 0.57 | -0.06 | 0.16 | 0.02 | -0.01 | -0.05 | -0.33 | -0.15 |
| 0.9 | 0.00 | 0.48 | 0.19 | 0.88 | 0.41 | 0.79 | -0.24 | -0.05 | -0.18 | -0.32 | 0.02 | -0.20 | 0.43 | 0.33 | 0.54 | -0.09 | 0.12 | 0.08 | -0.05 | -0.13 | -0.30 | -0.20 |
| 0.95 | -0.27 | -0.02 | 0.17 | 0.90 | 0.48 | 0.77 | -0.27 | 0.05 | -0.13 | -0.42 | -0.09 | -0.36 | 0.16 | 0.15 | 0.23 | -0.12 | 0.03 | 0.12 | 0.27 | -0.06 | -0.44 | -0.15 |

Table A12 – CC correction factors for 2050 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM), group E-Hype catchment 9744931

| duration | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| 0.05 | 0.08 | -0.36 | -0.40 | 2.41 | -0.17 | 0.13 | 0.19 | 0.17 | -0.31 | -0.14 | -0.09 | -0.14 | 0.14 | 0.20 | 0.43 | 0.39 | 0.28 | 0.44 | 0.03 | 0.10 | 0.06 | -0.15 |
| 0.1 | -0.03 | -0.35 | -0.45 | 2.05 | -0.01 | 0.00 | 0.19 | 0.05 | -0.34 | -0.04 | -0.30 | -0.09 | 0.14 | 0.12 | 0.43 | 0.36 | 0.29 | 0.38 | 0.03 | 0.03 | 0.06 | -0.15 |
| 0.15 | -0.13 | -0.35 | -0.41 | 1.64 | 0.07 | 0.13 | 0.21 | -0.05 | -0.27 | -0.08 | -0.44 | -0.09 | 0.10 | 0.11 | 0.44 | 0.35 | 0.23 | 0.37 | -0.01 | -0.01 | 0.02 | -0.17 |
| 0.2 | -0.09 | -0.29 | -0.29 | 1.54 | 0.11 | 0.25 | 0.24 | -0.08 | -0.24 | -0.14 | -0.39 | -0.09 | 0.04 | 0.08 | 0.41 | 0.35 | 0.17 | 0.39 | -0.01 | -0.05 | -0.02 | -0.18 |
| 0.25 | -0.05 | -0.24 | -0.21 | 1.41 | 0.15 | 0.25 | 0.26 | -0.09 | -0.21 | -0.13 | -0.35 | -0.09 | 0.00 | 0.08 | 0.40 | 0.32 | 0.11 | 0.36 | 0.01 | -0.06 | -0.04 | -0.16 |
| 0.3 | -0.03 | -0.24 | -0.18 | 1.37 | 0.16 | 0.27 | 0.24 | -0.11 | -0.27 | -0.11 | -0.32 | -0.09 | -0.01 | 0.07 | 0.40 | 0.29 | 0.09 | 0.35 | 0.00 | -0.10 | -0.04 | -0.17 |
| 0.35 | -0.04 | -0.22 | -0.15 | 1.27 | 0.18 | 0.29 | 0.19 | -0.12 | -0.31 | -0.10 | -0.30 | -0.11 | -0.01 | 0.06 | 0.40 | 0.25 | 0.07 | 0.32 | 0.02 | -0.13 | -0.05 | -0.18 |
| 0.4 | -0.06 | -0.21 | -0.13 | 1.12 | 0.20 | 0.32 | 0.18 | -0.12 | -0.34 | -0.07 | -0.29 | -0.11 | -0.03 | 0.04 | 0.42 | 0.26 | 0.06 | 0.29 | 0.02 | -0.16 | -0.06 | -0.19 |
| 0.45 | -0.06 | -0.22 | -0.14 | 1.02 | 0.20 | 0.33 | 0.17 | -0.12 | -0.36 | -0.08 | -0.28 | -0.10 | -0.05 | 0.01 | 0.46 | 0.26 | 0.05 | 0.29 | 0.02 | -0.18 | -0.06 | -0.20 |
| 0.5 | -0.05 | -0.23 | -0.14 | 0.93 | 0.22 | 0.34 | 0.18 | -0.14 | -0.39 | -0.07 | -0.27 | -0.11 | -0.07 | 0.00 | 0.50 | 0.28 | 0.04 | 0.28 | 0.00 | -0.20 | -0.08 | -0.20 |
| 0.55 | -0.06 | -0.24 | -0.13 | 0.90 | 0.24 | 0.35 | 0.16 | -0.15 | -0.41 | -0.06 | -0.25 | -0.11 | -0.06 | 0.01 | 0.56 | 0.29 | 0.03 | 0.28 | -0.01 | -0.21 | -0.12 | -0.22 |
| 0.6 | -0.06 | -0.25 | -0.12 | 0.92 | 0.28 | 0.37 | 0.15 | -0.15 | -0.43 | -0.09 | -0.28 | -0.11 | -0.06 | 0.02 | 0.58 | 0.29 | 0.06 | 0.27 | 0.02 | -0.24 | -0.17 | -0.24 |
| 0.65 | -0.09 | -0.27 | -0.13 | 0.85 | 0.29 | 0.41 | 0.14 | -0.15 | -0.44 | -0.10 | -0.32 | -0.11 | -0.09 | 0.02 | 0.64 | 0.30 | 0.07 | 0.27 | -0.03 | -0.28 | -0.21 | -0.25 |
| 0.7 | -0.09 | -0.31 | -0.13 | 0.81 | 0.28 | 0.41 | 0.11 | -0.14 | -0.44 | -0.11 | -0.31 | -0.10 | -0.10 | 0.05 | 0.77 | 0.30 | 0.07 | 0.27 | -0.03 | -0.34 | -0.24 | -0.29 |
| 0.75 | -0.08 | -0.32 | -0.13 | 0.85 | 0.35 | 0.39 | 0.09 | -0.14 | -0.44 | -0.17 | -0.35 | -0.06 | -0.11 | 0.05 | 0.87 | 0.23 | 0.05 | 0.28 | -0.03 | -0.42 | -0.27 | -0.33 |
| 0.8 | -0.17 | -0.30 | -0.09 | 0.93 | 0.42 | 0.26 | 0.08 | -0.13 | -0.45 | -0.20 | -0.37 | 0.01 | -0.12 | 0.05 | 0.90 | 0.21 | 0.03 | 0.33 | -0.03 | -0.46 | -0.29 | -0.39 |
| 0.85 | -0.19 | -0.28 | -0.04 | 1.18 | 0.47 | 0.11 | 0.05 | -0.18 | -0.45 | -0.24 | -0.41 | 0.05 | -0.09 | 0.05 | 1.12 | 0.20 | -0.04 | 0.35 | -0.07 | -0.48 | -0.32 | -0.43 |
| 0.9 | -0.18 | -0.22 | 0.00 | 1.51 | 0.55 | -0.03 | -0.06 | -0.27 | -0.42 | -0.33 | -0.49 | 0.03 | 0.04 | -0.07 | 1.38 | 0.20 | -0.07 | 0.51 | -0.06 | -0.53 | -0.32 | -0.49 |
| 0.95 | -0.39 | -0.21 | -0.09 | 1.39 | 0.70 | -0.27 | -0.68 | -0.49 | -0.43 | -0.76 | -0.76 | -0.04 | -0.10 | -0.27 | 1.62 | 0.32 | 0.08 | 0.49 | 0.05 | -0.65 | -0.32 | -0.56 |

Table A13 – CC correction factors for 2080 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM), group E-Hype catchment 9744931

Sub-catchment All Marzeno

| duration | summer | | | | | | | | | | | winter | | | | | | | | | | |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
| 0.05 | -0.25 | -0.42 | -0.15 | 0.46 | -0.29 | 0.12 | -0.03 | 0.11 | 0.12 | 0.06 | 0.06 | 0.01 | 0.30 | 0.26 | 0.24 | 0.21 | 0.17 | 0.04 | 0.05 | 0.17 | -0.03 | -0.03 |
| 0.1 | -0.28 | -0.38 | -0.16 | 0.29 | -0.19 | 0.15 | -0.14 | 0.08 | 0.00 | 0.03 | -0.05 | 0.06 | 0.27 | 0.22 | 0.29 | 0.22 | 0.22 | -0.01 | 0.07 | 0.10 | 0.04 | -0.02 |
| 0.15 | -0.27 | -0.26 | -0.11 | 0.18 | 0.01 | 0.22 | -0.10 | -0.05 | 0.00 | 0.01 | -0.07 | 0.03 | 0.22 | 0.18 | 0.28 | 0.19 | 0.20 | -0.04 | 0.06 | 0.02 | 0.05 | -0.07 |
| 0.2 | -0.19 | -0.20 | -0.07 | 0.16 | 0.05 | 0.37 | -0.11 | -0.01 | 0.04 | -0.05 | -0.05 | 0.06 | 0.18 | 0.11 | 0.23 | 0.20 | 0.16 | -0.02 | 0.04 | 0.01 | 0.07 | -0.10 |
| 0.25 | -0.15 | -0.18 | 0.02 | 0.26 | 0.06 | 0.30 | -0.20 | -0.07 | -0.01 | -0.08 | -0.05 | 0.04 | 0.17 | 0.10 | 0.20 | 0.16 | 0.15 | -0.03 | 0.07 | 0.02 | 0.07 | -0.11 |
| 0.3 | -0.18 | -0.10 | -0.02 | 0.21 | 0.08 | 0.36 | -0.19 | -0.09 | 0.01 | -0.18 | -0.02 | 0.02 | 0.16 | 0.08 | 0.17 | 0.14 | 0.15 | -0.03 | 0.07 | 0.02 | 0.04 | -0.10 |
| 0.35 | -0.19 | -0.14 | -0.02 | 0.16 | 0.13 | 0.38 | -0.21 | -0.13 | -0.02 | -0.05 | 0.04 | 0.00 | 0.17 | 0.06 | 0.18 | 0.14 | 0.13 | -0.02 | 0.10 | 0.03 | 0.02 | -0.10 |
| 0.4 | -0.19 | -0.12 | 0.01 | 0.19 | 0.11 | 0.35 | -0.22 | -0.13 | -0.04 | 0.00 | 0.05 | -0.02 | 0.19 | 0.04 | 0.19 | 0.14 | 0.13 | -0.01 | 0.09 | 0.03 | 0.00 | -0.11 |
| 0.45 | -0.16 | -0.11 | 0.00 | 0.23 | 0.07 | 0.37 | -0.20 | -0.11 | -0.03 | -0.07 | 0.03 | -0.03 | 0.20 | 0.01 | 0.19 | 0.14 | 0.12 | 0.00 | 0.09 | 0.04 | -0.02 | -0.12 |
| 0.5 | -0.15 | -0.11 | 0.01 | 0.23 | 0.09 | 0.35 | -0.20 | -0.09 | -0.01 | -0.09 | 0.03 | -0.05 | 0.22 | -0.01 | 0.17 | 0.14 | 0.12 | 0.01 | 0.11 | 0.04 | -0.03 | -0.12 |
| 0.55 | -0.17 | -0.07 | 0.02 | 0.25 | 0.11 | 0.34 | -0.20 | -0.06 | -0.01 | -0.11 | 0.02 | -0.05 | 0.25 | -0.01 | 0.15 | 0.13 | 0.11 | 0.00 | 0.09 | 0.04 | -0.02 | -0.12 |
| 0.6 | -0.15 | -0.07 | 0.00 | 0.27 | 0.10 | 0.31 | -0.22 | -0.03 | -0.01 | -0.13 | -0.01 | -0.06 | 0.30 | -0.01 | 0.17 | 0.11 | 0.09 | 0.01 | 0.11 | 0.05 | -0.02 | -0.14 |
| 0.65 | -0.17 | -0.07 | 0.00 | 0.26 | 0.12 | 0.28 | -0.25 | 0.00 | -0.01 | -0.14 | -0.04 | -0.05 | 0.34 | 0.03 | 0.23 | 0.10 | 0.07 | 0.00 | 0.13 | 0.04 | -0.03 | -0.14 |
| 0.7 | -0.17 | -0.05 | -0.04 | 0.20 | 0.12 | 0.24 | -0.32 | 0.03 | 0.01 | -0.13 | -0.08 | 0.00 | 0.35 | 0.04 | 0.23 | 0.10 | 0.08 | -0.02 | 0.15 | -0.02 | -0.02 | -0.16 |
| 0.75 | -0.17 | -0.02 | -0.05 | 0.17 | 0.13 | 0.21 | -0.35 | 0.08 | 0.01 | -0.13 | -0.11 | 0.02 | 0.38 | 0.04 | 0.25 | 0.13 | 0.06 | -0.04 | 0.20 | -0.04 | -0.03 | -0.20 |
| 0.8 | -0.20 | 0.02 | -0.06 | 0.12 | 0.17 | 0.16 | -0.43 | 0.13 | -0.04 | -0.06 | -0.09 | 0.05 | 0.44 | 0.02 | 0.30 | 0.13 | 0.00 | -0.07 | 0.28 | 0.00 | -0.02 | -0.22 |
| 0.85 | -0.27 | 0.10 | -0.15 | 0.07 | 0.17 | 0.12 | -0.52 | 0.15 | -0.09 | 0.02 | -0.06 | 0.02 | 0.32 | -0.06 | 0.40 | 0.11 | 0.02 | -0.13 | 0.24 | -0.16 | 0.05 | -0.28 |
| 0.9 | -0.19 | 0.23 | -0.58 | 0.29 | 0.15 | 0.26 | -0.60 | 0.10 | -0.21 | 0.08 | -0.19 | -0.13 | 0.10 | -0.17 | 0.41 | 0.07 | 0.10 | -0.05 | 0.11 | -0.20 | 0.01 | -0.36 |
| 0.95 | -0.94 | 0.35 | -1.00 | 3.33 | -0.06 | 3.48 | -0.77 | -0.43 | -0.82 | 0.20 | -0.88 | -0.23 | -0.14 | -0.06 | 0.49 | 0.11 | 0.35 | 0.24 | 0.44 | 0.07 | 0.12 | -0.26 |

Table A14 – CC correction factors for 2020 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM)- group E-Hype catchment 9780041

| duration | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHL_RCA4_HadGEM2-ES_rcp45 | SMHL_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHL_RCA4_HadGEM2-ES_rcp45 | SMHL_RCA4_HadGEM2-ES_rcp85 |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| 0.05 | -0.03 | -0.36 | -0.22 | 1.15 | -0.23 | 0.01 | 0.07 | 0.18 | -0.14 | 0.13 | 0.29 | -0.07 | 0.27 | 0.32 | 0.27 | 0.19 | 0.32 | 0.07 | 0.07 | 0.50 | -0.19 | 0.16 |
| 0.1 | -0.07 | -0.42 | -0.34 | 1.03 | -0.22 | 0.05 | 0.02 | -0.02 | -0.23 | -0.03 | -0.01 | -0.05 | 0.33 | 0.36 | 0.33 | 0.17 | 0.36 | 0.08 | 0.06 | 0.37 | -0.20 | 0.20 |
| 0.15 | -0.11 | -0.28 | -0.26 | 0.64 | -0.04 | 0.12 | -0.03 | -0.10 | -0.16 | -0.05 | -0.07 | -0.11 | 0.33 | 0.35 | 0.29 | 0.13 | 0.34 | 0.07 | 0.02 | 0.29 | -0.22 | 0.18 |
| 0.2 | -0.11 | -0.19 | -0.18 | 0.45 | -0.01 | 0.28 | 0.02 | -0.07 | -0.05 | -0.15 | -0.07 | -0.08 | 0.25 | 0.28 | 0.23 | 0.14 | 0.28 | 0.09 | 0.03 | 0.24 | -0.20 | 0.13 |
| 0.25 | -0.09 | -0.10 | -0.09 | 0.53 | 0.08 | 0.27 | -0.03 | -0.11 | -0.14 | -0.18 | -0.03 | -0.09 | 0.25 | 0.22 | 0.20 | 0.12 | 0.25 | 0.08 | 0.04 | 0.19 | -0.19 | 0.06 |
| 0.3 | -0.06 | -0.03 | -0.08 | 0.52 | 0.10 | 0.28 | 0.02 | -0.11 | -0.15 | -0.17 | -0.06 | -0.08 | 0.26 | 0.19 | 0.17 | 0.13 | 0.21 | 0.08 | 0.03 | 0.14 | -0.21 | 0.03 |
| 0.35 | -0.08 | -0.11 | -0.09 | 0.44 | 0.13 | 0.34 | -0.05 | -0.16 | -0.11 | -0.14 | -0.01 | -0.10 | 0.26 | 0.16 | 0.19 | 0.15 | 0.20 | 0.09 | 0.03 | 0.13 | -0.25 | -0.03 |
| 0.4 | -0.12 | -0.08 | -0.05 | 0.47 | 0.07 | 0.35 | -0.09 | -0.16 | -0.08 | -0.13 | 0.02 | -0.12 | 0.28 | 0.15 | 0.21 | 0.16 | 0.18 | 0.09 | 0.01 | 0.11 | -0.28 | -0.08 |
| 0.45 | -0.10 | -0.06 | -0.07 | 0.50 | 0.04 | 0.36 | -0.07 | -0.16 | -0.06 | -0.17 | 0.04 | -0.12 | 0.28 | 0.12 | 0.23 | 0.15 | 0.16 | 0.10 | 0.00 | 0.11 | -0.31 | -0.12 |
| 0.5 | -0.10 | -0.04 | -0.04 | 0.46 | 0.05 | 0.34 | -0.07 | -0.14 | -0.04 | -0.20 | 0.04 | -0.13 | 0.30 | 0.11 | 0.24 | 0.15 | 0.16 | 0.10 | -0.01 | 0.10 | -0.31 | -0.14 |
| 0.55 | -0.11 | 0.02 | -0.04 | 0.43 | 0.09 | 0.33 | -0.06 | -0.12 | -0.04 | -0.22 | 0.03 | -0.12 | 0.33 | 0.11 | 0.24 | 0.15 | 0.16 | 0.07 | -0.02 | 0.09 | -0.31 | -0.13 |
| 0.6 | -0.11 | 0.04 | -0.04 | 0.41 | 0.10 | 0.31 | -0.06 | -0.10 | -0.04 | -0.22 | 0.01 | -0.13 | 0.38 | 0.11 | 0.27 | 0.13 | 0.14 | 0.07 | 0.00 | 0.10 | -0.30 | -0.12 |
| 0.65 | -0.11 | 0.06 | -0.05 | 0.43 | 0.13 | 0.31 | -0.07 | -0.09 | -0.07 | -0.24 | -0.01 | -0.14 | 0.42 | 0.19 | 0.34 | 0.14 | 0.14 | 0.07 | 0.02 | 0.11 | -0.30 | -0.12 |
| 0.7 | -0.14 | 0.11 | -0.05 | 0.47 | 0.15 | 0.36 | -0.08 | -0.09 | -0.11 | -0.27 | -0.05 | -0.08 | 0.45 | 0.26 | 0.41 | 0.14 | 0.17 | 0.08 | 0.04 | 0.07 | -0.30 | -0.10 |
| 0.75 | -0.16 | 0.20 | -0.02 | 0.60 | 0.20 | 0.38 | -0.09 | -0.09 | -0.16 | -0.33 | -0.07 | -0.08 | 0.48 | 0.40 | 0.47 | 0.15 | 0.16 | 0.06 | 0.11 | 0.07 | -0.32 | -0.14 |
| 0.8 | -0.19 | 0.38 | 0.03 | 0.78 | 0.28 | 0.44 | -0.09 | -0.10 | -0.20 | -0.36 | -0.02 | -0.05 | 0.56 | 0.52 | 0.51 | 0.11 | 0.13 | 0.10 | 0.16 | 0.08 | -0.36 | -0.16 |
| 0.85 | -0.11 | 0.62 | 0.18 | 1.07 | 0.39 | 0.51 | -0.11 | -0.12 | -0.18 | -0.43 | 0.05 | -0.14 | 0.49 | 0.59 | 0.63 | 0.04 | 0.14 | 0.05 | 0.04 | -0.03 | -0.37 | -0.14 |
| 0.9 | 0.06 | 1.15 | 0.52 | 1.78 | 0.54 | 0.66 | -0.16 | -0.19 | -0.33 | -0.69 | 0.01 | -0.30 | 0.15 | 0.39 | 0.45 | -0.06 | 0.13 | 0.11 | 0.04 | -0.12 | -0.43 | -0.26 |
| 0.95 | -0.65 | 0.06 | 1.35 | 13.33 | 1.24 | 2.60 | -0.36 | -0.25 | -0.71 | -1.00 | -0.07 | -0.23 | 0.25 | 0.07 | 0.42 | -0.08 | 0.08 | 0.29 | 0.27 | -0.13 | -0.50 | -0.33 |

Table A1515 – CC correction factors for 2050 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM), group E-Hype catchment 9780041

| duration | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHL_RCA4_HadGEM2-ES_rcp45 | SMHL_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHL_RCA4_HadGEM2-ES_rcp45 | SMHL_RCA4_HadGEM2-ES_rcp85 |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| 0.05 | 0.14 | -0.42 | -0.46 | 3.14 | -0.26 | 0.01 | 0.23 | 0.27 | -0.39 | -0.14 | -0.10 | -0.12 | 0.20 | 0.23 | 0.40 | 0.41 | 0.28 | 0.55 | 0.03 | 0.15 | 0.05 | -0.18 |
| 0.1 | 0.00 | -0.41 | -0.52 | 2.70 | -0.19 | -0.06 | 0.15 | 0.10 | -0.43 | -0.15 | -0.33 | -0.09 | 0.17 | 0.13 | 0.42 | 0.42 | 0.29 | 0.48 | 0.04 | 0.05 | 0.02 | -0.20 |
| 0.15 | -0.09 | -0.34 | -0.39 | 1.70 | -0.01 | 0.00 | 0.13 | -0.03 | -0.37 | -0.12 | -0.36 | -0.13 | 0.12 | 0.09 | 0.43 | 0.41 | 0.26 | 0.45 | -0.01 | -0.03 | -0.01 | -0.23 |
| 0.2 | -0.10 | -0.34 | -0.32 | 0.93 | 0.01 | 0.10 | 0.18 | -0.07 | -0.40 | -0.14 | -0.35 | -0.11 | 0.04 | 0.05 | 0.32 | 0.40 | 0.17 | 0.43 | -0.02 | -0.05 | -0.03 | -0.23 |
| 0.25 | -0.05 | -0.34 | -0.29 | 0.93 | 0.04 | 0.09 | 0.11 | -0.10 | -0.40 | -0.17 | -0.39 | -0.11 | 0.03 | 0.04 | 0.26 | 0.35 | 0.12 | 0.38 | -0.02 | -0.09 | -0.04 | -0.23 |
| 0.3 | 0.01 | -0.32 | -0.30 | 1.00 | 0.02 | 0.09 | 0.20 | -0.10 | -0.33 | -0.21 | -0.39 | -0.11 | 0.02 | 0.04 | 0.26 | 0.28 | 0.08 | 0.33 | -0.03 | -0.15 | -0.06 | -0.23 |
| 0.35 | 0.02 | -0.33 | -0.28 | 1.07 | 0.02 | 0.12 | 0.21 | -0.11 | -0.30 | -0.17 | -0.31 | -0.13 | 0.00 | 0.02 | 0.28 | 0.27 | 0.06 | 0.31 | -0.01 | -0.18 | -0.08 | -0.25 |
| 0.4 | -0.01 | -0.29 | -0.24 | 1.18 | 0.04 | 0.12 | 0.12 | -0.11 | -0.33 | -0.12 | -0.28 | -0.14 | -0.01 | 0.02 | 0.31 | 0.26 | 0.04 | 0.31 | -0.01 | -0.20 | -0.11 | -0.28 |
| 0.45 | 0.01 | -0.28 | -0.23 | 1.28 | 0.04 | 0.15 | 0.10 | -0.11 | -0.36 | -0.11 | -0.28 | -0.14 | -0.03 | -0.01 | 0.33 | 0.24 | 0.02 | 0.29 | -0.01 | -0.21 | -0.13 | -0.30 |
| 0.5 | 0.02 | -0.30 | -0.22 | 1.14 | 0.06 | 0.16 | 0.10 | -0.11 | -0.39 | -0.11 | -0.28 | -0.14 | -0.04 | -0.03 | 0.34 | 0.22 | 0.00 | 0.26 | -0.02 | -0.23 | -0.15 | -0.31 |
| 0.55 | 0.00 | -0.31 | -0.22 | 0.91 | 0.09 | 0.15 | 0.12 | -0.11 | -0.41 | -0.10 | -0.30 | -0.13 | -0.04 | -0.05 | 0.34 | 0.21 | -0.02 | 0.24 | -0.04 | -0.25 | -0.16 | -0.30 |
| 0.6 | 0.01 | -0.32 | -0.22 | 0.81 | 0.09 | 0.14 | 0.13 | -0.10 | -0.44 | -0.10 | -0.32 | -0.12 | -0.03 | -0.05 | 0.40 | 0.17 | -0.03 | 0.25 | -0.05 | -0.27 | -0.19 | -0.28 |
| 0.65 | -0.01 | -0.36 | -0.21 | 0.76 | 0.10 | 0.15 | 0.11 | -0.10 | -0.47 | -0.10 | -0.35 | -0.12 | -0.03 | 0.01 | 0.50 | 0.19 | -0.05 | 0.26 | -0.04 | -0.32 | -0.21 | -0.27 |
| 0.7 | -0.05 | -0.40 | -0.21 | 0.75 | 0.13 | 0.17 | 0.10 | -0.10 | -0.50 | -0.11 | -0.41 | -0.07 | -0.06 | 0.05 | 0.54 | 0.21 | -0.05 | 0.26 | -0.01 | -0.35 | -0.23 | -0.30 |
| 0.75 | -0.12 | -0.44 | -0.20 | 0.86 | 0.17 | 0.18 | 0.08 | -0.10 | -0.52 | -0.12 | -0.47 | -0.06 | -0.09 | 0.08 | 0.65 | 0.26 | -0.04 | 0.30 | 0.04 | -0.35 | -0.25 | -0.35 |
| 0.8 | -0.28 | -0.44 | -0.17 | 1.07 | 0.21 | 0.13 | 0.07 | -0.10 | -0.53 | -0.09 | -0.54 | -0.05 | -0.08 | 0.08 | 0.86 | 0.24 | -0.06 | 0.40 | 0.12 | -0.35 | -0.30 | -0.42 |
| 0.85 | -0.31 | -0.44 | -0.11 | 1.59 | 0.25 | 0.00 | 0.08 | -0.15 | -0.46 | -0.14 | -0.65 | 0.02 | -0.12 | -0.02 | 1.14 | 0.24 | -0.08 | 0.42 | 0.07 | -0.48 | -0.35 | -0.52 |
| 0.9 | -0.13 | -0.49 | 0.04 | 2.89 | 0.33 | -0.02 | -0.03 | -0.24 | -0.60 | -0.31 | -0.86 | 0.04 | -0.23 | -0.16 | 1.33 | 0.16 | -0.12 | 0.30 | 0.10 | -0.59 | -0.46 | -0.59 |
| 0.95 | -1.00 | -1.00 | -0.53 | 19.67 | 0.85 | 0.40 | -1.00 | -0.53 | -1.00 | -0.73 | -1.00 | -0.08 | -0.25 | -0.20 | 1.50 | 0.15 | 0.05 | 0.33 | 0.06 | -0.48 | -0.38 | -0.54 |

