Analyzing the water-energy-food-ecosystem nexus by integrating hydrological modeling and system dynamics tools

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XXXVII CYCLE - ICAR/02 Hydraulic and
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Department of Civil, Environmental,
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Analyzing the Water-Energy-Food-Ecosystem Nexus by Integrating Hydrological Modeling and System Dynamics Tools

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Al Magnifico Rettore del Politecnico di Bari

la sottoscritta **YASEEN Marwah** nato a **Erbil-IRAQ** il **10/12/1990** residente a **Valenzano (BA)** in via **ALCIDE DE GASPERI 60** e-mail **marwah.yaseen@poliba.it** iscritto al 3° anno di Corso di Dottorato di Ricerca in **Rischio, Sviluppo Ambientale, Territoriale ed Edilizio** ciclo **XXXVII** ed essendo stato ammesso a sostenere l'esame finale con la prevista discussione della tesi dal titolo: Analyzing the Water-Energy-Food-Ecosystem Nexus by Integrating Hydrological Modeling and System Dynamics Tools

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RISK ENVIRONMENTAL, TERRITORIAL, AND BUILDING

SSD: ICAR/02 - Hydraulic and Maritime Constructions and Hydrology

Final Dissertation

Analyzing the Water-Energy-Food-Ecosystem Nexus by Integrating Hydrological Modeling and System Dynamics Tools

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By

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EXTENDED ABSTRACT (eng)

Effective and integrated management of natural resources is crucial for achieving sustainability, particularly in the context of interrelated challenges posed by using these resources. This study addresses four complementary aspects of resource management using a ‘Nexus’ approach within the Tarquinia/ Marta River, highlighting how this region serves as a model that could be applied to other areas of the Mediterranean. The study proposes an innovative approach based on System Dynamics Modeling techniques and hydrological modeling, which is summarized below.

The first chapter emphasizes the Nexus concept, which has gained interest as a theoretical framework for understanding the complex interconnections among natural resources. It highlights the need for tools and methods to effectively map and analyze these interdependencies, facilitating stakeholder engagement in sustainability transitions. In this context, the study employs a Participatory System Dynamics Modeling (PSDM) approach to enhance the understanding and management of the Water-Energy-Food-Ecosystem Nexus (WEFE Nexus). This approach is tested concerning the Tarquinia plain in Italy, where a strong interdependency and conflict exists between agriculture and environmental conditions. The approach aims to achieve stakeholder consensus on challenges arising from conflicts between different sectors and subsectors in areas under intensive agricultural activity, while also considering future changes due to climate change. The analysis of the Causal Loop Diagram (CLD) helps identify the main challenges for the area and highlights the need for a better understanding and modeling of key phenomena. The centrality of agricultural activities, in terms of productivity, relevance for farmers, and impacts on water quality and natural areas, underscores the necessity of investigating these impacts and potential mitigation measures using specific agro-hydrological models.

The second chapter builds on the main challenges identified using PSDM and proposes well-established hydrological modeling (SWAT) to further enhance the understanding and management of the WEFE Nexus. In line with the research

objectives, the SWAT model has been utilized with the available datasets to first establish the current conditions in the watershed and, secondly, to develop specific scenarios representing the effects of climate change. The Sequential Uncertainty Fitting algorithm version 2 (SUFI-2), a part of the SWAT-CUP tool package, has been employed for calibration, validation, and sensitivity analysis. Data from the EURO-CORDEX initiative includes various climate models involving regional climate models (RCMs) nested in different global circulation models (GCMs) used in this study. Historical experiments and future projections (based on the RCP 8.5 worst-case greenhouse gas emission scenario) have been selected. The most reliable EURO-CORDEX climate projections have been selected following a rigorous performance evaluation of several high-resolution combinations (GCMs-RCMs) over the area. This section of the study has investigated the hydrological balance, soil erosion and nutrient yield in the study watershed, focusing particularly on agricultural practices and climate change impacts. The study findings have revealed significant soil loss and changes in total nitrogen (TN) and total phosphorus (TP) yield under both current and future scenarios, with agricultural practices exacerbating these issues. Conclusively, this chapter highlights the need for the implementation of effective management strategies and mitigation measures to address these challenges.