Table A16 – CC correction factors for 2080 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM), group E-Hype catchment 9744931

Sub-catchment all remaining

| duration | summer | | | | | | | | | | | winter | | | | | | | | | | |
|----------|-------------------------------|-------------------------------|-------------------------------|--------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|--------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-CM5A-MR_rcp45 | KNMI_RACM022E_EC-EARTH_rcp45 | KNMI_RACM022E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-CM5A-MR_rcp45 | KNMI_RACM022E_EC-EARTH_rcp45 | KNMI_RACM022E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
| 0.05 | -0.21 | -0.39 | -0.14 | 0.41 | -0.29 | 0.03 | -0.06 | 0.07 | 0.11 | 0.04 | 0.04 | 0.02 | 0.23 | 0.18 | 0.22 | 0.17 | 0.20 | 0.03 | 0.04 | 0.15 | -0.01 | 0.03 |
| 0.1 | -0.29 | -0.36 | -0.14 | 0.20 | -0.24 | 0.08 | -0.11 | 0.04 | -0.02 | 0.06 | -0.07 | 0.02 | 0.24 | 0.15 | 0.25 | 0.14 | 0.21 | -0.03 | 0.03 | 0.08 | 0.04 | -0.03 |
| 0.15 | -0.31 | -0.32 | -0.13 | 0.09 | -0.16 | 0.28 | -0.20 | -0.04 | -0.11 | 0.07 | -0.01 | 0.03 | 0.19 | 0.12 | 0.24 | 0.16 | 0.20 | -0.02 | 0.03 | 0.04 | 0.04 | -0.06 |
| 0.2 | -0.31 | -0.31 | -0.14 | 0.10 | -0.11 | 0.33 | -0.19 | -0.10 | -0.13 | 0.11 | -0.07 | 0.02 | 0.16 | 0.09 | 0.18 | 0.14 | 0.21 | -0.03 | 0.03 | 0.04 | 0.07 | -0.09 |
| 0.25 | -0.22 | -0.27 | -0.05 | 0.13 | -0.05 | 0.38 | -0.15 | -0.11 | -0.05 | 0.02 | -0.06 | 0.02 | 0.14 | 0.07 | 0.16 | 0.14 | 0.18 | -0.03 | 0.04 | 0.03 | 0.07 | -0.10 |
| 0.3 | -0.16 | -0.20 | -0.01 | 0.16 | -0.03 | 0.39 | -0.20 | -0.18 | -0.07 | -0.04 | -0.04 | 0.00 | 0.14 | 0.07 | 0.14 | 0.14 | 0.16 | -0.01 | 0.07 | 0.04 | 0.05 | -0.10 |
| 0.35 | -0.19 | -0.12 | -0.01 | 0.14 | 0.03 | 0.36 | -0.22 | -0.19 | -0.07 | -0.13 | -0.02 | -0.02 | 0.15 | 0.05 | 0.13 | 0.16 | 0.14 | 0.00 | 0.07 | 0.05 | 0.04 | -0.12 |
| 0.4 | -0.20 | -0.12 | 0.00 | 0.11 | 0.05 | 0.35 | -0.18 | -0.16 | -0.04 | -0.08 | 0.03 | -0.04 | 0.16 | 0.05 | 0.14 | 0.15 | 0.14 | 0.01 | 0.07 | 0.07 | 0.03 | -0.10 |
| 0.45 | -0.20 | -0.10 | -0.01 | 0.14 | 0.06 | 0.34 | -0.18 | -0.15 | -0.02 | -0.05 | -0.01 | -0.04 | 0.18 | 0.02 | 0.14 | 0.16 | 0.14 | 0.03 | 0.09 | 0.10 | 0.00 | -0.10 |
| 0.5 | -0.19 | -0.08 | 0.00 | 0.16 | 0.05 | 0.33 | -0.17 | -0.13 | -0.01 | -0.05 | 0.00 | -0.05 | 0.21 | -0.01 | 0.13 | 0.15 | 0.10 | 0.05 | 0.09 | 0.10 | -0.03 | -0.11 |
| 0.55 | -0.17 | -0.06 | 0.01 | 0.19 | 0.06 | 0.30 | -0.17 | -0.12 | -0.01 | -0.08 | -0.01 | -0.07 | 0.27 | -0.01 | 0.13 | 0.14 | 0.09 | 0.05 | 0.10 | 0.11 | -0.02 | -0.12 |
| 0.6 | -0.16 | -0.06 | 0.00 | 0.19 | 0.07 | 0.28 | -0.18 | -0.10 | -0.01 | -0.08 | -0.01 | -0.08 | 0.31 | -0.02 | 0.13 | 0.12 | 0.09 | 0.05 | 0.09 | 0.10 | -0.02 | -0.12 |
| 0.65 | -0.15 | -0.05 | -0.01 | 0.16 | 0.10 | 0.25 | -0.19 | -0.10 | 0.00 | -0.08 | -0.02 | -0.08 | 0.35 | 0.00 | 0.10 | 0.11 | 0.07 | 0.03 | 0.08 | 0.10 | -0.03 | -0.16 |
| 0.7 | -0.16 | -0.03 | -0.02 | 0.10 | 0.10 | 0.24 | -0.22 | -0.09 | 0.01 | -0.07 | -0.04 | -0.09 | 0.42 | 0.00 | 0.10 | 0.07 | 0.05 | 0.02 | 0.06 | 0.06 | -0.02 | -0.16 |
| 0.75 | -0.17 | -0.01 | -0.04 | 0.04 | 0.09 | 0.26 | -0.25 | -0.08 | -0.01 | -0.03 | -0.04 | -0.05 | 0.43 | 0.00 | 0.12 | 0.07 | 0.04 | 0.00 | 0.08 | 0.05 | 0.00 | -0.16 |
| 0.8 | -0.16 | 0.05 | -0.08 | -0.02 | 0.11 | 0.24 | -0.30 | -0.06 | -0.04 | 0.01 | -0.05 | 0.06 | 0.41 | -0.01 | 0.12 | 0.06 | 0.04 | -0.05 | 0.11 | -0.01 | 0.01 | -0.20 |
| 0.85 | -0.13 | 0.12 | -0.13 | -0.04 | 0.12 | 0.24 | -0.33 | -0.06 | -0.10 | 0.05 | -0.08 | 0.12 | 0.40 | -0.05 | 0.12 | 0.09 | -0.02 | -0.13 | 0.12 | -0.04 | 0.05 | -0.21 |
| 0.9 | -0.08 | 0.29 | -0.34 | -0.11 | 0.03 | 0.30 | -0.40 | -0.09 | -0.19 | 0.11 | -0.21 | -0.01 | 0.31 | -0.02 | 0.19 | 0.03 | 0.01 | -0.14 | 0.05 | -0.14 | 0.05 | -0.31 |
| 0.95 | -0.17 | 0.31 | -0.48 | -0.25 | -0.13 | 0.47 | -0.44 | -0.22 | -0.50 | 0.17 | -0.54 | -0.12 | 0.04 | -0.03 | 0.38 | 0.00 | 0.27 | 0.13 | 0.01 | -0.13 | 0.05 | -0.25 |

Table A17 – CC correction factors for 2020 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM)- group E-Hype catchment 9780149

| duration | summer | | | | | | | | | | | winter | | | | | | | | | | |
|----------|-------------------------------|-------------------------------|-------------------------------|--------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|--------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-CM5A-MR_rcp45 | KNMI_RACM022E_EC-EARTH_rcp45 | KNMI_RACM022E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-CM5A-MR_rcp45 | KNMI_RACM022E_EC-EARTH_rcp45 | KNMI_RACM022E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
| 0.05 | -0.01 | -0.32 | -0.21 | 1.01 | -0.23 | -0.06 | 0.06 | 0.19 | -0.14 | 0.10 | 0.29 | -0.04 | 0.22 | 0.28 | 0.24 | 0.18 | 0.28 | 0.06 | 0.09 | 0.39 | -0.14 | 0.18 |
| 0.1 | -0.06 | -0.38 | -0.28 | 0.89 | -0.25 | -0.02 | 0.00 | -0.02 | -0.24 | 0.04 | 0.00 | -0.02 | 0.29 | 0.32 | 0.27 | 0.10 | 0.25 | 0.07 | 0.04 | 0.33 | -0.15 | 0.13 |
| 0.15 | -0.05 | -0.40 | -0.33 | 0.63 | -0.26 | 0.09 | -0.03 | -0.15 | -0.39 | -0.02 | -0.09 | -0.07 | 0.26 | 0.30 | 0.27 | 0.10 | 0.25 | 0.07 | 0.03 | 0.26 | -0.21 | 0.12 |
| 0.2 | -0.03 | -0.35 | -0.32 | 0.62 | -0.17 | 0.13 | -0.02 | -0.18 | -0.37 | -0.07 | -0.18 | -0.08 | 0.24 | 0.25 | 0.20 | 0.09 | 0.28 | 0.07 | 0.03 | 0.22 | -0.20 | 0.07 |
| 0.25 | -0.07 | -0.24 | -0.19 | 0.52 | -0.11 | 0.21 | 0.02 | -0.16 | -0.25 | -0.20 | -0.15 | -0.08 | 0.23 | 0.21 | 0.17 | 0.11 | 0.24 | 0.07 | 0.03 | 0.16 | -0.20 | 0.04 |
| 0.3 | -0.07 | -0.18 | -0.16 | 0.50 | -0.08 | 0.25 | -0.03 | -0.16 | -0.24 | -0.21 | -0.13 | -0.09 | 0.23 | 0.16 | 0.14 | 0.13 | 0.22 | 0.08 | 0.02 | 0.14 | -0.23 | 0.00 |
| 0.35 | -0.05 | -0.12 | -0.14 | 0.46 | -0.01 | 0.27 | -0.06 | -0.17 | -0.21 | -0.22 | -0.12 | -0.10 | 0.23 | 0.14 | 0.14 | 0.15 | 0.19 | 0.09 | 0.02 | 0.12 | -0.25 | -0.06 |
| 0.4 | -0.08 | -0.09 | -0.11 | 0.39 | 0.01 | 0.29 | -0.05 | -0.16 | -0.15 | -0.20 | -0.05 | -0.12 | 0.24 | 0.13 | 0.16 | 0.14 | 0.19 | 0.09 | 0.01 | 0.12 | -0.27 | -0.10 |
| 0.45 | -0.11 | -0.07 | -0.09 | 0.35 | 0.01 | 0.29 | -0.08 | -0.17 | -0.12 | -0.19 | -0.06 | -0.12 | 0.25 | 0.12 | 0.18 | 0.15 | 0.19 | 0.11 | 0.01 | 0.13 | -0.29 | -0.13 |
| 0.5 | -0.11 | -0.03 | -0.07 | 0.31 | 0.02 | 0.27 | -0.07 | -0.16 | -0.09 | -0.20 | -0.04 | -0.12 | 0.28 | 0.11 | 0.20 | 0.12 | 0.15 | 0.11 | -0.01 | 0.12 | -0.31 | -0.15 |
| 0.55 | -0.12 | 0.00 | -0.07 | 0.31 | 0.03 | 0.27 | -0.08 | -0.15 | -0.09 | -0.21 | -0.05 | -0.13 | 0.34 | 0.11 | 0.22 | 0.11 | 0.15 | 0.09 | -0.01 | 0.11 | -0.31 | -0.17 |
| 0.6 | -0.12 | 0.01 | -0.09 | 0.29 | 0.05 | 0.28 | -0.08 | -0.14 | -0.09 | -0.23 | -0.04 | -0.16 | 0.38 | 0.14 | 0.26 | 0.09 | 0.16 | 0.06 | -0.03 | 0.09 | -0.32 | -0.18 |
| 0.65 | -0.12 | 0.02 | -0.11 | 0.27 | 0.08 | 0.28 | -0.08 | -0.14 | -0.10 | -0.26 | -0.04 | -0.19 | 0.40 | 0.15 | 0.24 | 0.07 | 0.15 | 0.03 | -0.04 | 0.07 | -0.33 | -0.20 |
| 0.7 | -0.14 | 0.05 | -0.10 | 0.30 | 0.09 | 0.28 | -0.11 | -0.14 | -0.12 | -0.29 | -0.05 | -0.20 | 0.43 | 0.17 | 0.24 | 0.04 | 0.11 | 0.00 | -0.05 | 0.06 | -0.31 | -0.19 |
| 0.75 | -0.16 | 0.09 | -0.10 | 0.32 | 0.11 | 0.35 | -0.12 | -0.14 | -0.15 | -0.31 | -0.04 | -0.17 | 0.44 | 0.22 | 0.28 | 0.04 | 0.08 | -0.01 | -0.02 | 0.07 | -0.27 | -0.15 |
| 0.8 | -0.16 | 0.17 | -0.07 | 0.34 | 0.16 | 0.38 | -0.14 | -0.14 | -0.18 | -0.35 | -0.03 | -0.08 | 0.44 | 0.31 | 0.31 | -0.01 | 0.10 | -0.03 | 0.01 | 0.01 | -0.31 | -0.17 |
| 0.85 | -0.08 | 0.28 | 0.01 | 0.46 | 0.22 | 0.43 | -0.15 | -0.16 | -0.22 | -0.39 | -0.01 | -0.04 | 0.44 | 0.40 | 0.36 | -0.06 | 0.08 | -0.01 | 0.03 | -0.02 | -0.36 | -0.16 |
| 0.9 | 0.16 | 0.48 | 0.19 | 0.56 | 0.27 | 0.53 | -0.26 | -0.19 | -0.27 | -0.46 | -0.03 | -0.19 | 0.37 | 0.47 | 0.37 | -0.17 | 0.03 | -0.01 | -0.06 | -0.12 | -0.36 | -0.28 |
| 0.95 | -0.19 | 0.12 | 0.49 | 0.68 | 0.36 | 0.45 | -0.38 | -0.17 | -0.32 | -0.62 | -0.20 | -0.25 | 0.24 | 0.09 | 0.30 | -0.21 | 0.04 | 0.10 | 0.00 | -0.19 | -0.44 | -0.34 |

Table A1816 – CC correction factors for 2050 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM), group E-Hype catchment 9780149

| duration | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 | CSC_REMO2009_MPI-ESM-LR_rcp26 | CSC_REMO2009_MPI-ESM-LR_rcp45 | CSC_REMO2009_MPI-ESM-LR_rcp85 | IPSL-IPSL-CM5A-MR_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp45 | KNMI_RACMO22E_EC-EARTH_rcp85 | SMHI_RCA4_EC-EARTH_rcp26 | SMHI_RCA4_EC-EARTH_rcp45 | SMHI_RCA4_EC-EARTH_rcp85 | SMHI_RCA4_HadGEM2-ES_rcp45 | SMHI_RCA4_HadGEM2-ES_rcp85 |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------|------------------------------|------------------------------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------------|
| 0.05 | 0.17 | -0.35 | -0.44 | 2.44 | -0.27 | -0.02 | 0.18 | 0.23 | -0.39 | -0.15 | -0.03 | -0.07 | 0.14 | 0.19 | 0.33 | 0.40 | 0.26 | 0.43 | 0.04 | 0.13 | 0.05 | -0.11 |
| 0.1 | 0.03 | -0.37 | -0.55 | 2.18 | -0.22 | -0.05 | 0.09 | 0.04 | -0.49 | -0.11 | -0.29 | -0.09 | 0.11 | 0.15 | 0.33 | 0.38 | 0.27 | 0.36 | 0.01 | 0.06 | 0.06 | -0.21 |
| 0.15 | -0.05 | -0.39 | -0.58 | 1.59 | -0.18 | -0.04 | 0.04 | -0.03 | -0.59 | -0.15 | -0.40 | -0.09 | 0.09 | 0.11 | 0.37 | 0.35 | 0.24 | 0.39 | -0.01 | 0.00 | 0.01 | -0.20 |
| 0.2 | -0.08 | -0.42 | -0.49 | 1.56 | -0.11 | -0.03 | 0.07 | -0.07 | -0.58 | -0.21 | -0.46 | -0.10 | 0.04 | 0.06 | 0.30 | 0.31 | 0.20 | 0.36 | -0.03 | -0.03 | -0.02 | -0.22 |
| 0.25 | -0.04 | -0.37 | -0.40 | 1.13 | -0.06 | 0.02 | 0.17 | -0.09 | -0.51 | -0.21 | -0.47 | -0.10 | 0.02 | 0.05 | 0.26 | 0.31 | 0.15 | 0.33 | -0.04 | -0.10 | -0.05 | -0.22 |
| 0.3 | 0.01 | -0.34 | -0.33 | 1.01 | -0.06 | 0.04 | 0.11 | -0.14 | -0.47 | -0.23 | -0.45 | -0.11 | 0.01 | 0.03 | 0.23 | 0.27 | 0.10 | 0.31 | -0.04 | -0.14 | -0.08 | -0.23 |
| 0.35 | 0.05 | -0.30 | -0.28 | 1.00 | -0.03 | 0.08 | 0.09 | -0.13 | -0.44 | -0.26 | -0.39 | -0.13 | 0.00 | 0.01 | 0.25 | 0.28 | 0.08 | 0.29 | -0.03 | -0.17 | -0.09 | -0.25 |
| 0.4 | 0.04 | -0.28 | -0.24 | 0.95 | -0.01 | 0.09 | 0.11 | -0.13 | -0.40 | -0.19 | -0.32 | -0.15 | -0.01 | 0.01 | 0.28 | 0.26 | 0.06 | 0.27 | -0.02 | -0.18 | -0.10 | -0.26 |
| 0.45 | 0.00 | -0.26 | -0.22 | 0.99 | 0.02 | 0.10 | 0.09 | -0.16 | -0.40 | -0.14 | -0.31 | -0.14 | -0.02 | 0.00 | 0.29 | 0.24 | 0.05 | 0.27 | -0.02 | -0.19 | -0.12 | -0.28 |
| 0.5 | -0.01 | -0.24 | -0.20 | 0.93 | 0.03 | 0.12 | 0.08 | -0.15 | -0.39 | -0.11 | -0.30 | -0.14 | -0.02 | -0.03 | 0.28 | 0.20 | 0.01 | 0.27 | -0.01 | -0.23 | -0.15 | -0.30 |
| 0.55 | -0.02 | -0.23 | -0.20 | 0.82 | 0.05 | 0.13 | 0.09 | -0.15 | -0.40 | -0.11 | -0.30 | -0.14 | -0.04 | -0.04 | 0.28 | 0.19 | -0.01 | 0.26 | -0.01 | -0.26 | -0.18 | -0.31 |
| 0.6 | 0.00 | -0.24 | -0.20 | 0.71 | 0.08 | 0.13 | 0.09 | -0.14 | -0.42 | -0.11 | -0.30 | -0.15 | -0.06 | -0.05 | 0.33 | 0.18 | -0.04 | 0.26 | -0.03 | -0.29 | -0.21 | -0.33 |
| 0.65 | -0.01 | -0.26 | -0.21 | 0.67 | 0.10 | 0.13 | 0.10 | -0.15 | -0.42 | -0.12 | -0.32 | -0.14 | -0.06 | -0.07 | 0.33 | 0.17 | -0.07 | 0.29 | -0.03 | -0.30 | -0.24 | -0.33 |
| 0.7 | -0.03 | -0.28 | -0.19 | 0.67 | 0.11 | 0.13 | 0.09 | -0.15 | -0.43 | -0.13 | -0.36 | -0.14 | -0.04 | -0.08 | 0.34 | 0.14 | -0.09 | 0.27 | -0.05 | -0.33 | -0.24 | -0.31 |
| 0.75 | -0.08 | -0.29 | -0.20 | 0.64 | 0.14 | 0.16 | 0.08 | -0.16 | -0.45 | -0.14 | -0.38 | -0.10 | -0.01 | -0.04 | 0.38 | 0.13 | -0.10 | 0.27 | -0.02 | -0.36 | -0.22 | -0.31 |
| 0.8 | -0.11 | -0.28 | -0.19 | 0.66 | 0.17 | 0.13 | 0.04 | -0.16 | -0.47 | -0.15 | -0.44 | 0.00 | -0.04 | -0.02 | 0.46 | 0.17 | -0.07 | 0.27 | 0.00 | -0.41 | -0.27 | -0.36 |
| 0.85 | -0.09 | -0.27 | -0.13 | 0.84 | 0.22 | 0.02 | 0.02 | -0.21 | -0.49 | -0.25 | -0.51 | 0.06 | -0.06 | -0.01 | 0.64 | 0.17 | -0.10 | 0.35 | 0.01 | -0.46 | -0.31 | -0.43 |
| 0.9 | -0.03 | -0.18 | -0.03 | 1.03 | 0.27 | -0.11 | -0.15 | -0.29 | -0.55 | -0.35 | -0.64 | 0.13 | -0.07 | -0.04 | 0.92 | 0.15 | -0.17 | 0.41 | 0.00 | -0.55 | -0.39 | -0.54 |
| 0.95 | -0.34 | -0.11 | 0.13 | 0.98 | 0.44 | -0.29 | -0.40 | -0.64 | -0.87 | -0.52 | -0.93 | 0.07 | 0.01 | -0.15 | 1.40 | 0.00 | 0.03 | 0.33 | -0.04 | -0.62 | -0.35 | -0.56 |

Table A19– CC correction factors for 2080 to be applied to actual reference FDCs, basing on the possible combinations of Model input/forcing stand for various elements of the modelling chain: Representative Concentration Pathway (RCP), Global Circulation Model (GCM) and Regional Climate Model (RCM), group E-Hype catchment 9780149

2.8 Suitability Map

To build the suitability map for the identification of potential sites for new ponds implementation, we set feasibility criteria based on physical characteristics. We analysed and used the characteristics of existing ponds to define the suitable sites. The table reports the statistical distribution of values used to set feasibility thresholds.

| | Min | 1st Qu | Median | Mean | 3rd Qu | Max |
|--------------------------------------|-------|---------|---------|---------|----------|----------|
| Slope (degree) | 0.612 | 2.581 | 5.667 | 6.800 | 9.796 | 23.565 |
| Distance (m) | 3.00 | 15.71 | 43.00 | 94.05 | 91.01 | 1014.02 |
| Area (m2) | 43.31 | 3890.12 | 6667.18 | 8551.44 | 10327.39 | 69500.09 |
| Shape factor (area/perimeter) | 2.00 | 15.00 | 19.50 | 20.06 | 24.00 | 61.00 |

Table A20 - Summary statistics of existing water retention ponds characteristics for suitability analysis.

2.9 The existing GI Network

Here we show the map resulted from the Morphological Spatial Pattern Analysis and the graph representation of the existing potential GI Network. The analysis identified core areas (or nodes) and connections (or links) existing in the area of study. GI network includes existing water retention ponds, protected area, riparian zones.

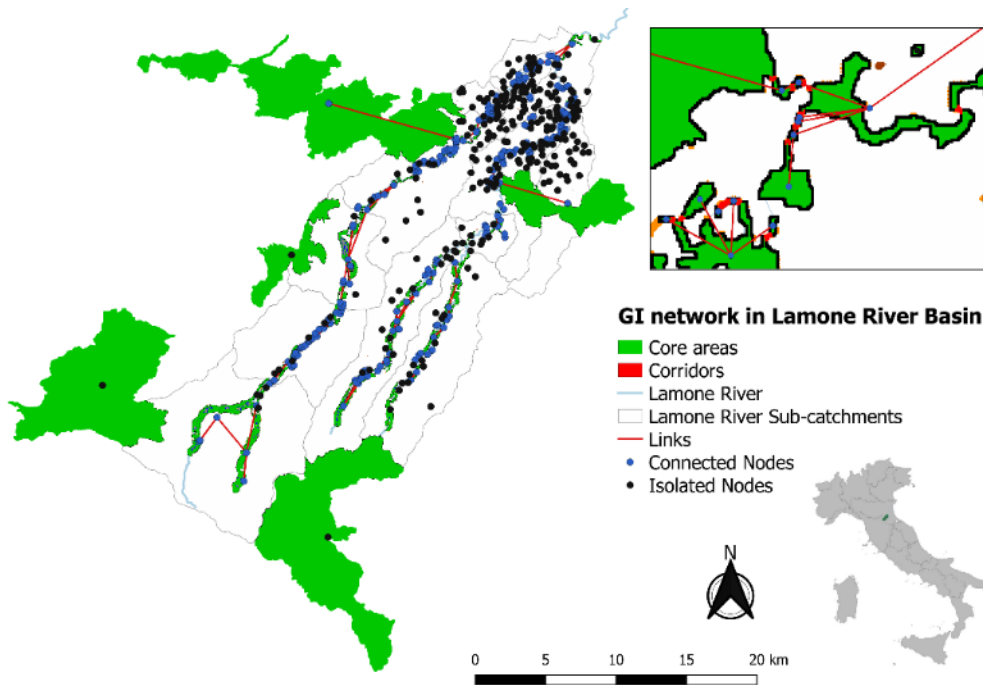


Figure A12 – Water retention ponds, protected areas and riparian zones network. The green areas represent the core elements and the red ones the corridors. The graph network overlaid the MSPA results. The black dots are isolated nodes, while the blue dots have at least one connection

2.10 Integral Index of Connectivity results for suitable areas

Here we show the graph representation of the new potential GI Network, including existing water retention ponds, protected area, riparian zones and suitable area identified for the construction of new ponds. Figure A13 shows the rank of nodes importance in term of *IICconnector*.

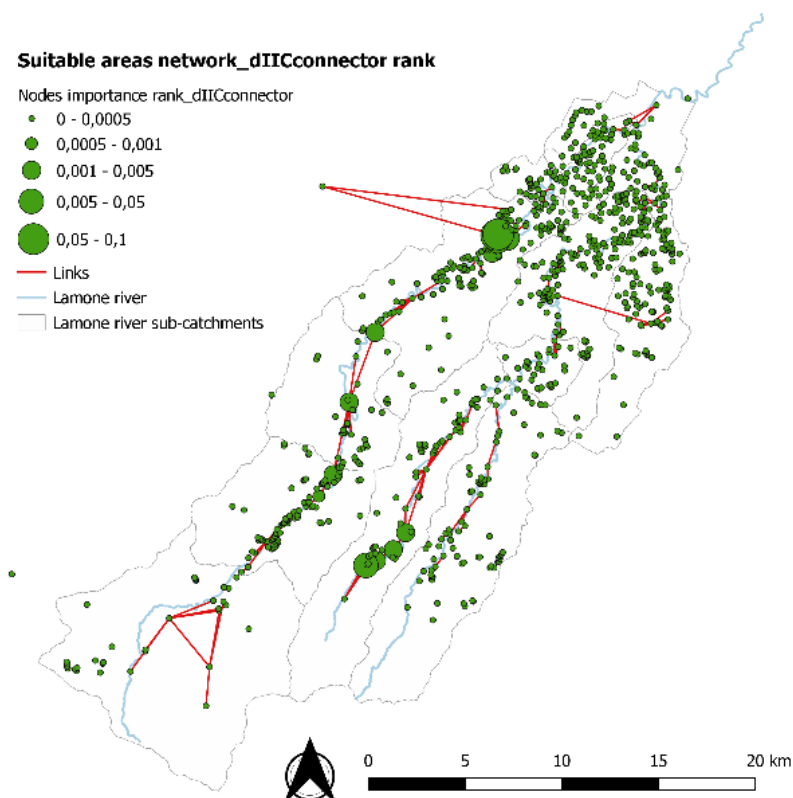


Figure A13 - Nodes importance rank of new potential network according to the *dIICconnector* values

2.11 Climate Change condition water balance results - no NBS implementation

Next graphs report results of water balance for each scenario of Table A.11 in the form of selected indexes for 3-time horizons, respectively 2020, 2050 and 2080.

Water availability

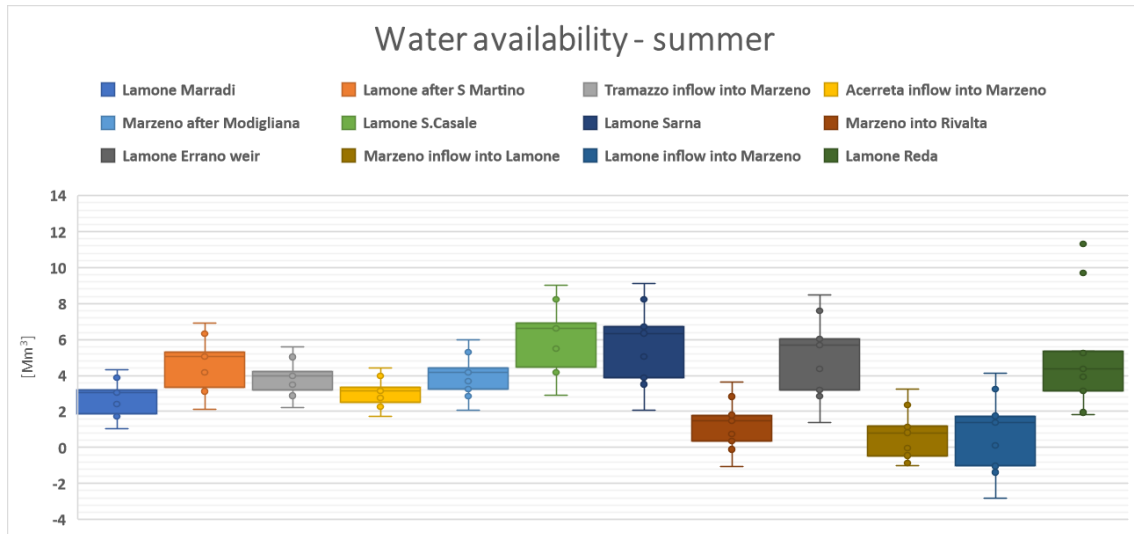


Figure A14 – Summer water availability in 2020 with no action

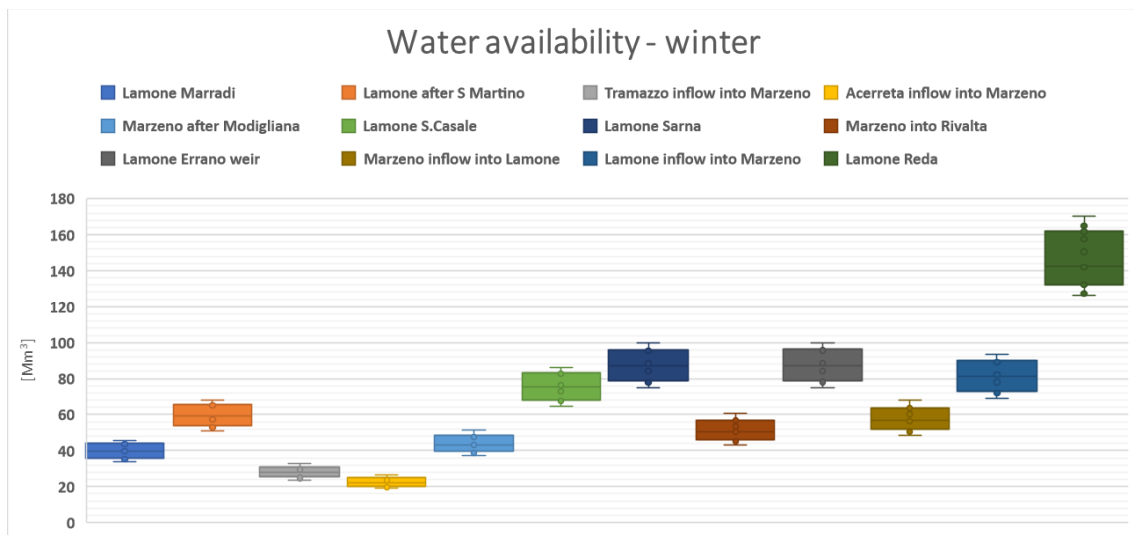


Figure A15 – Winter water availability in 2020 with no action

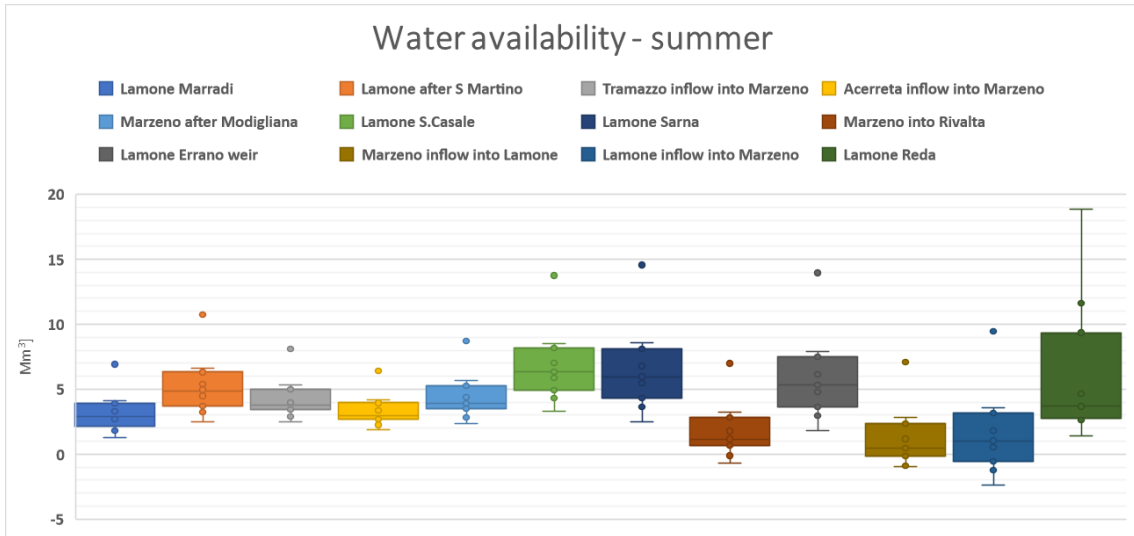


Figure A16 – Summer water availability in 2050 with no action

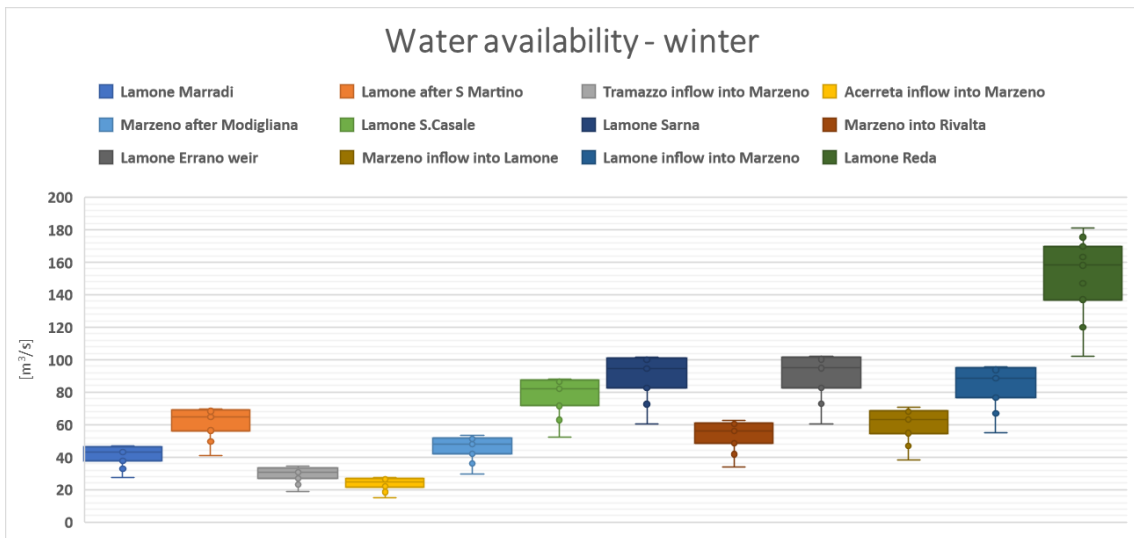


Figure A17 – Winter water availability in 2050 with no action

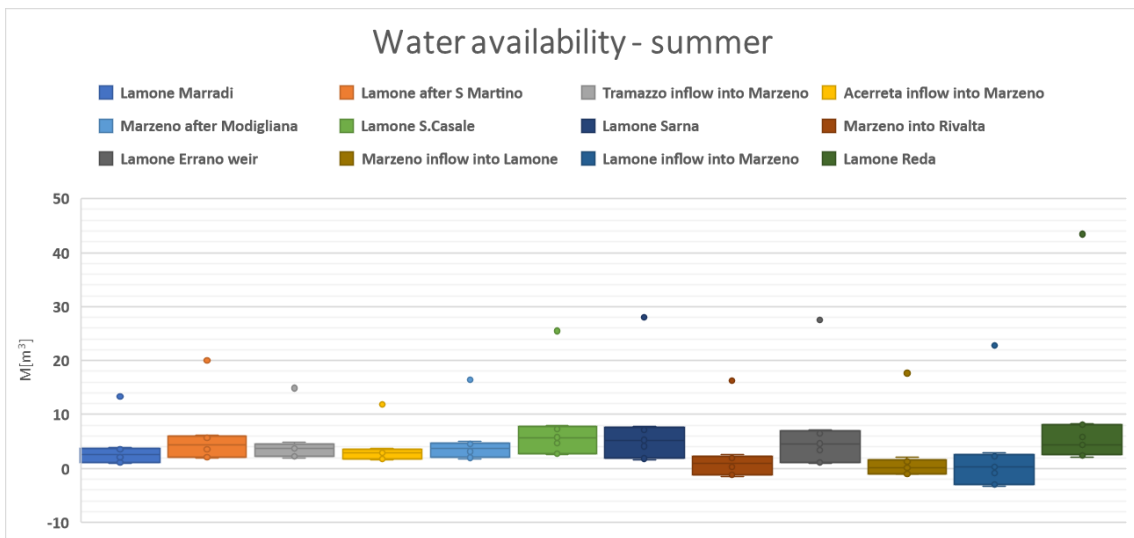


Figure A18 – Summer water availability in 2080 with no action

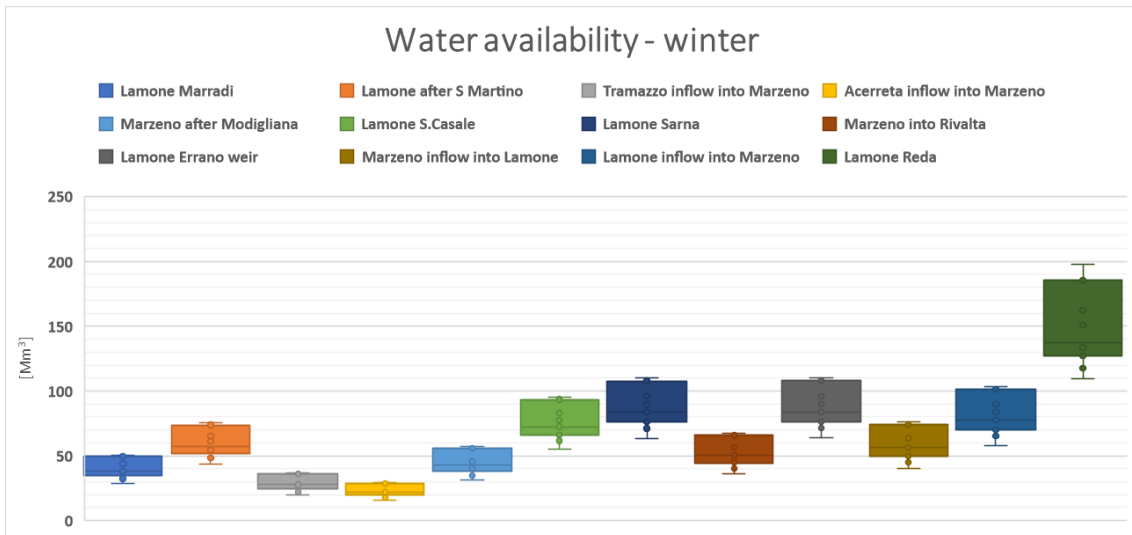


Figure A19 – Winter water availability in 2080 with no action

Time of no withdrawal

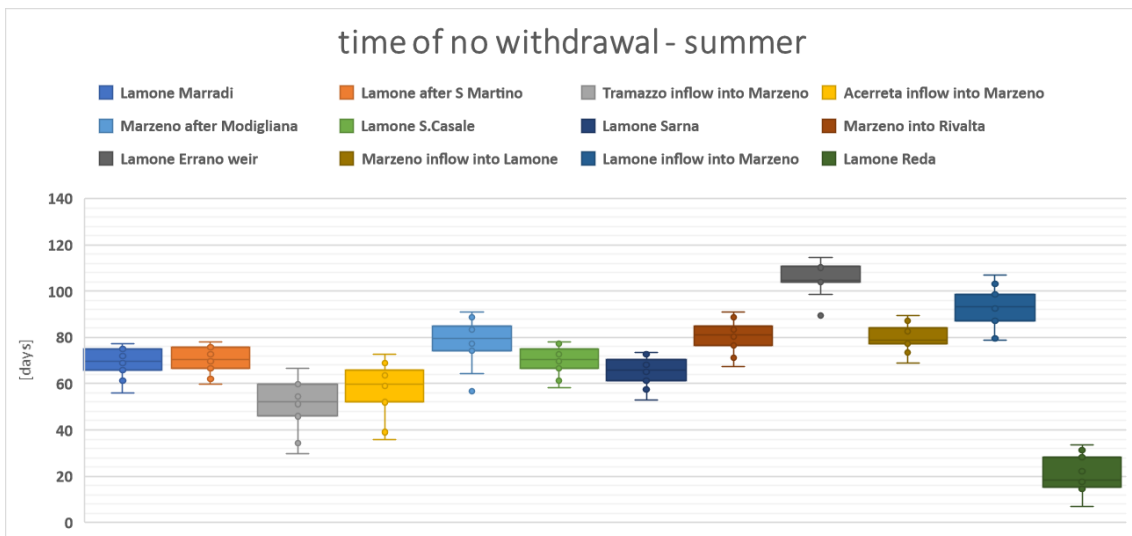


Figure A20 – Time of no withdrawal in summer 2020 with no action

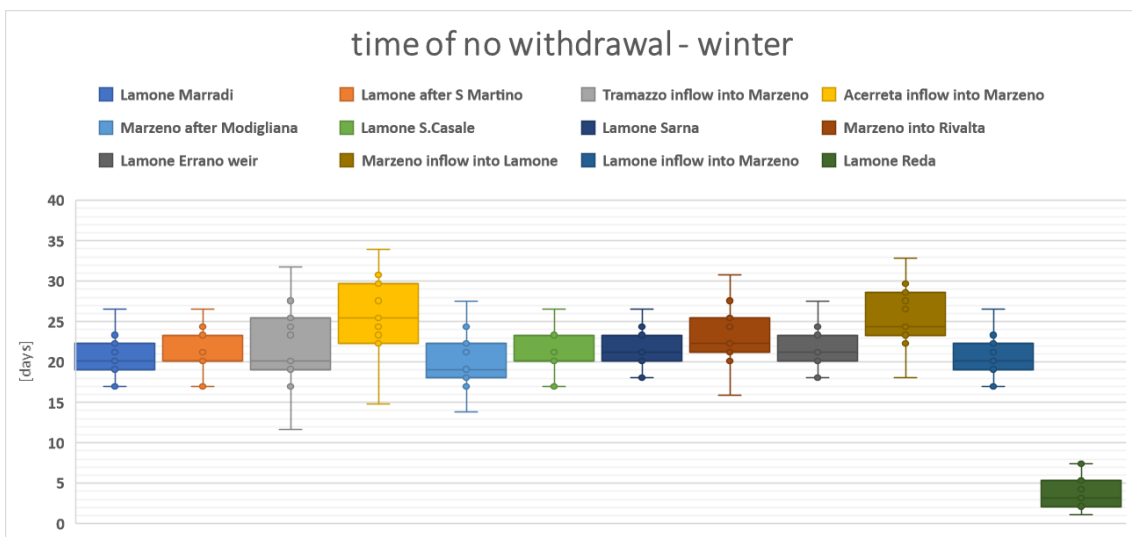


Figure A21 – Time of no withdrawal in winter 2020 with no action

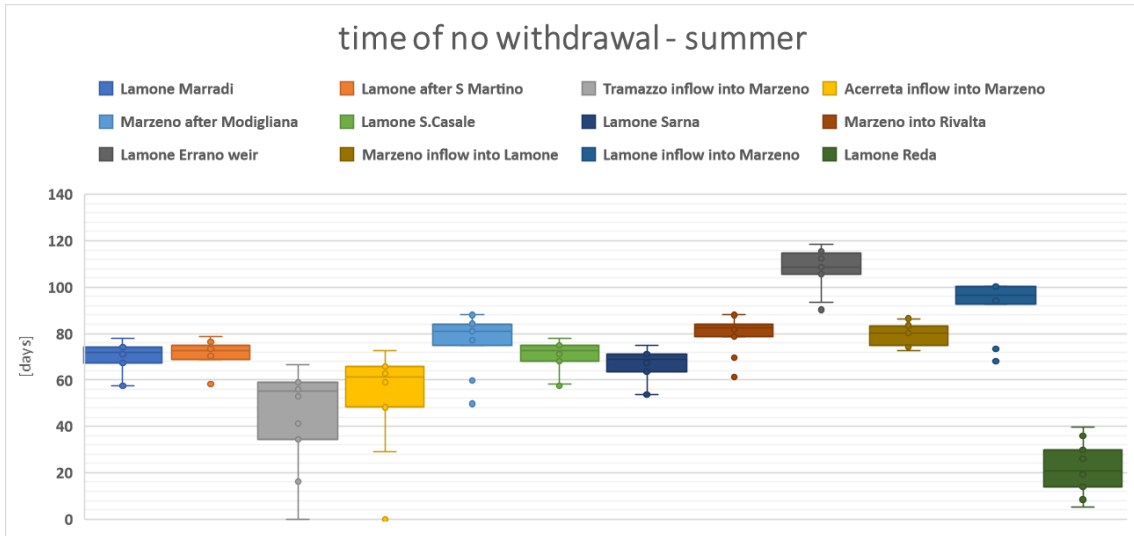


Figure A22 – Time of no withdrawal in summer 2050 with no action

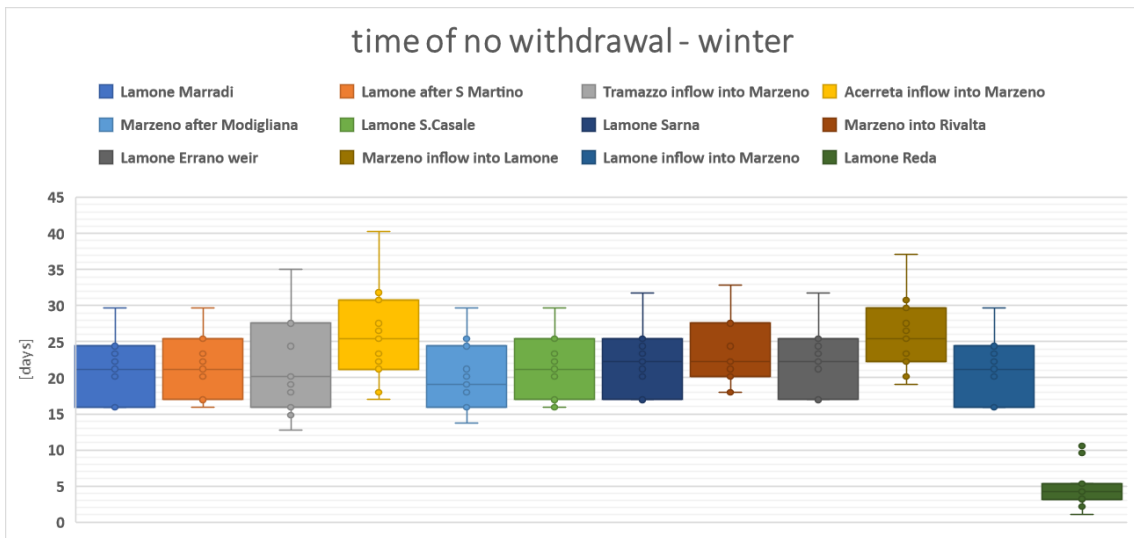


Figure A23 – Time of no withdrawal in winter 2050 with no action

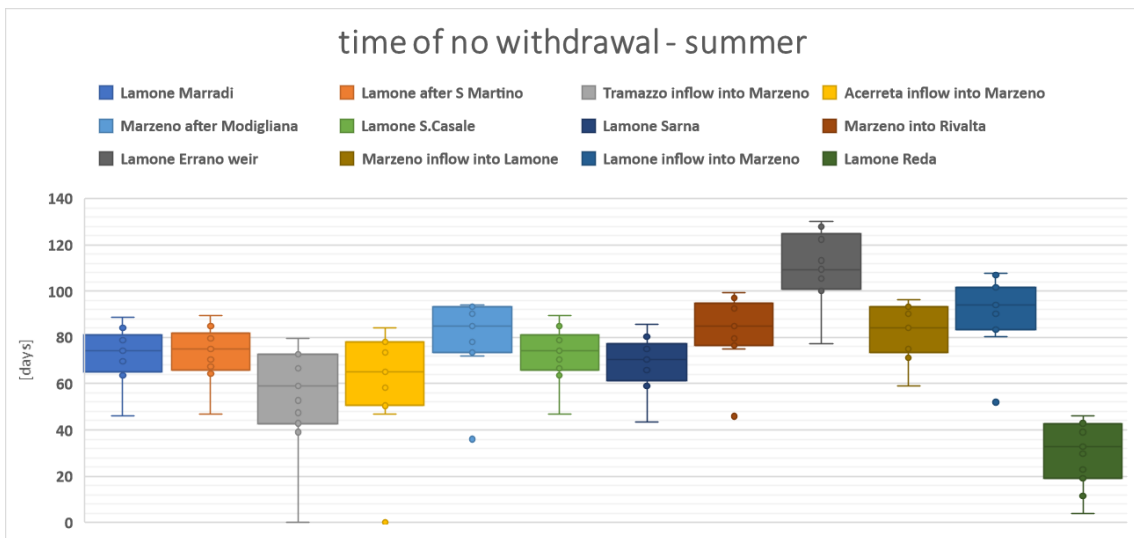


Figure A24 – Time of no withdrawal in summer 2080 with no action

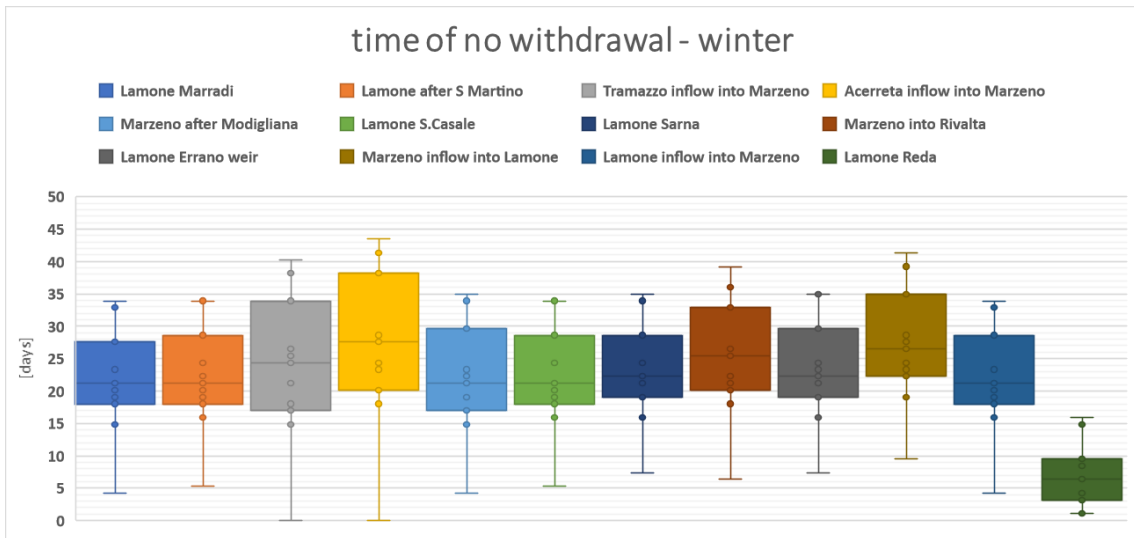


Figure A25 – Time of no withdrawal in winter 2080 with no action

sWEI+

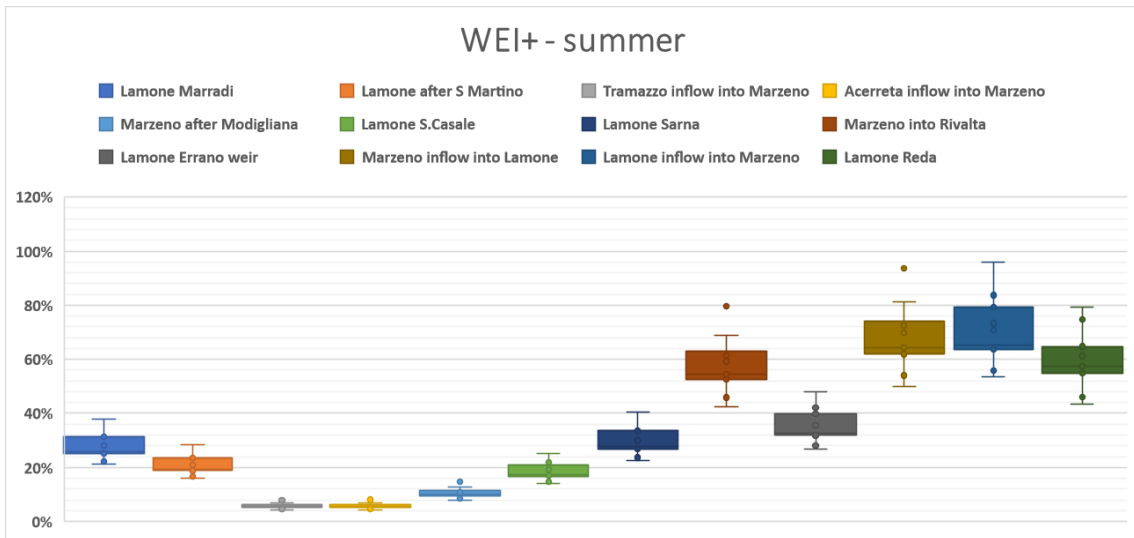


Figure A26 – sWEI+ in summer 2020 with no action

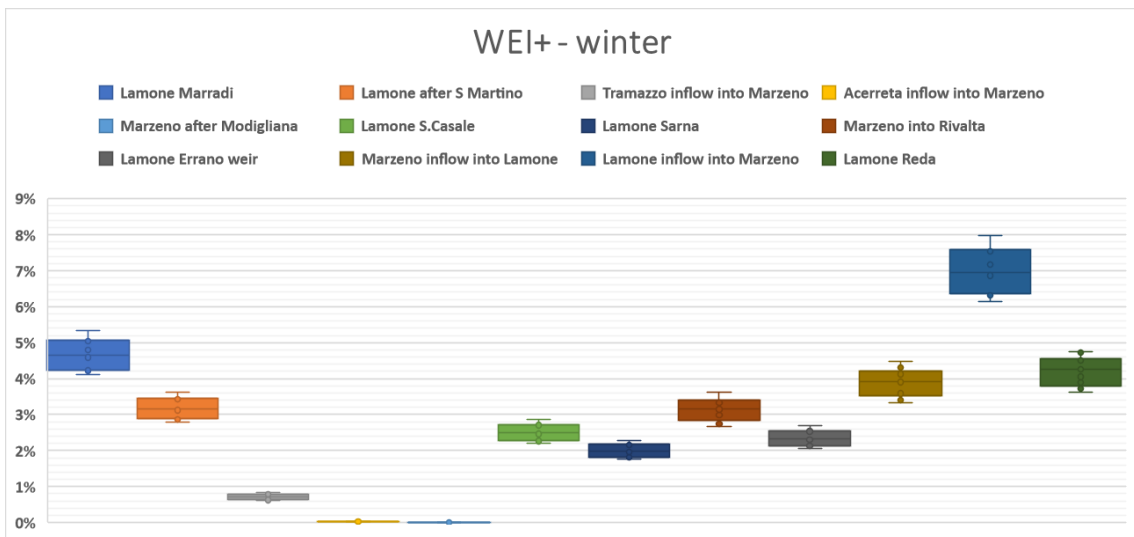


Figure A27 – sWEI+ in winter 2020 with no action

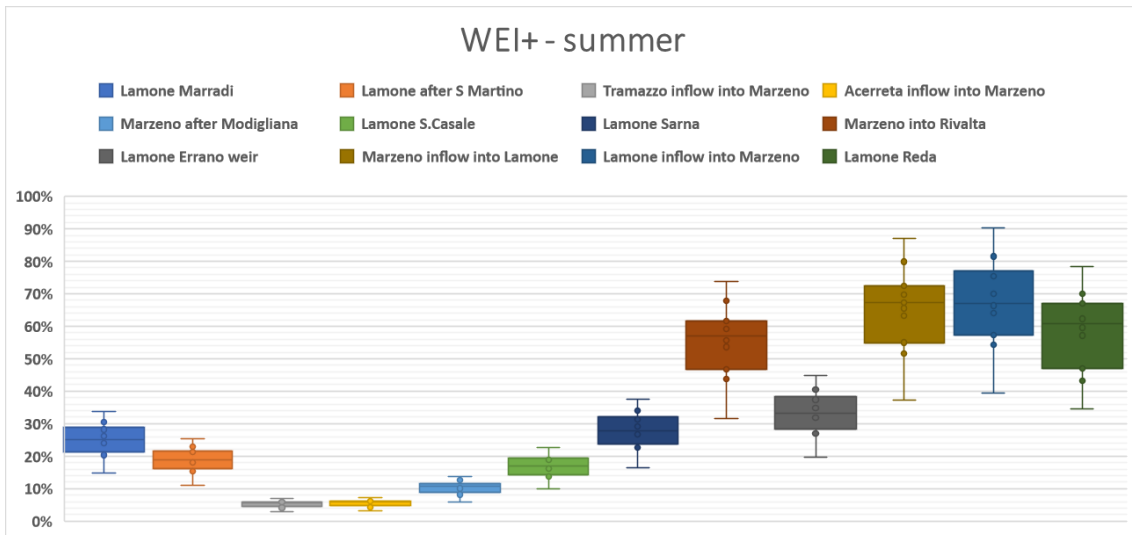


Figure A28 – sWEI+ in summer 2050 with no action

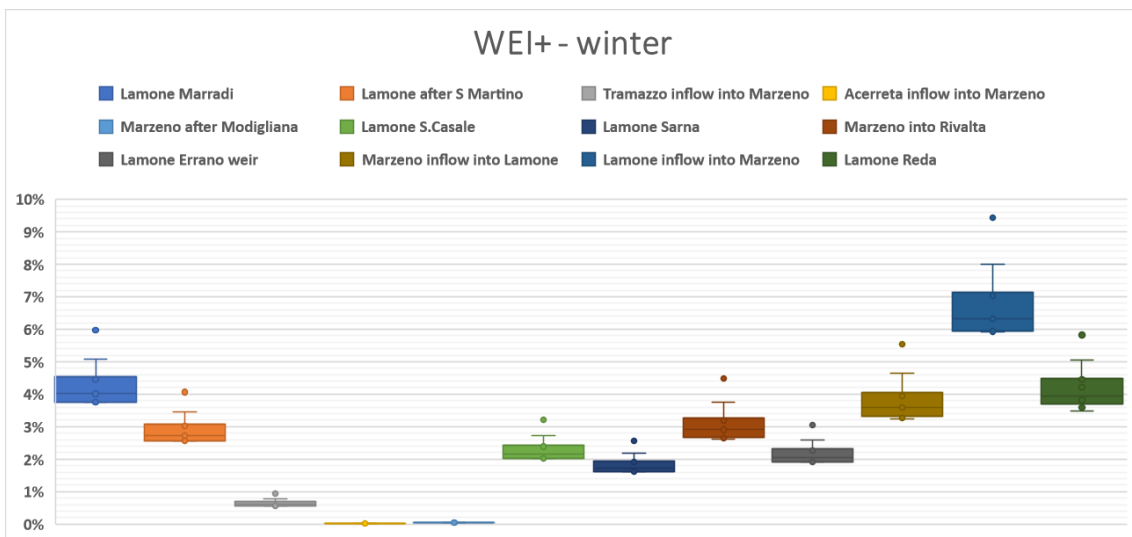


Figure A29 – sWEI+ in winter 2050 with no action

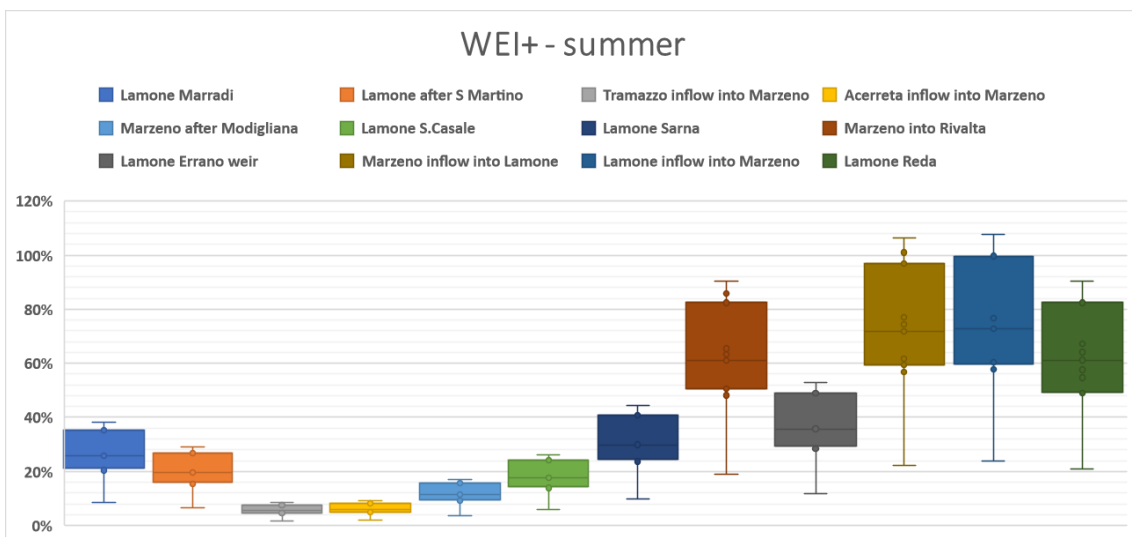


Figure A30 – sWEI+ in summer 2080 with no action

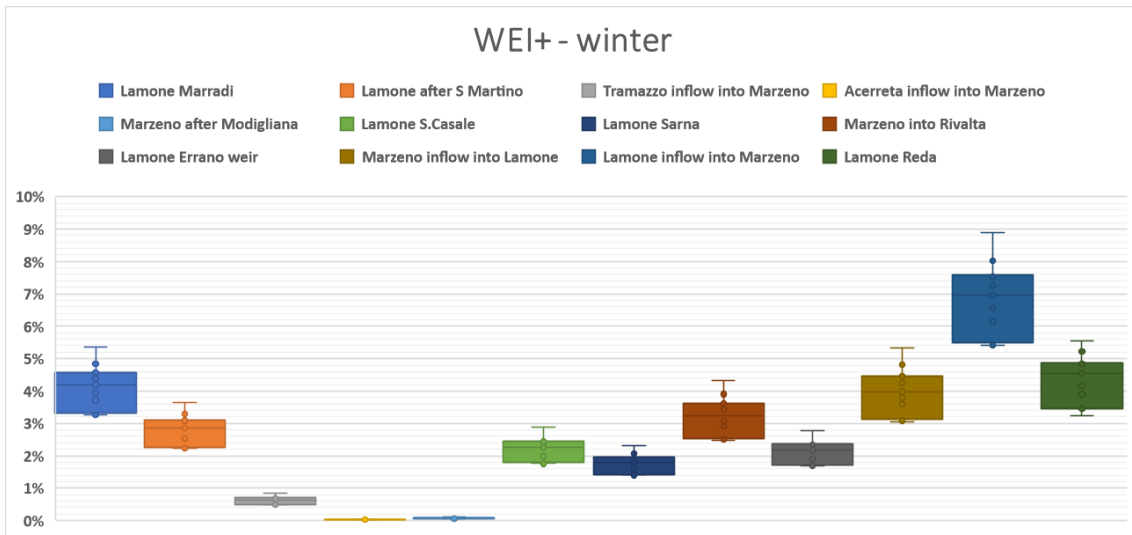


Figure A31 – sWEI+ in winter 2080 with no action

2.12 Climate Change condition water balance results - implementation of NBS scenario

Next graphs report results of water balance for each scenario of Table A.11 in the form of selected indexes for 3-time horizons, respectively 2020, 2050 and 2080.

Water availability

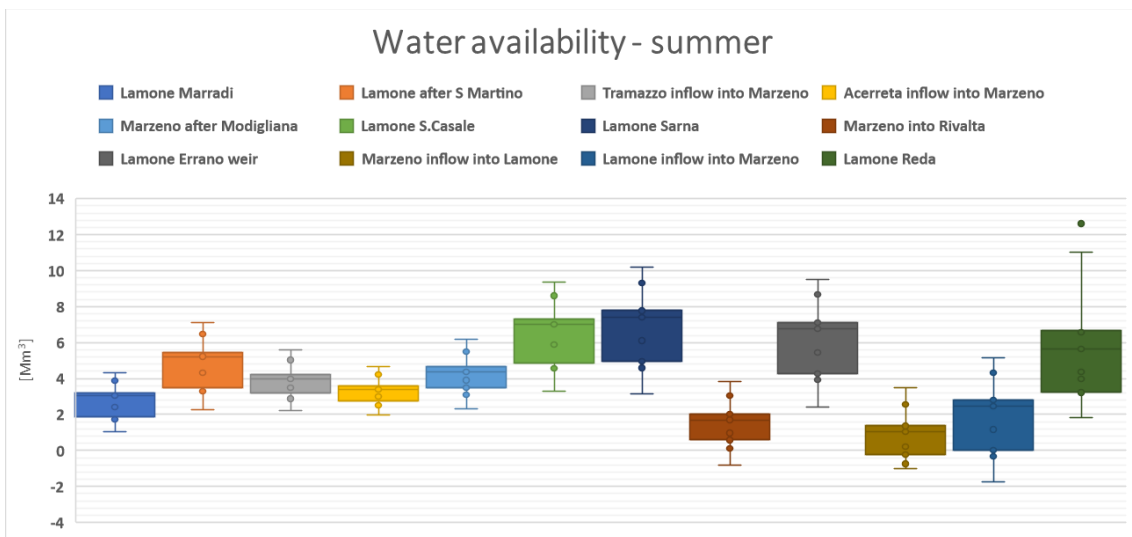


Figure A32 – Summer water availability in 2020 with NBS action

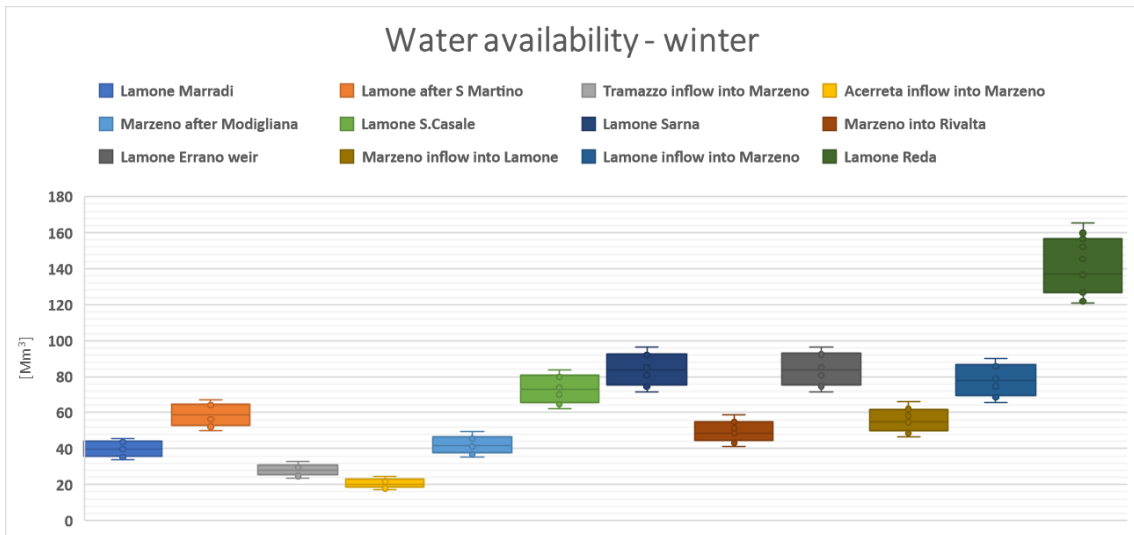


Figure A33 – Winter water availability in 2020 with NBS action

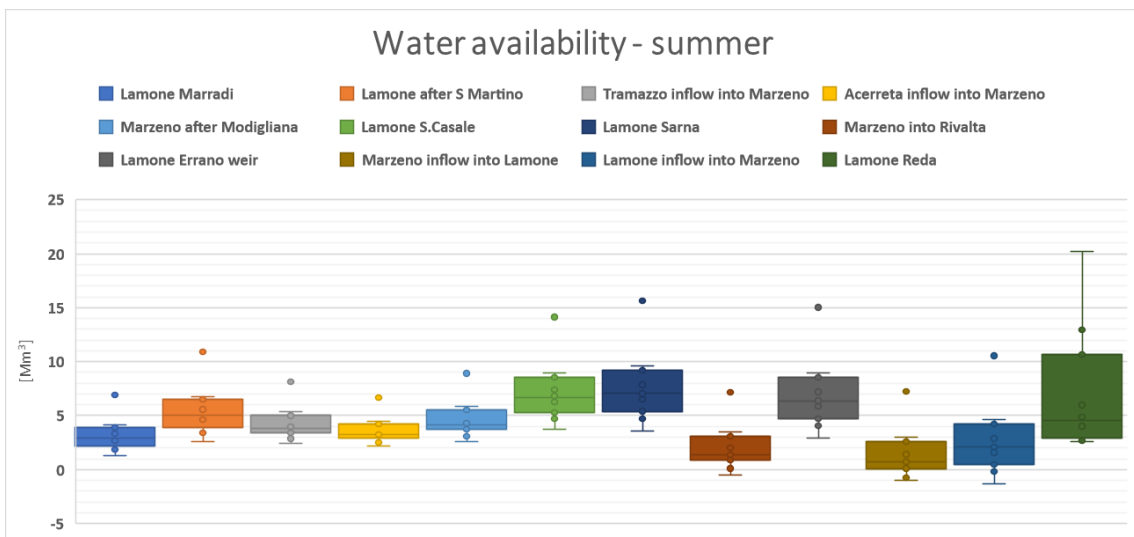


Figure A33 – Summer water availability in 2050 with NBS action

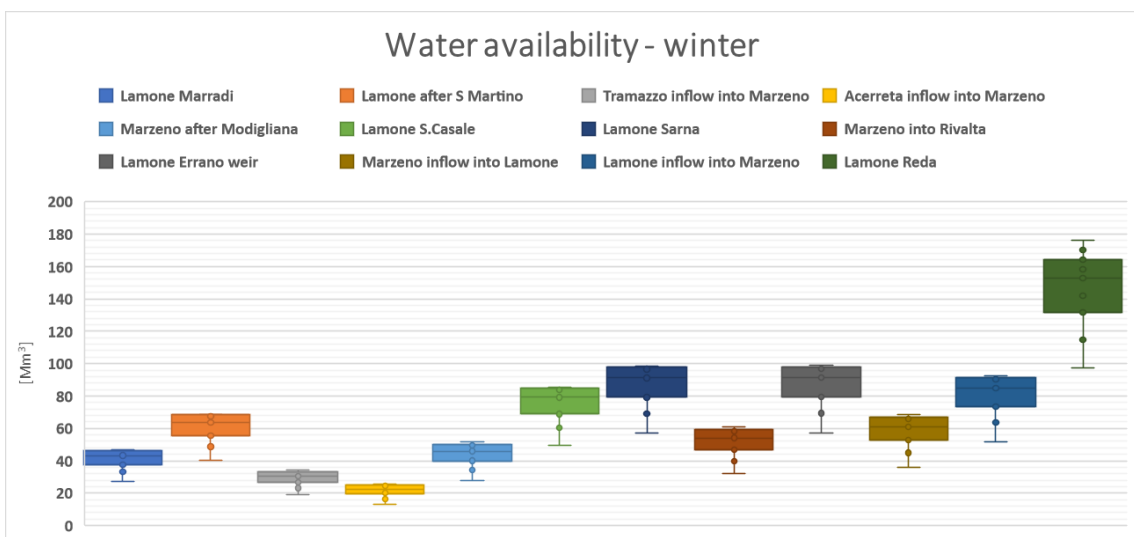


Figure A34 – Winter water availability in 2050 with NBS action

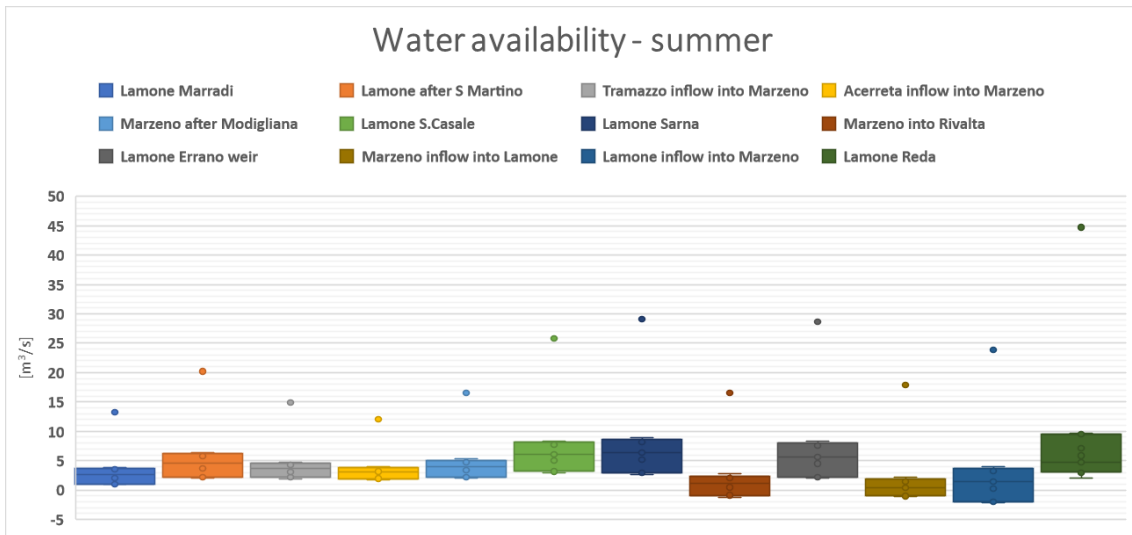


Figure A35 – Summer water availability in 2080 with NBS action

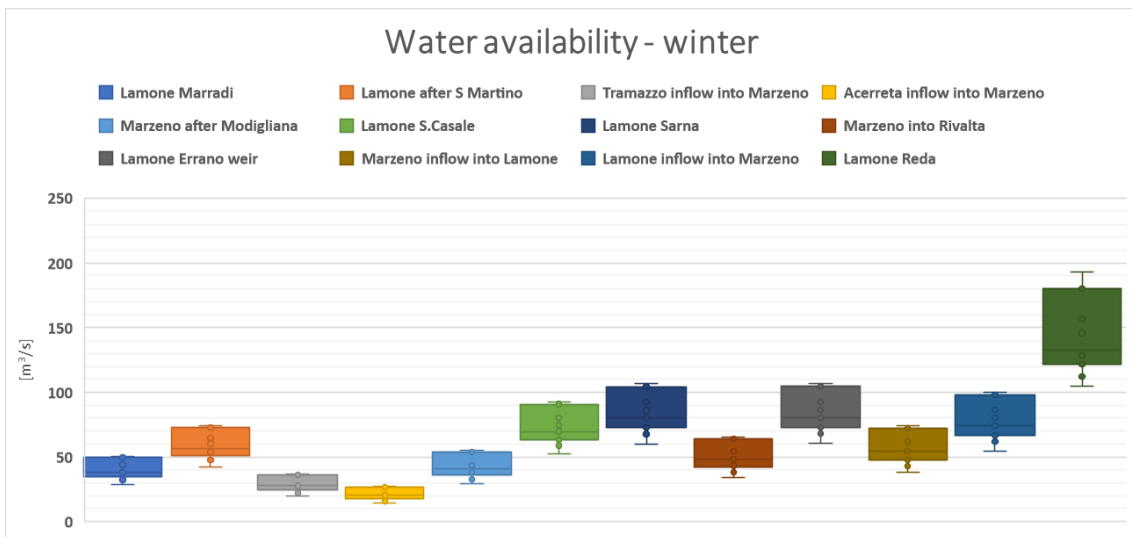


Figure A36 – Winter water availability in 2080 with NBS action

Time of no withdrawal –

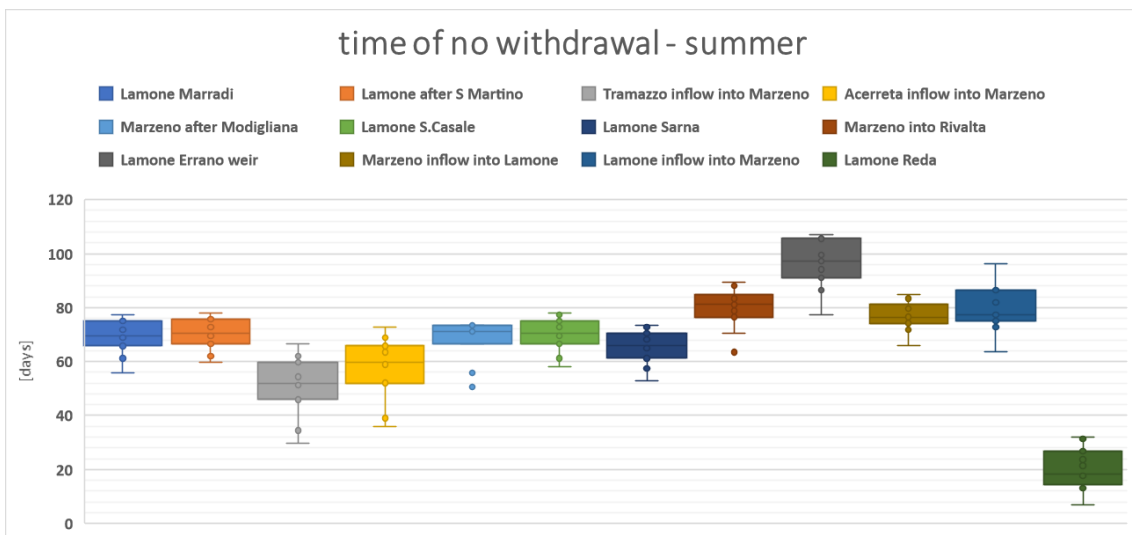


Figure A37 – Time of no withdrawal in summer 2080 with NBS action

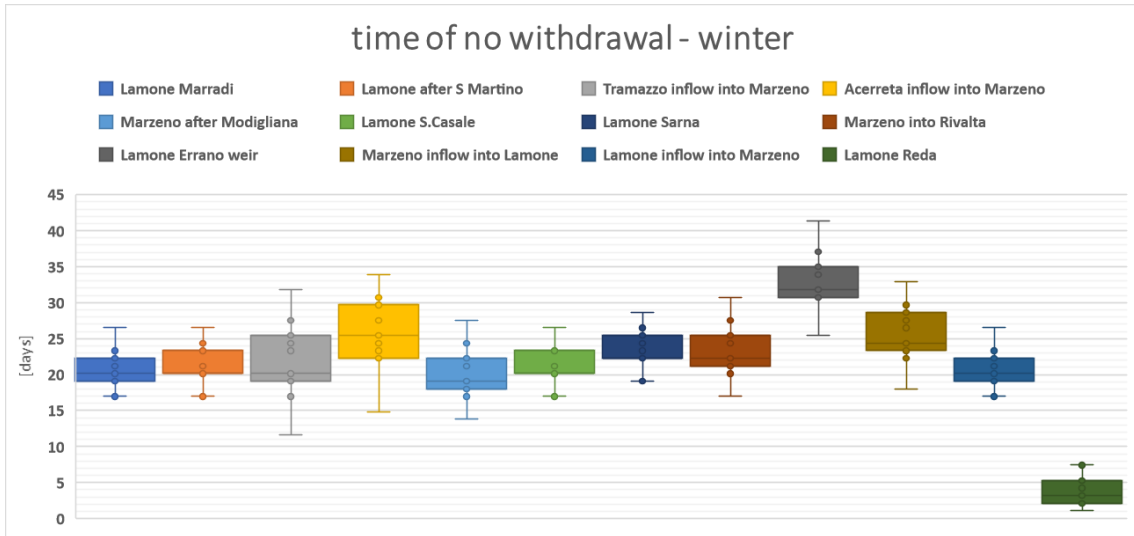


Figure A38 – Time of no withdrawal in winter 2020 with NBS action

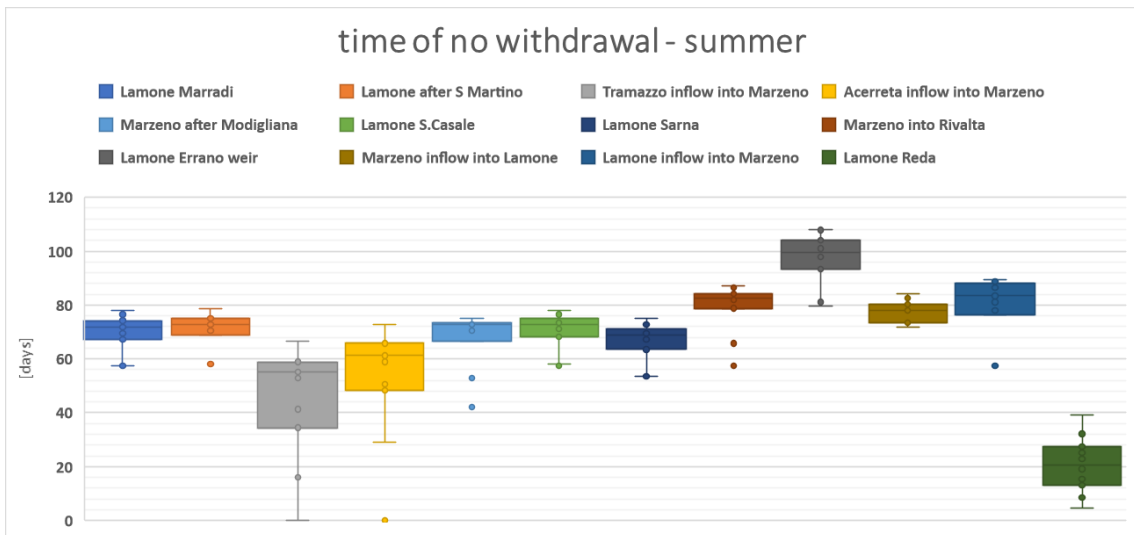


Figure A39 – Time of no withdrawal in summer 2050 with NBS action

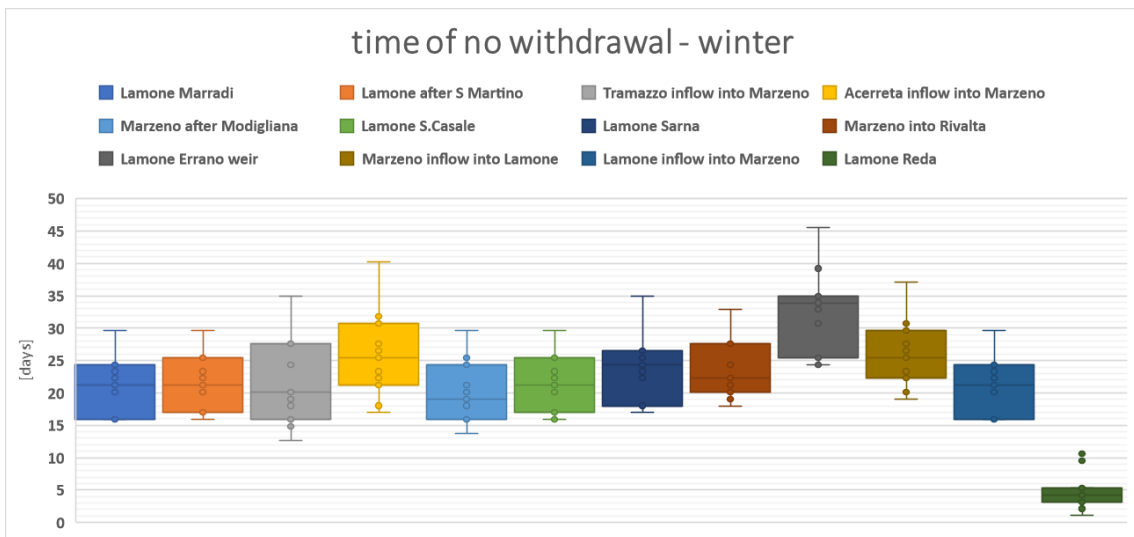


Figure A40 – Time of no withdrawal in winter 2020 with NBS action

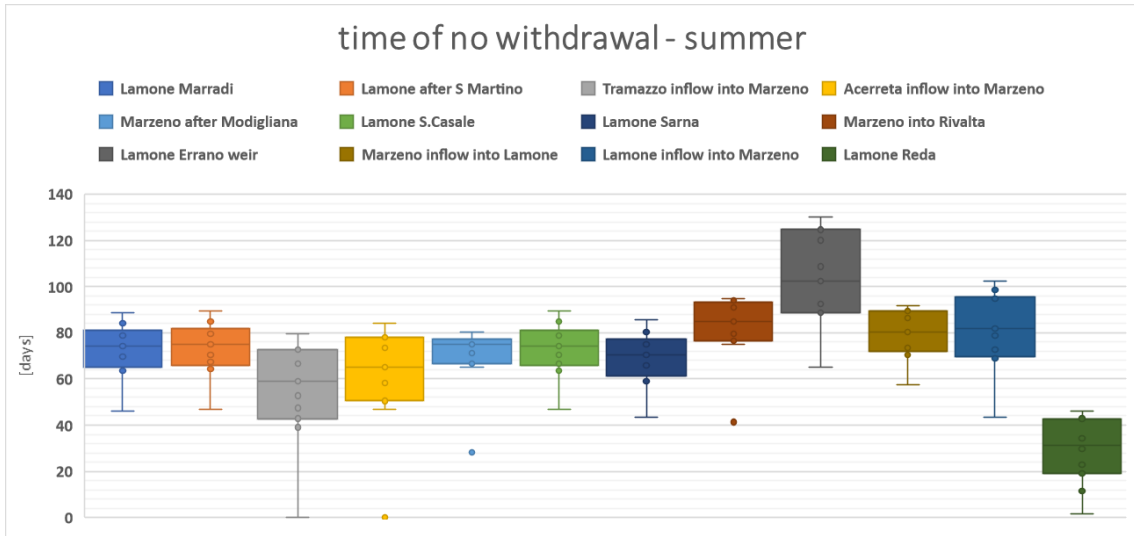


Figure A41 – Time of no withdrawal in summer 2050 with NBS action

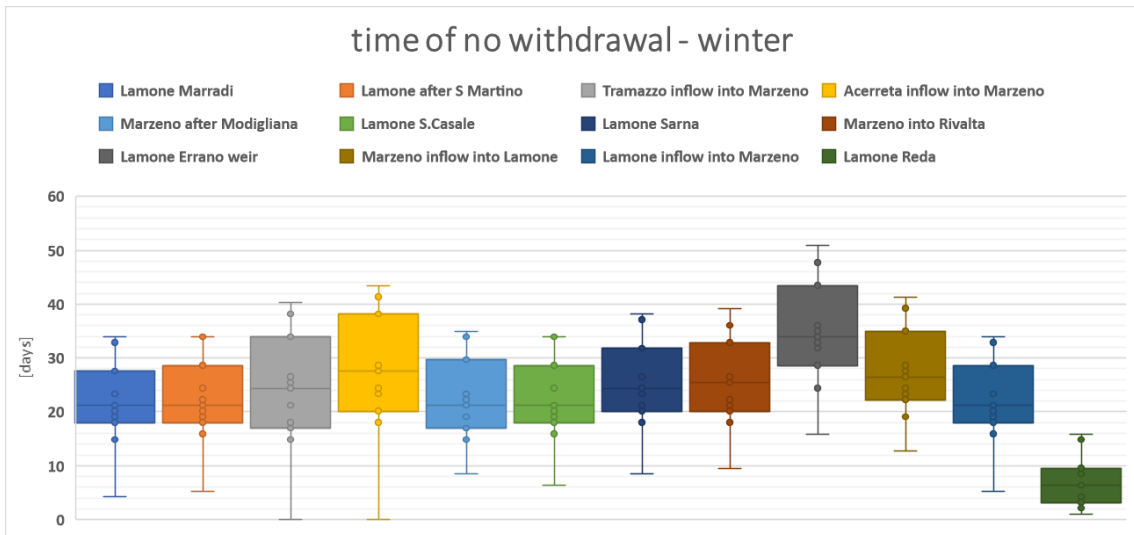


Figure A42 – Time of no withdrawal in winter 2020 with NBS action

sWEI+

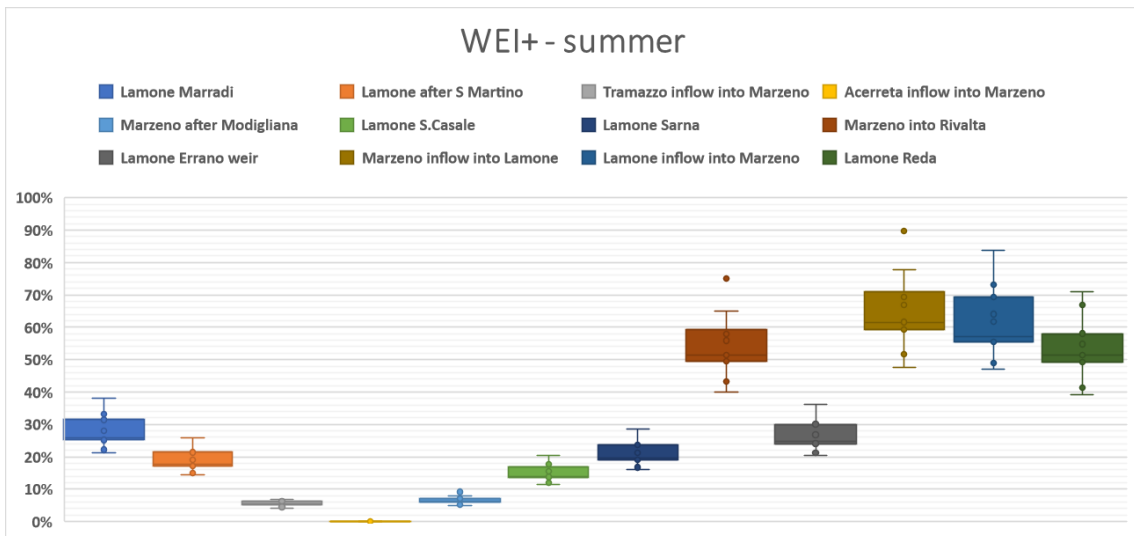


Figure A43 – sWEI+ in summer 2020 with NBS action

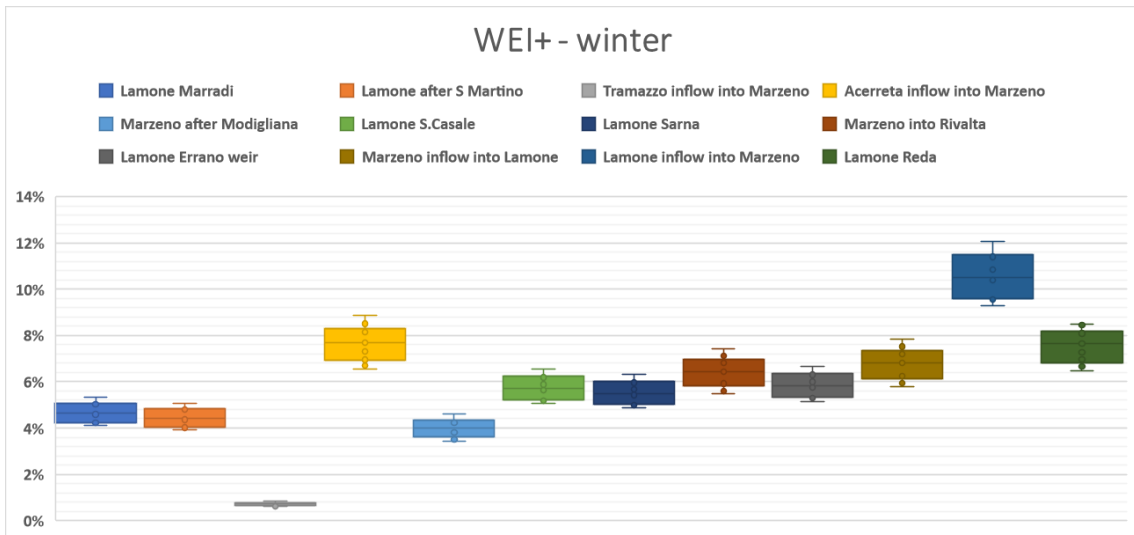


Figure A44 – sWEI+ in winter2020 with NBS action

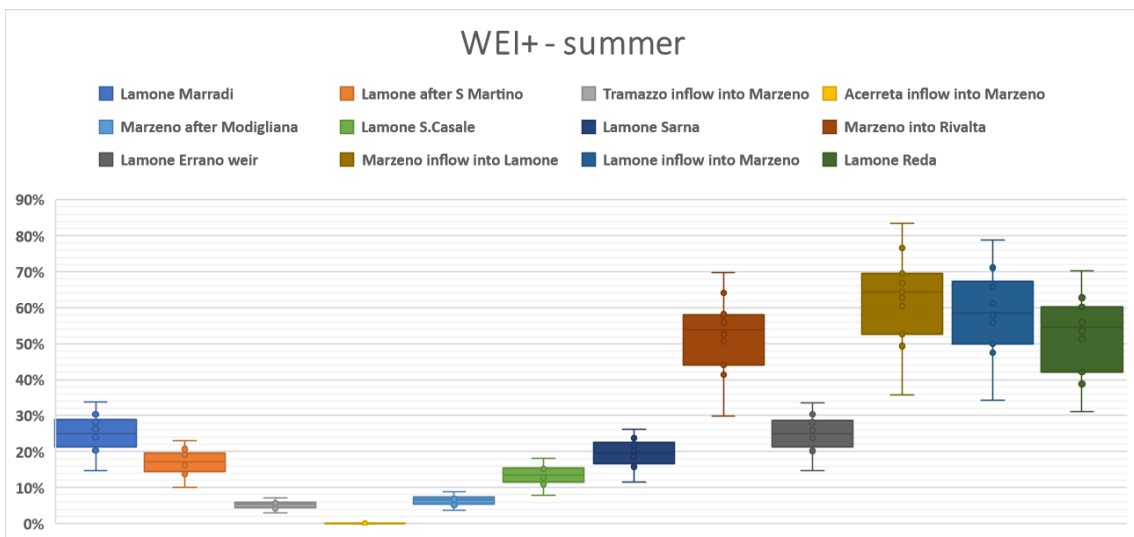


Figure A45 – sWEI+ in summer 2050 with NBS action

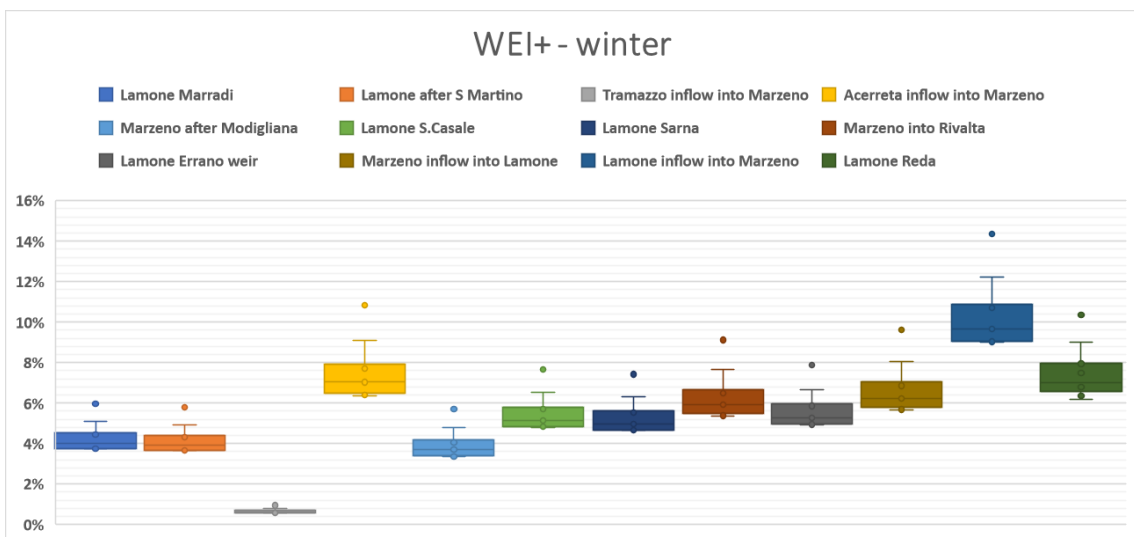


Figure A46 – sWEI+ in winter2050 with NBS action

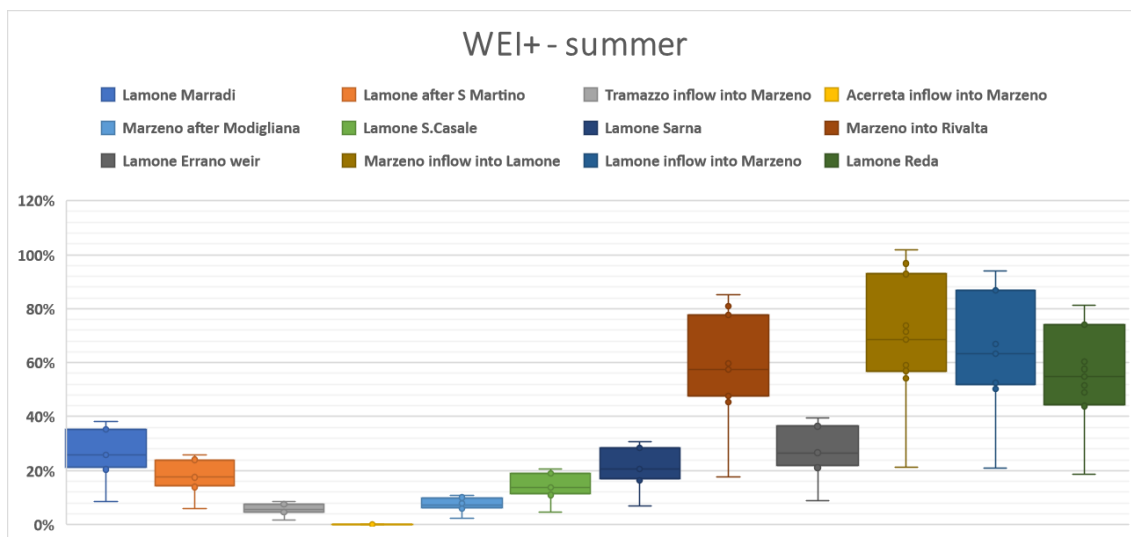


Figure A47 – sWEI+ in summer 2080 with NBS action

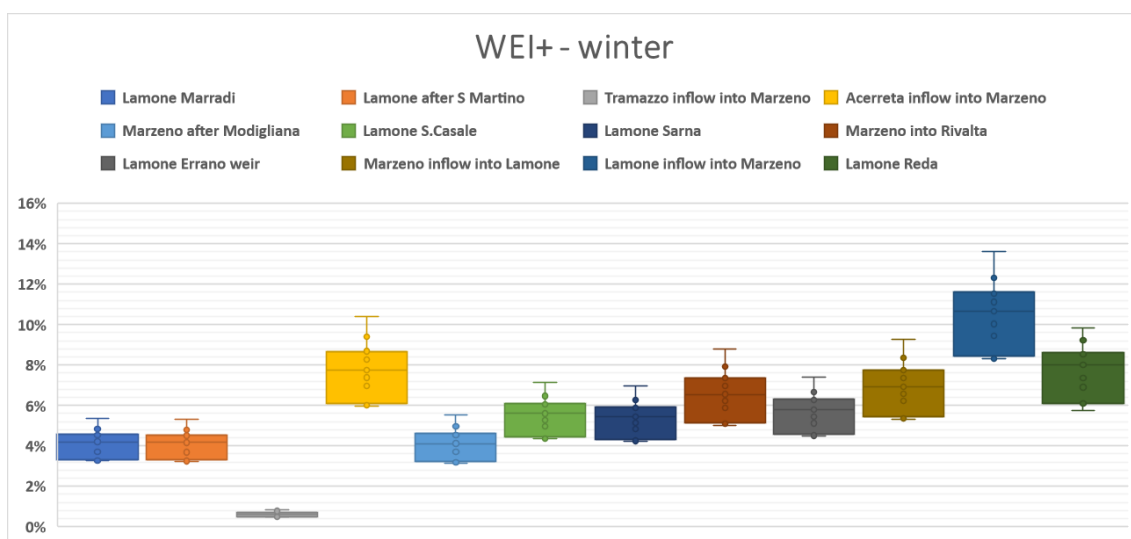


Figure A48 – sWEI+ in winter 2080 with NBS action

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Annex Chapter 3

3.1 Level of protection

| Cat. | Name | Description |
|------------|--|--|
| Ia | Strict nature reserve | Strictly protected for biodiversity and geological/ geomorphological features, where human visitation, use and impacts are controlled and limited to ensure protection of the conservation values |
| Ib | Wilderness area | Large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, protected and managed to preserve their natural condition |
| II | National park | Large natural or near-natural areas protecting large-scale ecological processes with characteristic species and ecosystems, which also have environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities |
| III | Natural monument or feature | Areas set aside to protect a specific natural monument, which can be a landform, sea mount, marine cavern, geological feature such as a cave, or a living feature such as an ancient grove |
| IV | Habitat/species management area | Areas to protect particular species or habitats, where management reflects this priority. |
| V | Protected landscape or seascape | Where the interaction of people and nature over time has produced a distinct character with significant ecological, biological, cultural and scenic value; and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated nature conservation and other values |
| VI | Protected areas with sustainable use of natural resources | Areas which conserve ecosystems, together with associated cultural values and traditional natural resource management systems. Generally large, mainly in a natural condition, with a proportion under sustainable natural resource management and where low-level non-industrial natural resource use compatible with nature conservation is seen as one of the main aims |

Table A.217 – IUCN categories definition by Dudley, 2008.

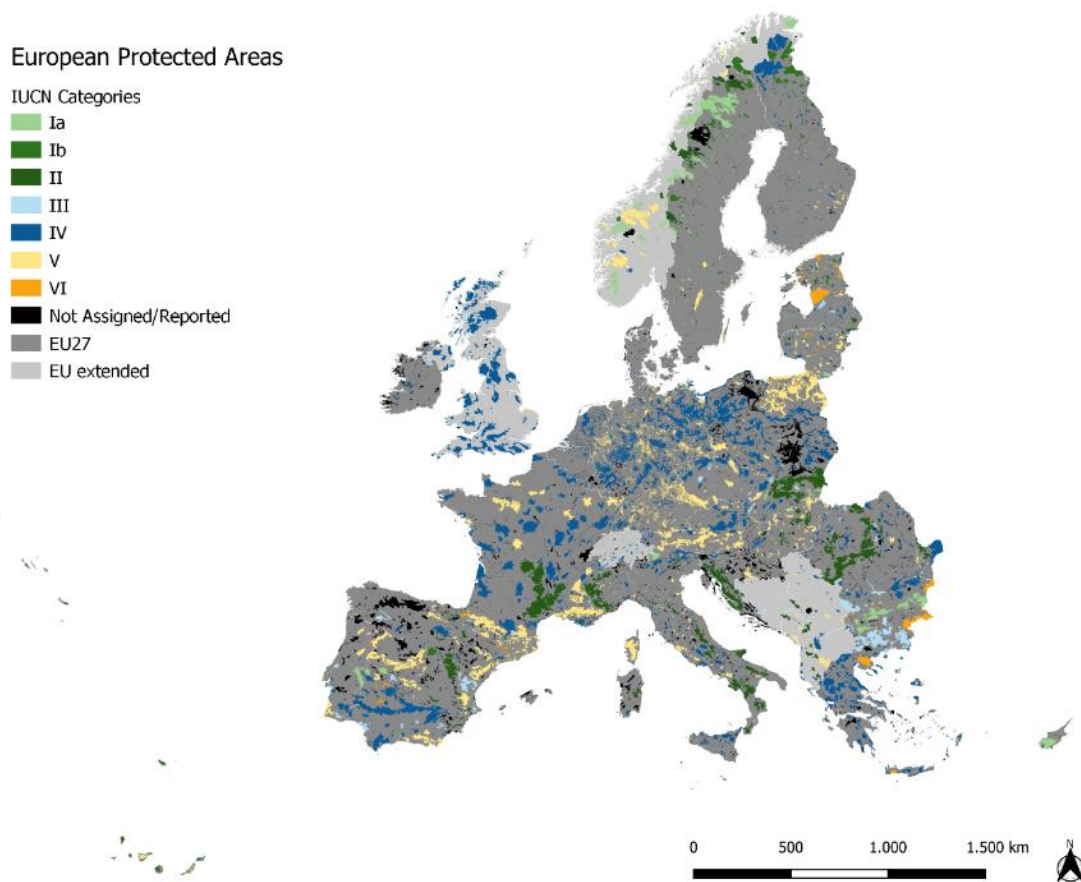


Figure A49 – IUCN categories assigned to the existing EU Protected Areas.

3.2 PAs Distances definition

| | |
|--------------------------|----------|
| Min | 0.075 km |
| 1st qt | 1.5 km |
| Mean | 8 km |
| Median | 2.65 km |
| 3rd qt | 5.75 km |
| Max | 233.5 km |

Table A.218 - Summary of existing PAs distances

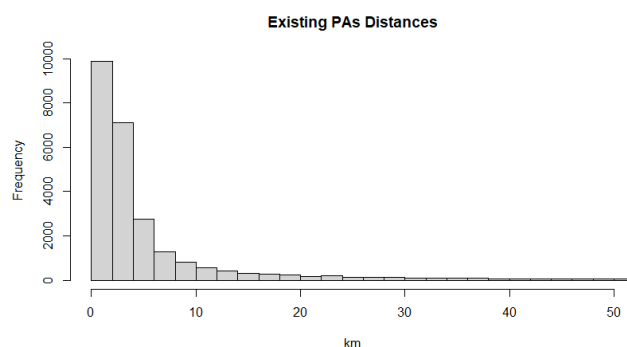


Figure A50 – Histogram of PAs distances distribution

Distances are computed as linear distances among PAs centroids. Very large distances can be biased by PAs size. To define the distance threshold to use in the analysis, we excluded very long distances. We selected a reasonable value around the mean, to include the majority of existing distance values (10 km).

3.3 Cost raster for least-cost path analysis

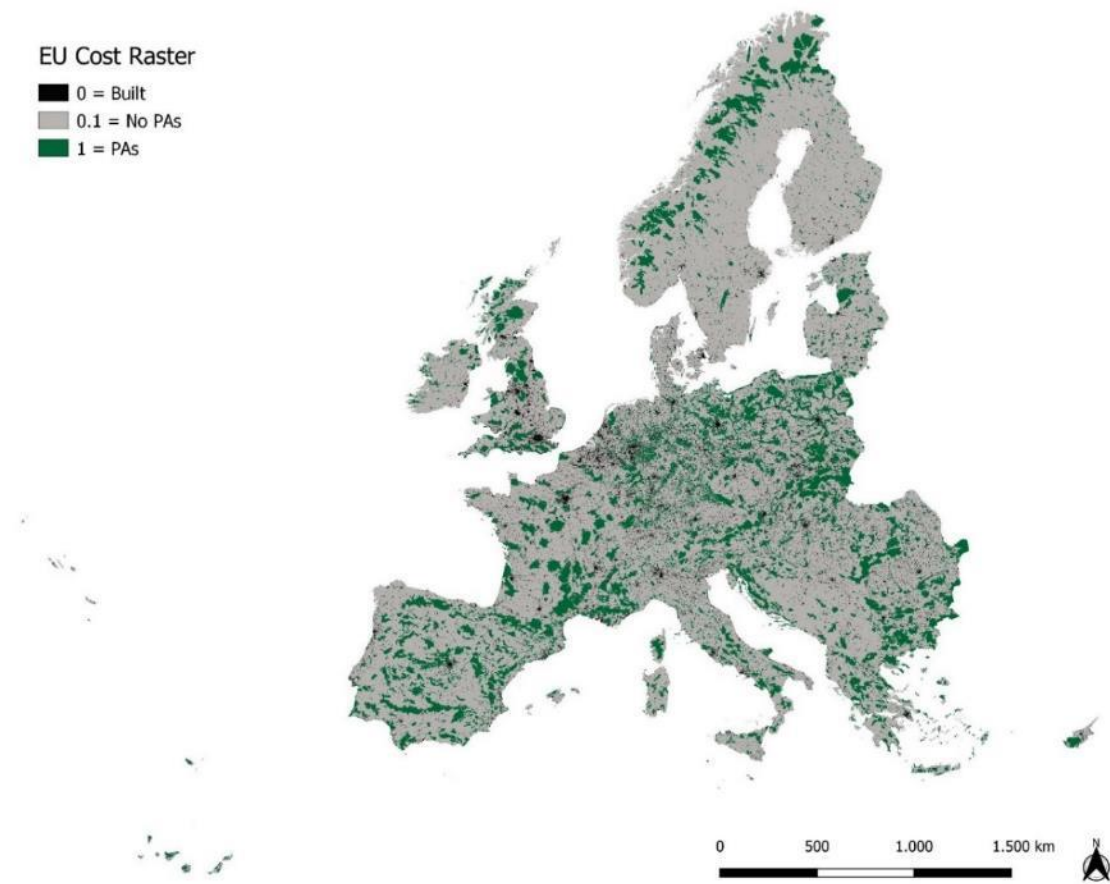


Figure A51 – Cost raster for least-cost path analysis.

We built the raster merging the EU PAs and the built areas. Built areas are based on the Corine Land Cover data, particularly we used the artificial surfaces, i.e. urban fabric; industrial, commercial and transport unit; mine, dump and construction sites; artificial, non-agricultural vegetated areas (EU, 2018). The cost raster has a resolution of 1 km.

3.4 Land use changes

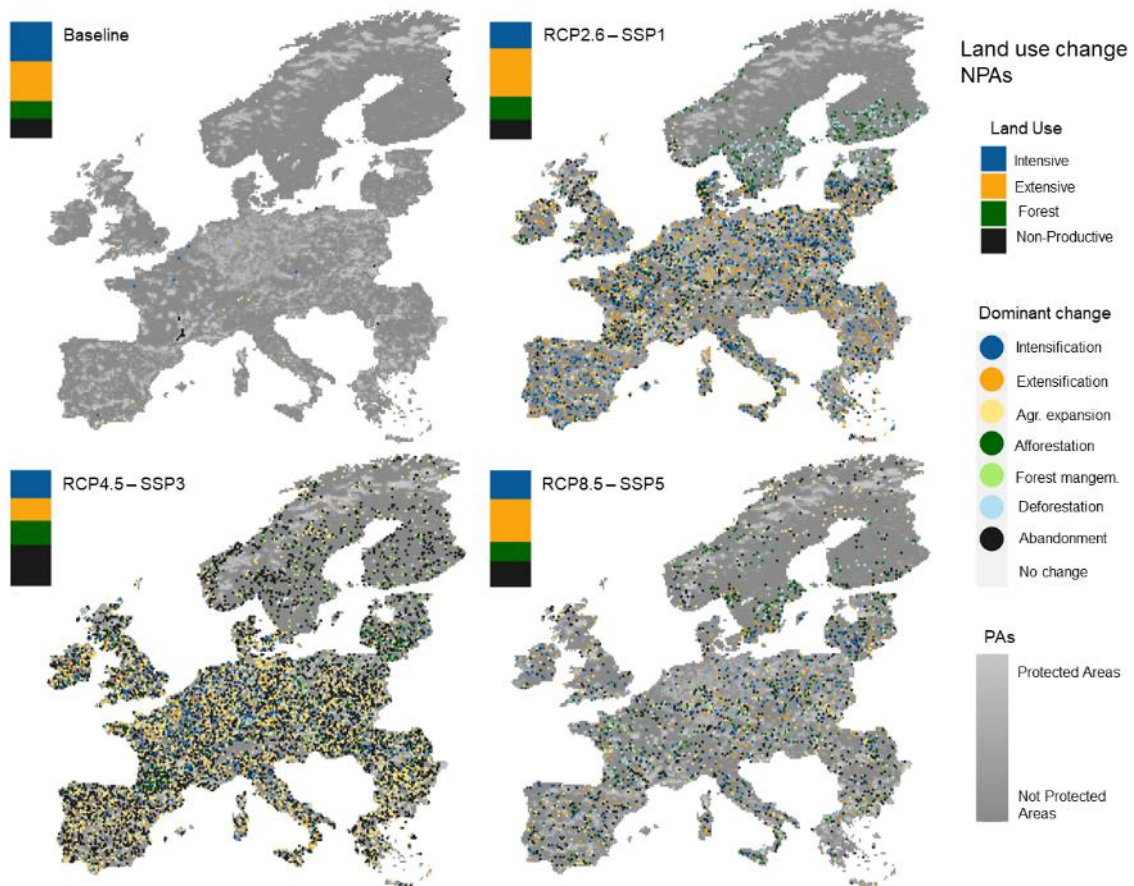


Figure A52 –Dominant land use changes in 2080s from enhanced network connectivity under the NPA configuration, for baseline conditions and for three different future scenarios. Dominant changes are computed with respect to the EPA configuration in each scenario. Changes are classified as: Extensification – intensive land use changing to extensive, Intensification – extensive land use changing to intensive, Afforestation – forest on previously unforested land, Deforestation – forest changing to unforested land uses, Abandonment – active management of any sort changing to unmanaged, Agricultural expansion – non-agricultural use to intensive or extensive agriculture, Forest management – unmanaged or semi-natural forest to managed forest. The bar charts represent the final percentage of broad land cover types per scenario, grouped in four main categories: Intensive (intensive arable farming, intensive agroforestry mosaic, intensive farming, intensive pastoral farming), Extensive (mixed farming, mixed pastoral farming, extensive agroforestry mosaic, peri-urban, extensive pastoral farming, very extensive pastoral farming, multifunctional), Forest (managed forestry, mixed forest), Non-productive use (unmanaged land, unmanaged forest, minimal management, urban). PAs are represented as a share of areas in the cells.

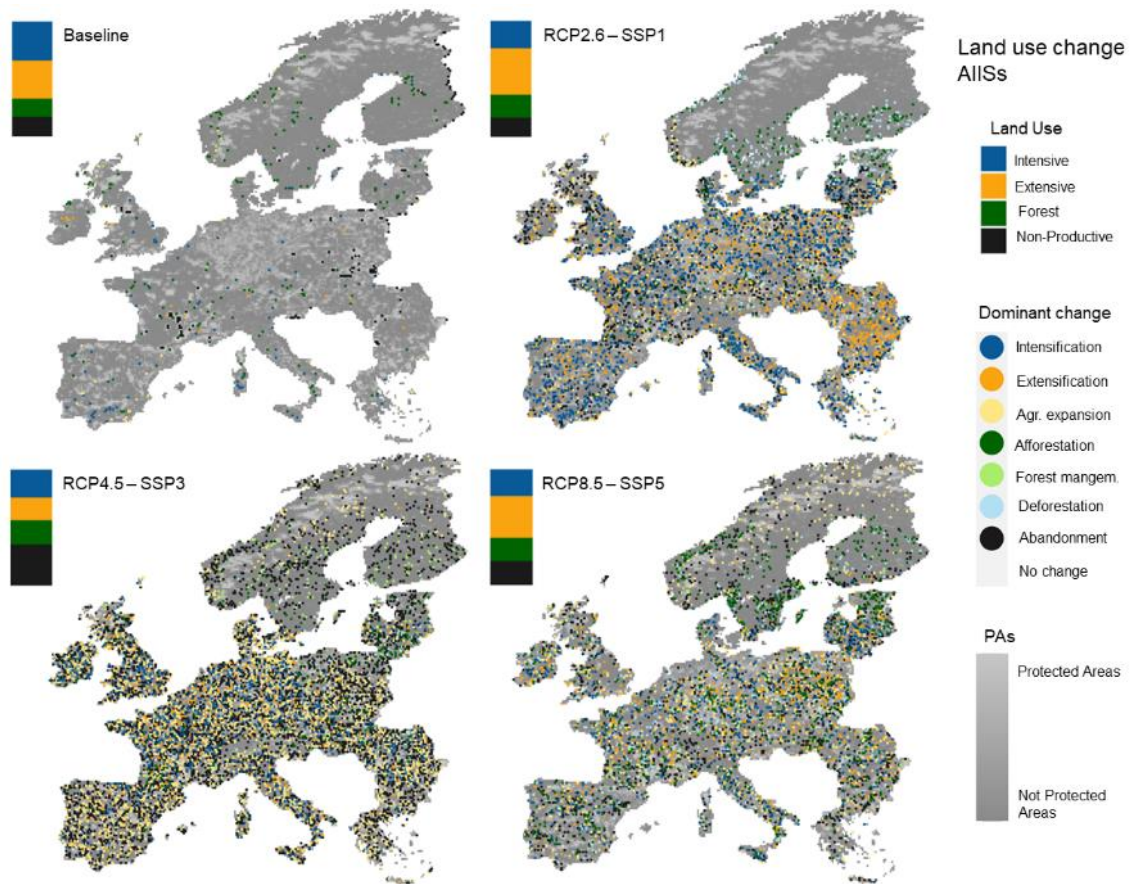


Figure A53– Dominant land use changes in 2080s from enhanced network connectivity under the AllS configuration, for baseline conditions and for three different future scenarios. Dominant changes are computed with respect to the EPA configuration in each scenario. Changes are classified as: Extensification – intensive land use changing to extensive, Intensification – extensive land use changing to intensive, Afforestation – forest on previously unforested land, Deforestation – forest changing to unforested land uses, Abandonment – active management of any sort changing to unmanaged, Agricultural expansion – non-agricultural use to intensive or extensive agriculture, Forest management – unmanaged or semi-natural forest to managed forest. The bar charts represent the final percentage of broad land cover types per scenario, grouped in four main categories: Intensive (intensive arable farming, intensive agroforestry mosaic, intensive farming, intensive pastoral farming), Extensive (mixed farming, mixed pastoral farming, extensive agroforestry mosaic, peri-urban, extensive pastoral farming, very extensive pastoral farming, multifunctional), Forest (managed forestry, mixed forest), Non-productive use (unmanaged land, unmanaged forest, minimal management, urban). PAs are represented as a share of areas in the cells.

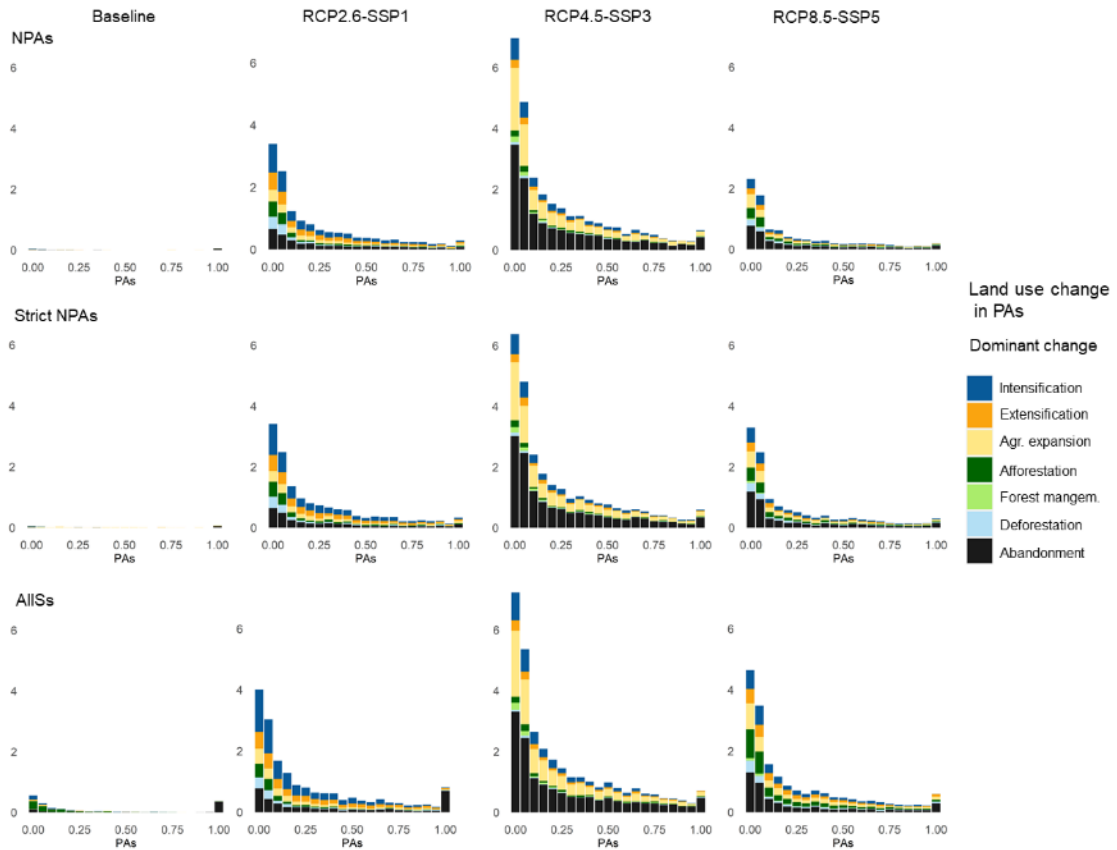


Figure A54 - Dominant land use change per level of protection in the different configurations and climate change scenarios. PAs axes represent the percentage of protection in each cell of the mode, ranging from 0 (not protected) to 1 (fully protected). Dominant changes are computed with respect to the EPA configuration in each scenario. Changes are classified as: Extensification – intensive land use changing to extensive, Intensification – extensive land use changing to intensive, Afforestation – forest on previously unforested land, Deforestation – forest changing to unforested land uses, Abandonment – active management of any sort changing to unmanaged, Agricultural expansion – non-agricultural use to intensive or extensive agriculture, Forest management – unmanaged or semi-natural forest to managed forest.

3.5 Ecosystem services changes

Services supply and demand trends

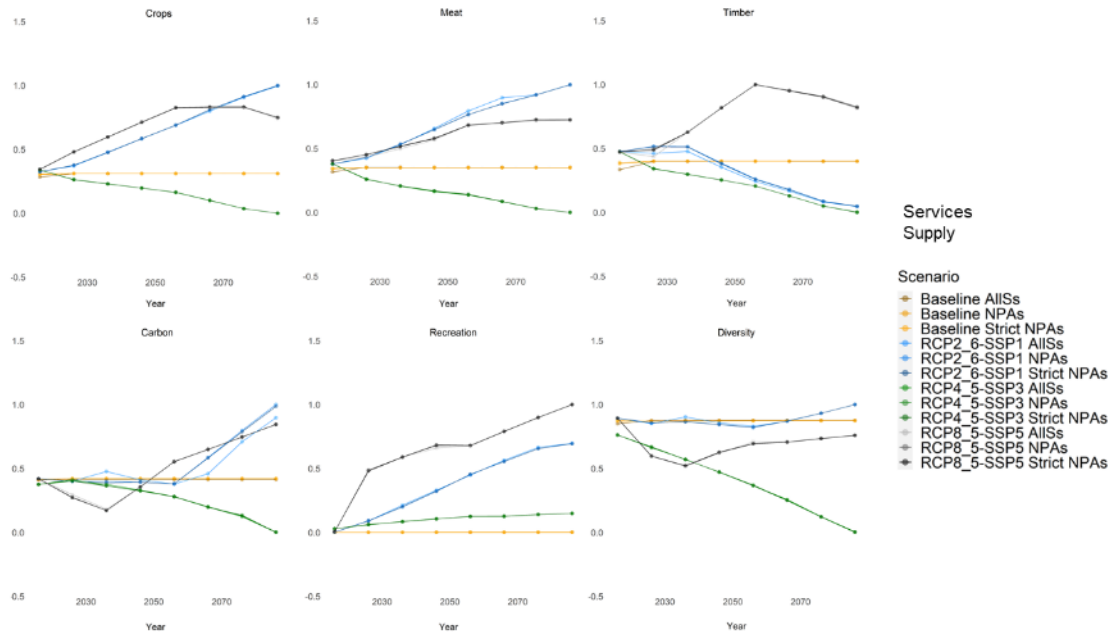


Figure A55 - Trends of services supply for each network configuration in climatic and socio-economic scenarios. The y axis reports the ratio between supply and demand scaled by the size of demand: positive values indicate that supply is equal to or greater than demand.

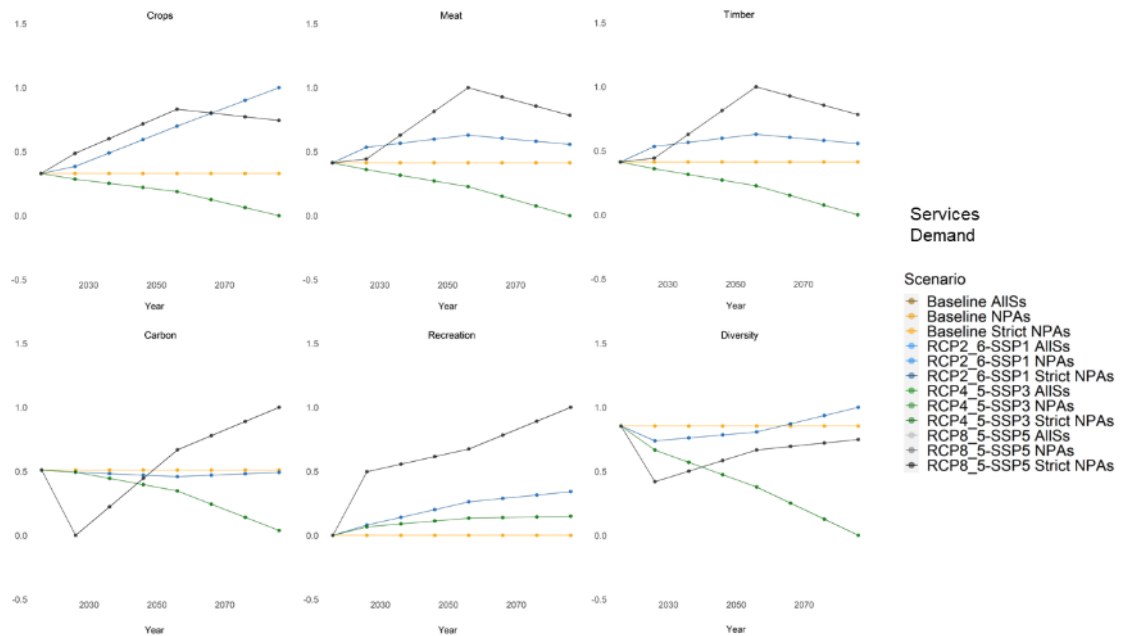


Figure A56 - Trends of services demand for each network configuration in climatic and socio-economic scenarios. The y axis reports the ratio between supply and demand scaled by the size of demand: positive values indicate that supply is equal to or greater than demand.

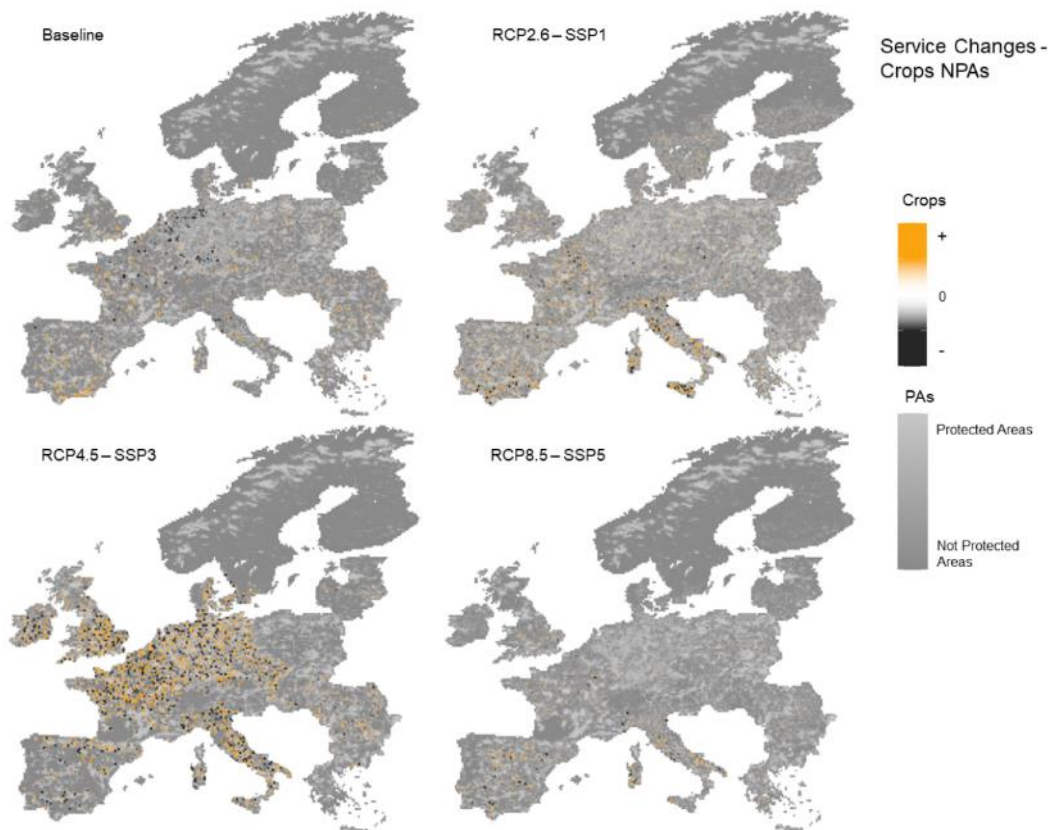


Figure A57 - Changes in crop production across Europe in 2080s in each scenario, with the NPA configuration compared to the EPA configuration (change values are ratios of production within each cell). Yellow dots represent gains (+), while black dots represent losses (-) in production.

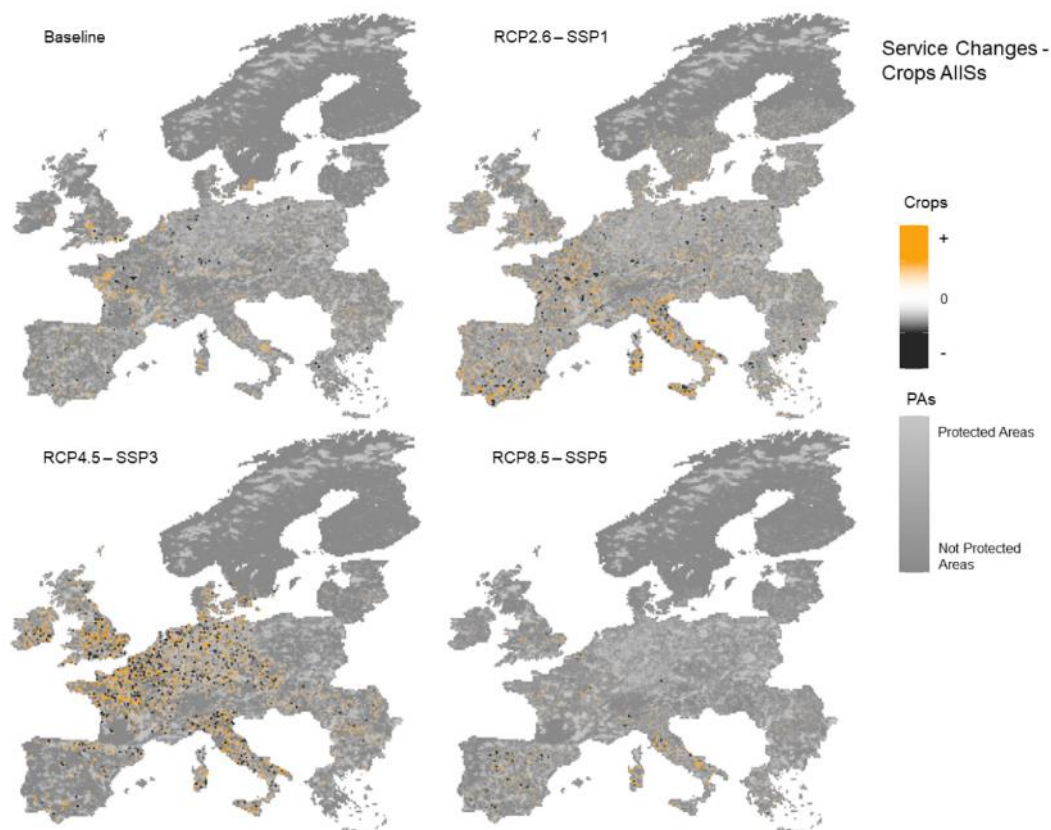


Figure A58 - Changes in crop production across Europe in 2080s in each scenario, with the AllS configuration compared to the EPA configuration (change values are ratios of production within each cell). Yellow dots represent gains (+), while black dots represent losses (-) in production.

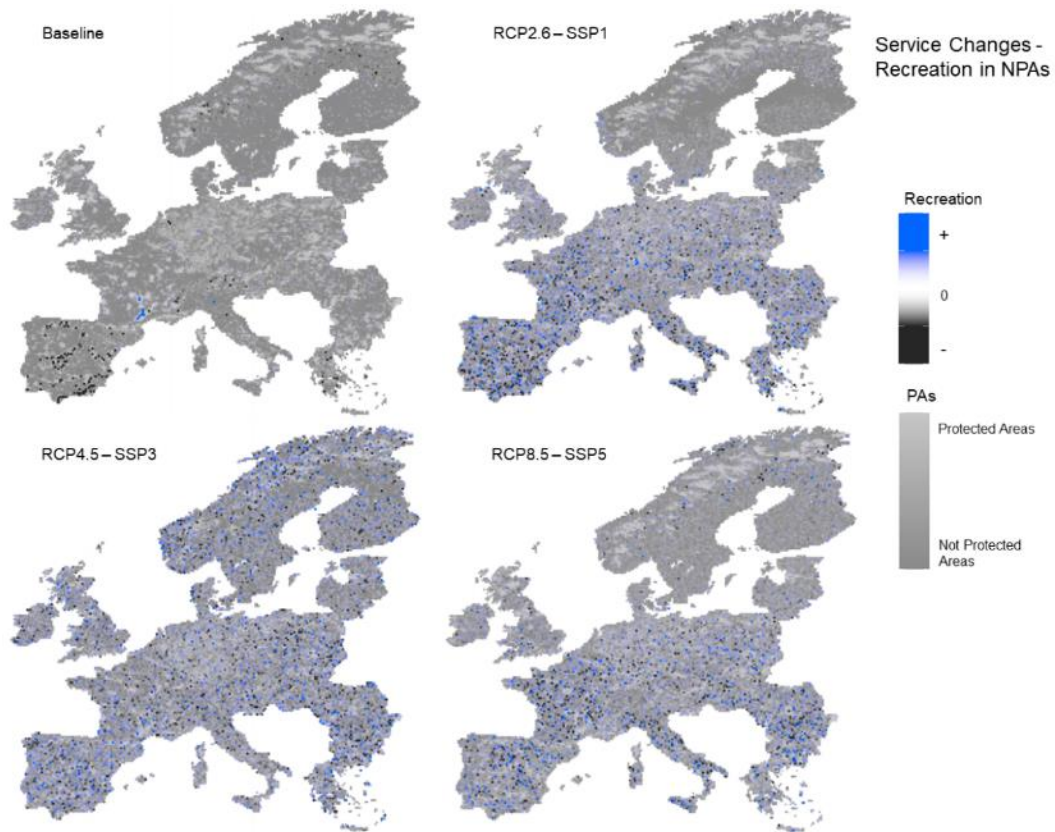


Figure A59 - Changes in recreational service across Europe in 2080s in each scenario, with the NPA configuration compared to the EPA configuration (change values are ratios of provision within each cell). Blue dots represent gains (+), while black dots represent losses (-) of recreation.

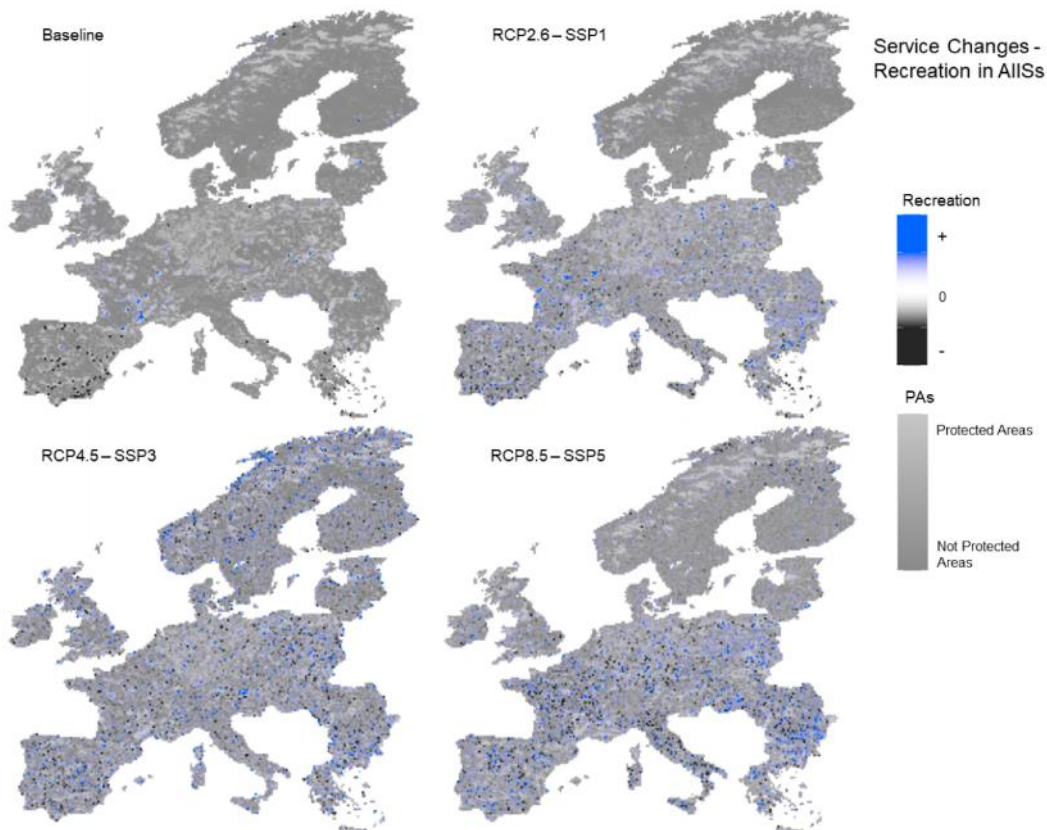


Figure A60 - Changes in recreational service across Europe in 2080s in each scenario, with the AllS configuration compared to the EPA configuration (change values are ratios of provision within each cell). Blue dots represent gains (+), while black dots represent losses (-) of recreation.

References

Dudley, N.: Guidelines for Applying Protected Area Management Categories, Gland, Switzerland. [online] Available from: www.iucn.org/pa_guidelines (Accessed 12 January 2022), 2008.

EU: Copernicus Land Monitoring Service 2018: Corine Land Cover v 2020_20u1, [online] Available from: <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=metadata>, 2018.

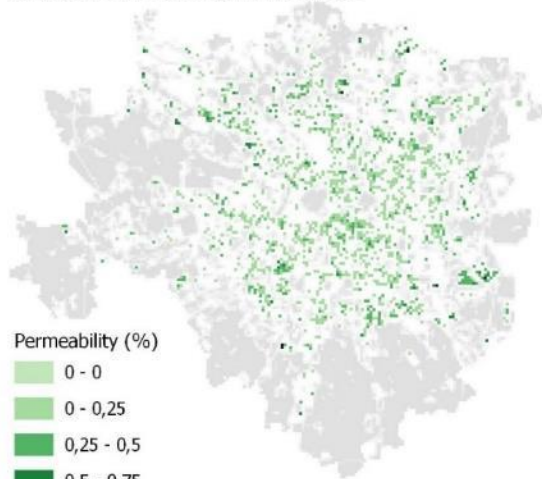
Annex Chapter 4

4.1 Scenarios of green conversion

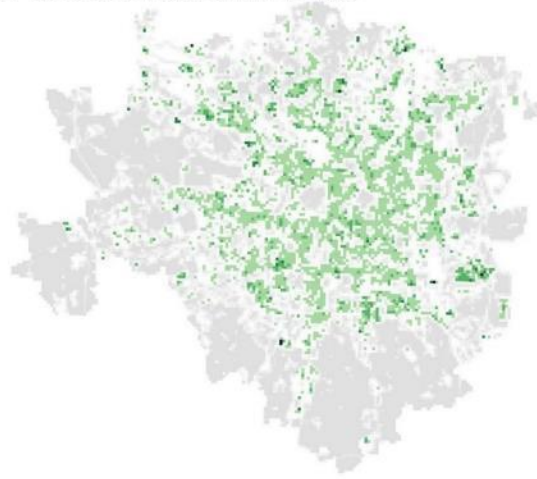
Here we report the different percentage of green conversion associated to the different scenarios of green improvement (Green Buildings, Green Spaces, Green City) for minimize the damage and population exposed.

Green Buildings to minimize damage

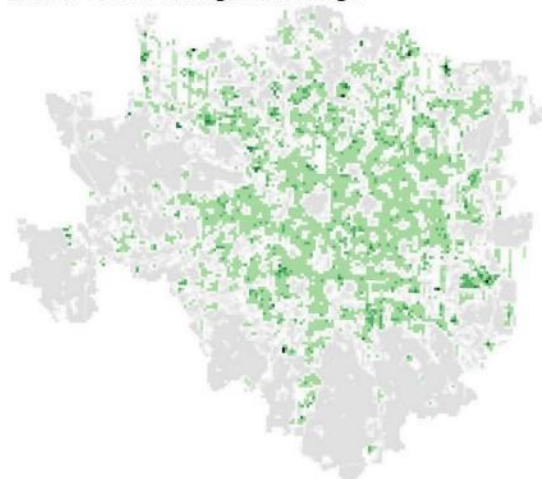
a. 25% Green Buildings min damage



b. 50% Green Buildings min damage



c. 75% Green Buildings min damage



d. 100% Green Buildings min damage

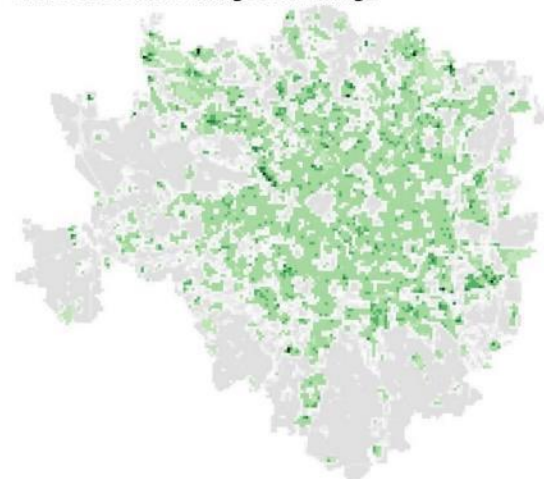
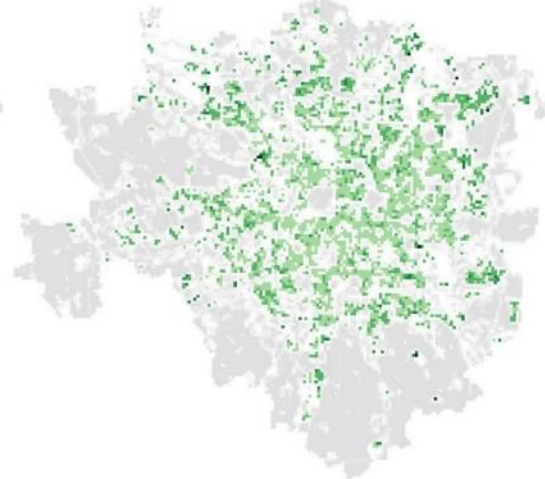
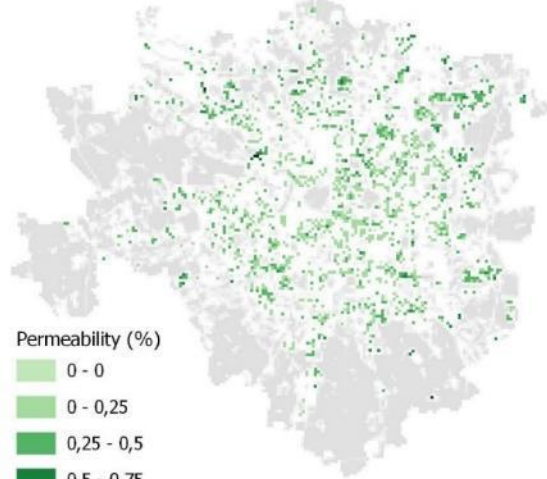


Figure A61 – Percentage of green conversion for the Green Buildings scenario to minimize damage. Grey cells represent the existing green network.

Green Spaces to minimize damage

a. 25% Green Spaces min damage

b. 50% Green Spaces min damage



Permeability (%)

0 - 0

0 - 0,25

0,25 - 0,5

0,5 - 0,75

0,75 - 1

c. 75% Green Spaces min damage

d. 100% Green Spaces min damage

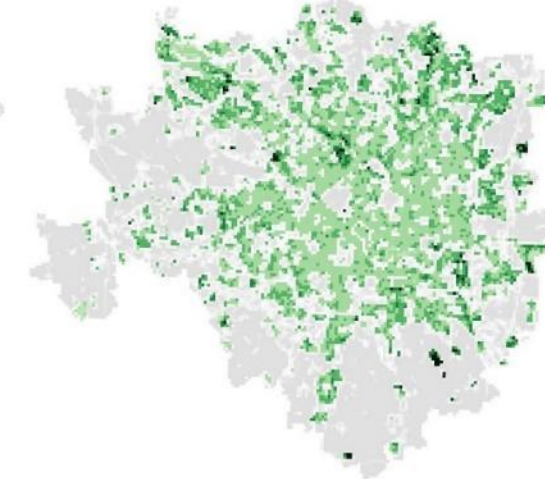
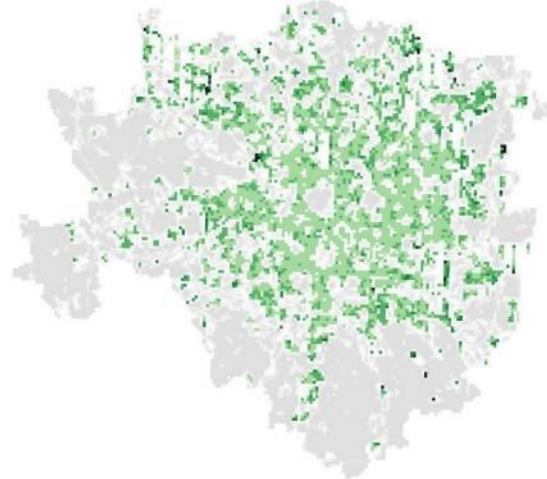
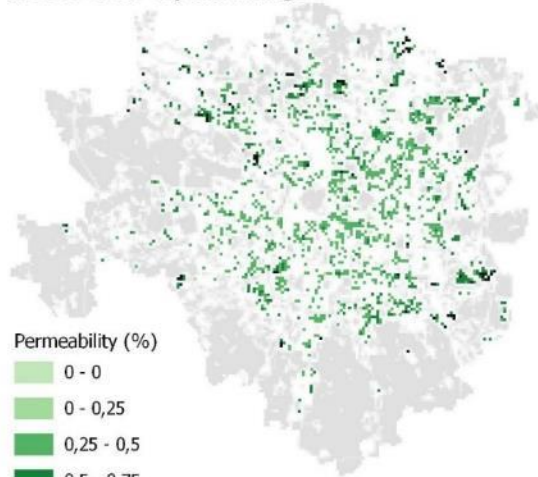


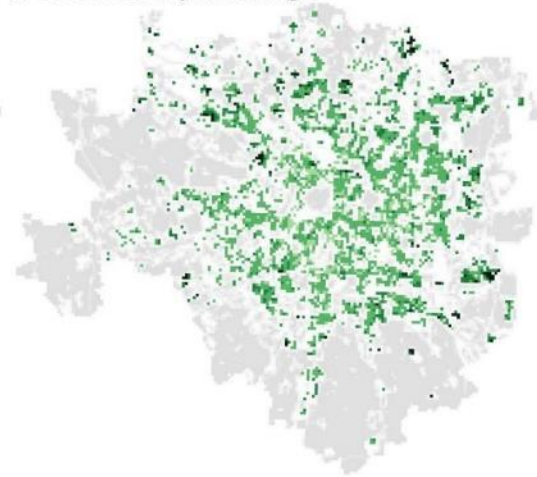
Figure A62 – Percentage of green conversion for the Green Spaces scenario to minimize damage. Grey cells represent the existing green network.

Green City to minimize damage

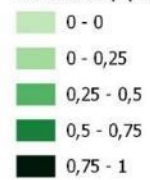
a. 25% Green City min damage



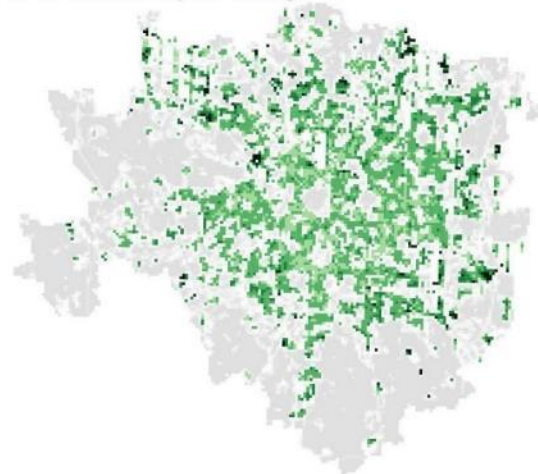
b. 50% Green City min damage



Permeability (%)



c. 75% Green City min damage



d. 100% Green City min damage

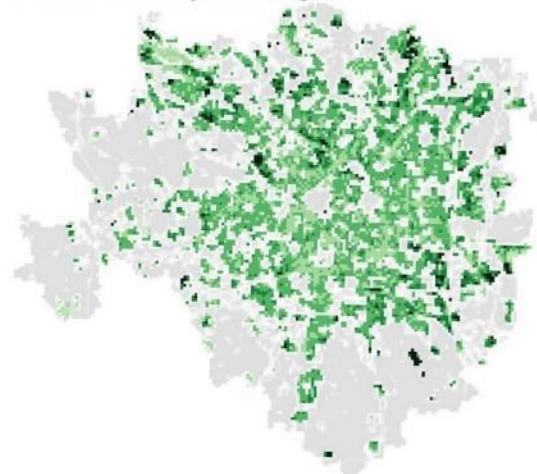


Figure A63– Percentage of green conversion for the Green City scenario to minimize damage. Grey cells represent the existing green network.

Green Buildings to minimize population exposed

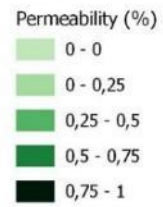
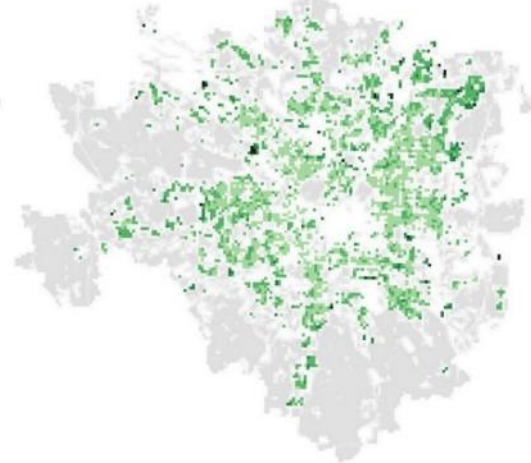
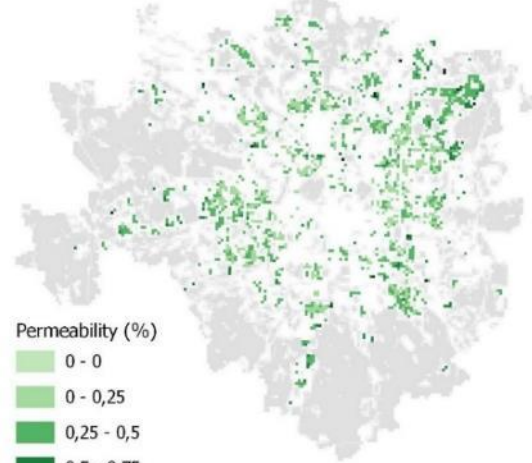


Figure A64 – Percentage of green conversion for the Green Buildings scenario to minimize population exposed. Grey cells represent the existing green network.

Green Spaces to minimize population exposed

a. 25% Green Spaces min pop exposed

b. 50% Green Spaces min pop exposed



c. 75% Green Spaces min pop exposed

d. 100% Green Spaces min pop exposed

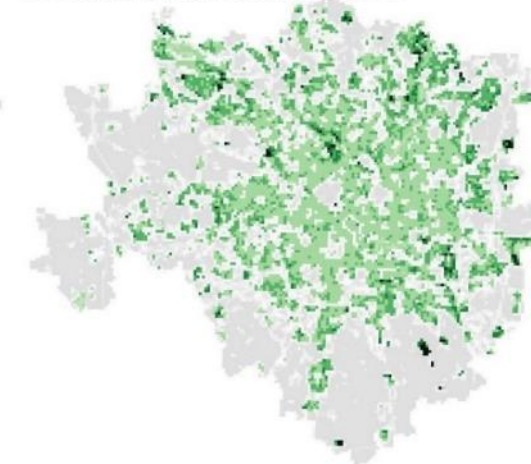
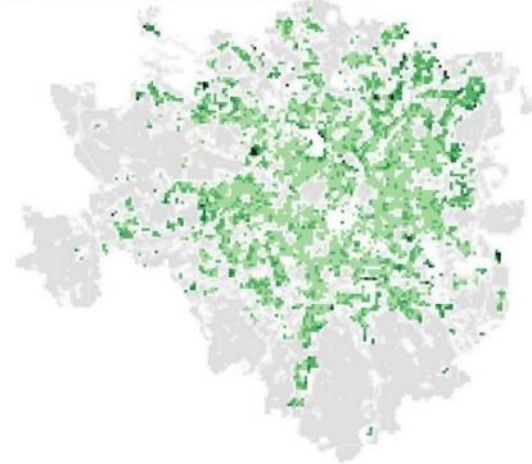
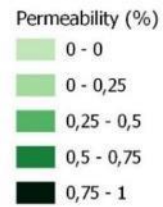
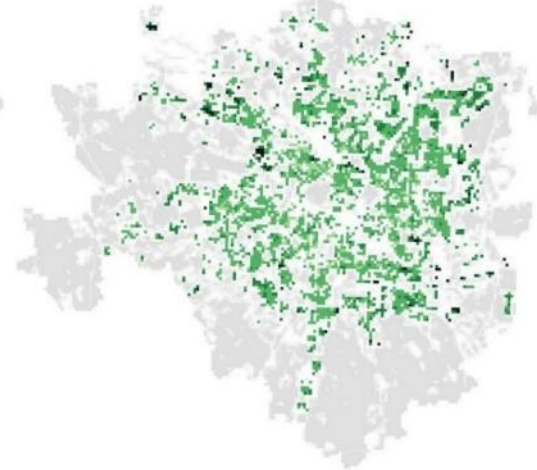
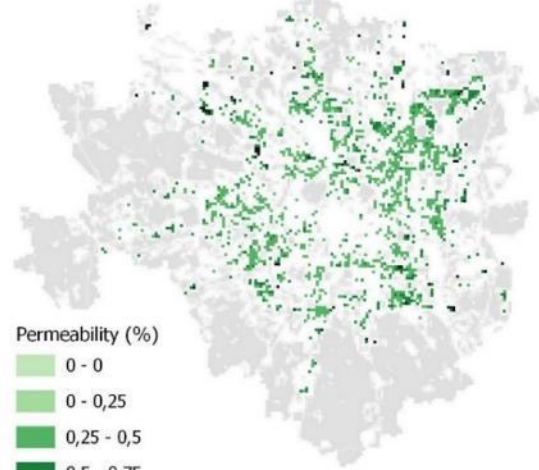


Figure A65 – Percentage of green conversion for the Green Spaces scenario to minimize population exposed. Grey cells represent the existing green network.

Green City to minimize population exposed

a. 25% Green City min pop exposed

b. 50% Green City min pop exposed



c. 75% Green City min pop exposed

d. 100% Green City min pop exposed

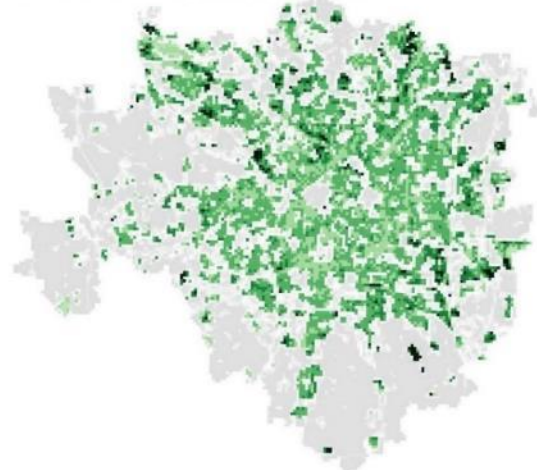
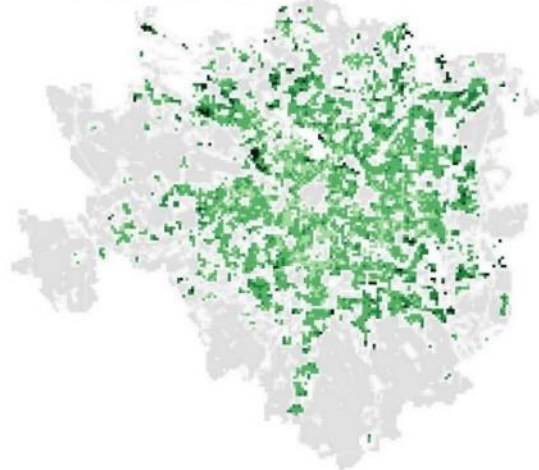


Figure A66 – Percentage of green conversion for the Green City scenario to minimize population exposed. Grey cells represent the existing green network.

4.2 Expected Annual Damage

The following figure shows the expected annual damage to buildings for minimization of population exposed configuration.

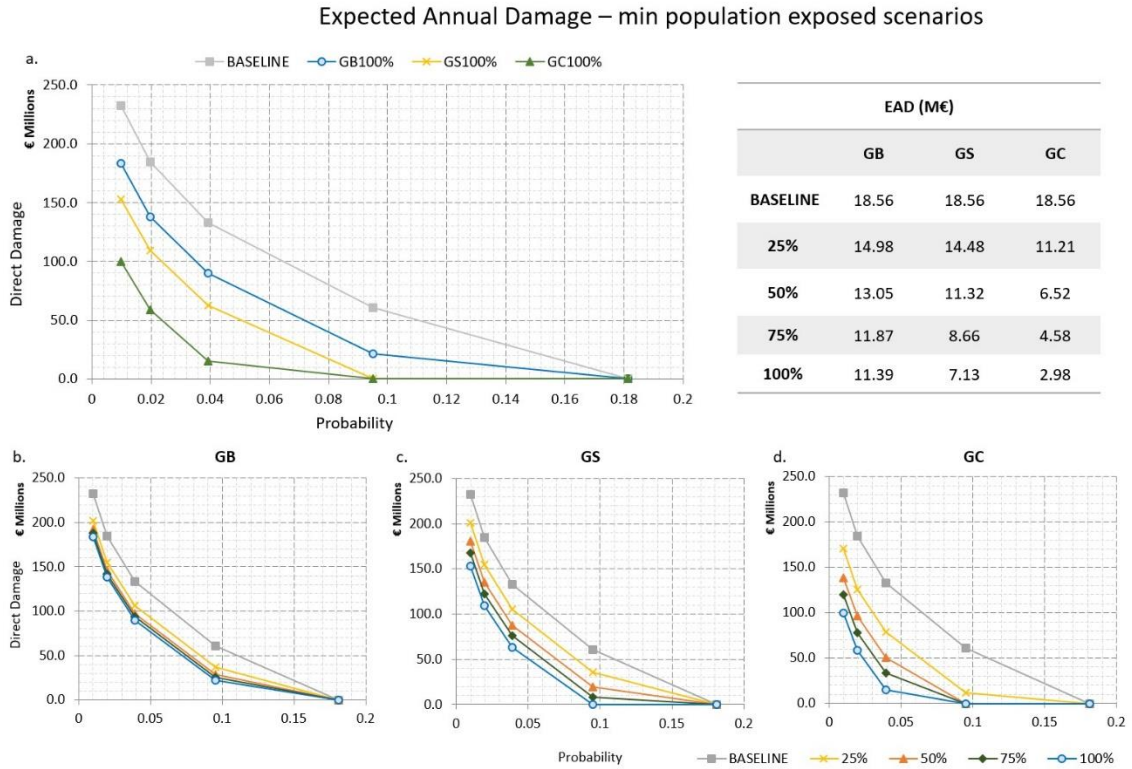


Figure A.67 – Estimated expected annual damage values and curves. A) comparison of EAD for 100% of green in all scenarios; b) EAD estimated for Green Buildings scenarios; c) EAD estimated for Green Spaces scenarios; d) EAD for Green City scenarios.

4.3 Expected Annual Exposed Population

The following figures show the expected annual exposed population for minimization of damage configuration for classes of water depth > 5cm and >100cm.

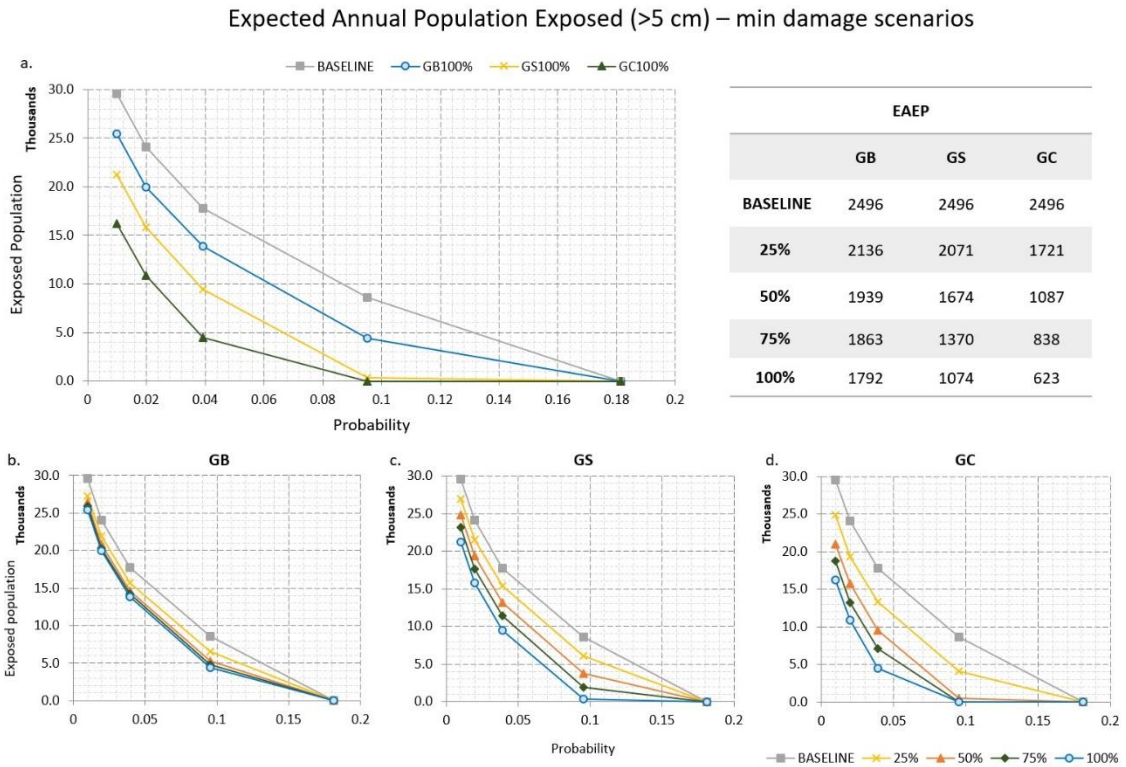


Figure A.68 - Estimated expected annual population exposed values and curves for classes of water depth >5 cm. A) comparison of EAPE for 100% of green in all scenarios; b) EAPE estimated for Green Buildings scenarios; c) EAPE estimated for Green Spaces scenarios; d) EAPE for Green City scenarios.

Expected Annual Population Exposed (>100 cm) – min damage scenarios

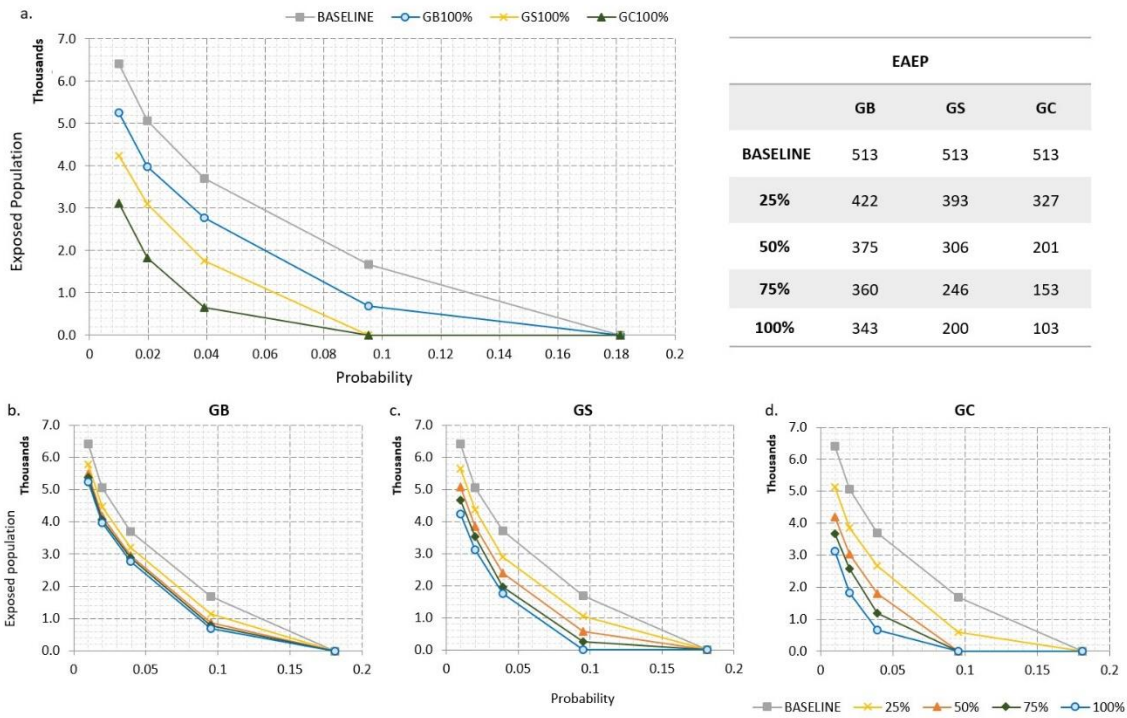


Figure A.69 - Estimated expected annual population exposed values and curves for class of water depth >100 cm. A) comparison of EAPE for 100% of green in all scenarios; b) EAPE estimated for Green Buildings scenarios; c) EAPE estimated for Green Spaces scenarios; d) EAPE for Green City scenarios

ACKNOWLEDGEMENTS

PhD was a great adventure.

During these years, I grew up and learned a lot. I had the chance to live stimulating experiences that contribute to build my profile as a researcher. The path was not always easy and I have to thank all the people that supported me during this journey.

Thank you to Jaro for guiding me in the research world from the beginning. The many opportunities to travel and interface with other points of views, helped me to become a more independent, curious, and prepared researcher.

Thanks to all CMCC colleagues for welcoming and supporting me, with your knowledge, suggestions, and fruitful discussions. Elisa, Francesca, Veronica, Silvia, Sepehr, Arthur, Mattia for running together through deadlines, proposals, maps, models, and achievements.

Thank you to the Gecosistema team for supporting my research project with your great expertise and competencies.

I am very grateful to all KIT people. Thank you Almut and Mark for hosting me in the splendid setting of Garmisch and in your stimulating research groups. Thank you to Calum for the precious contribution and kind availability. Thank you to all the friends, Kathi, Isabel, Richard, Karina, Heera and Bumsuk for sharing coffee, hiking, walking and chat. Starting a new journey with you all is a privilege.

A big thanks to my PhD mates. Thank you for sharing struggles and satisfaction during the 1st year of courses. To the junior RAAS team for the lunches, the smiles and for making working days more shining. To Sebastian for all the chats and laughs between a map and a paper draft. Thank you to the Quixote friends, all around the world, for inspiring me that make-the-change is possible.

And finally, thank you to my family and friends. To my parents for giving me all the instruments to follow my way. To Noemi for being there beside me. To Mauro for walking with me every day unconditionally. To all my friends and Mestre2 family for sharing also this adventure together.

Thank you all to be there along the way.

“...è la strada di chi parte ed arriva per partire”



Università
Ca' Foscari
Venezia

DEPOSITO ELETTRONICO DELLA TESI DI DOTTORATO

DICHIARAZIONE SOSTITUTIVA DELL'ATTO DI NOTORIETA'

(Art. 47 D.P.R. 445 del 28/12/2000 e relative modifiche)

Io sottoscritto Andrea Staccione

nat a. a Genova (prov. GE) il 27/06/1991

residente a Venezia in Via Adige n. 2F

Matricola (se posseduta) 835047 Autore della tesi di dottorato dal titolo:
Green Infrastructure Network for Climate Change Adaptation and Disaster Risk Reduction:
performance assessment of spatial connectivity

Dottorato di ricerca in Science and Management of Climate Change

(in cotutela con

Ciclo 34°

Anno di conseguimento del titolo 2022-2023

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.....

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L'estratto va firmato e rilegato come ultimo foglio della tesi.

Studente: ANDREA STACCIONE _____ matricola: 835047 _____

Dottorato: SCIENCE AND MANAGEMENT OF CLIMATE CHANGE _____

Ciclo: 34° _____

Titolo della tesi¹: GREEN INFRASTRUCTURE NETWORK FOR CLIMATE CHANGE ADAPTATION AND DISASTER RISK REDUCTION: PERFORMANCE ASSESSMENT OF SPATIAL CONNECTIVITY

Abstract (italiano):

Virare verso una relazione più sostenibile tra natura e società è fondamentale per una maggiore resilienza climatica. Le infrastrutture verdi possono contribuire a questa transizione. Ma il modo in cui esse sono distribuite e connesse nel territorio ne influenza l'efficacia. La tesi esplora i vantaggi di costruire una rete di infrastrutture verdi per rispondere ai bisogni della società in condizioni di cambiamento climatico. I capitoli studiano l'implementazione e la valutazione di una rete verde a diverse scale. Viene presentata una metodologia per progettare di una rete di infrastrutture verdi e studiarne gli effetti in termini di disponibilità idrica in agricoltura, cambiamento di uso di suolo e servizi ecosistemici forniti, mitigazione del rischio alluvionale. I risultati mostrano gli effetti positivi di una rete verde per l'adattamento ai cambiamenti climatici, fornendo spunti per un miglior uso di questo approccio da un punto di vista ambientale, sociale ed economico.

Abstract (english):

A transition towards a more sustainable interaction between nature and society is fundamental for climate resilience. Green infrastructures can contribute to pursue this transformation. But the way they are distributed and connected across the landscape is crucial to build effective solutions. The thesis explores the benefits of building a green infrastructure as a network to enable the desired response to societal needs in climate change conditions. The chapters study the implementation and assessment of a green network at different spatial scales. The work presents a methodology to plan a green infrastructure network and to study the effects for water scarcity in agriculture, for land use and ecosystem services changes, for pluvial flood risk mitigation. Results show positive effects of green infrastructure networks for climate change adaptation and disaster risk reduction, providing insights to better use a network approach from an environmental, social and economic perspective.

Firma dello studente



¹ Il titolo deve essere quello definitivo, uguale a quello che risulta stampato sulla copertina dell'elaborato consegnato.