The third chapter explores the implementation of Best Management Practices (BMPs) to address on- and off-site impacts resulting from soil erosion and nutrient pollution in the study area, a region susceptible to these environmental challenges due to its Mediterranean climate and intensive agricultural practices. Utilizing the Soil and Water Assessment Tool (SWAT), the study assesses different individual BMPs, such as terracing, contour farming, no-tillage, and residue management as well as their combination. The results underscore the effectiveness of combined BMPs in reducing erosion and nutrient pollution, with terracing being particularly impactful in minimizing soil loss in hotspot areas within the watershed and reducing sediment and nutrient loading into the river. The analysis emphasizes the importance of integrated BMP approaches for sustainable soil

and water management in agricultural areas as well as highlighting the need for targeted management strategies to mitigate environmental impacts and enhance water quality.

The last chapter focuses on the application of PSDM, describing how a transition from Causal Loop Diagrams to quantitative models (stock and flow) can help explore potential future trajectories of the system under various conditions, particularly aiming to enhance its resilience. Stakeholders, including policy and decision-makers, were actively involved in co-designing, analyzing, and discussing relevant scenarios. The study emphasizes the integration of stakeholder knowledge with technical modeling efforts to identify sustainable management strategies for water resources, ecosystems, and agricultural practices in the region. At the core of the chapter is the development of a comprehensive stock and flow model, coupled with the SWAT hydrological model, to investigate the long-term impacts of agricultural practices on water resources and ecosystem sustainability. This integrated modeling approach enables a detailed analysis of how management strategies, particularly those involving Nature-Based Solutions (NBS) affect water quantity, quality, and agricultural productivity under varying climate change scenarios. Besides supporting system understanding, the proposed approach showed the potential to foster stakeholder dialogue, which is crucial for building consensus on sustainable development pathways for the area. Key methodological challenges and potential needs for further innovation are also included.

key words

WEFE Nexus, System Dynamics Modeling, participatory approach, Causal Loop Diagram, agro-hydrological model, SWAT, SWAT-CUP, EURO-CORDEX, The Aras Diagram, performance evaluation, climate change, hydrological balance, soil erosion, nutrient pollution, Best Management Practices, Stock and Flow model, scenario analysis.

EXTENDED ABSTRACT (ita)

La gestione efficace e integrata delle risorse naturali è cruciale per raggiungere la sostenibilità, in particolare nel contesto delle sfide interconnesse poste dall'uso di queste risorse. Questo studio affronta quattro aspetti complementari della gestione delle risorse utilizzando un approccio ‘Nexus’ nel contesto di Tarquinia/Fiume Marta, evidenziando come questa regione possa servire da modello applicabile ad altre aree del Mediterraneo. Lo studio propone un approccio innovativo basato su tecniche di System Dynamics Modeling e modellazione idrologica, sintetizzato di seguito.

Il primo capitolo enfatizza il concetto di Nexus, che ha guadagnato interesse come quadro teorico per comprendere le complesse interconnessioni tra le risorse naturali. Evidenzia la necessità di strumenti e metodi per mappare e analizzare efficacemente queste interdipendenze, facilitando il coinvolgimento delle parti interessate nelle transizioni verso la sostenibilità. In questo contesto, lo studio utilizza un approccio di Participatory System Dynamics Modeling (PSDM) per migliorare la comprensione e la gestione del Nexus acqua-energia-cibo-ecosistema (WEFE Nexus). Questo approccio è stato testato riguardo alla pianura di Tarquinia in Italia, dove esiste una forte interdipendenza e conflitto tra l'agricoltura e le condizioni ambientali. L’approccio mira a raggiungere il consenso delle parti interessate sulle sfide derivanti dai conflitti tra diversi settori e sottosettori nelle aree soggette ad attività agricola intensiva, considerando anche i futuri cambiamenti dovuti ai cambiamenti climatici. L’analisi del Causal Loop Diagram (CLD) aiuta a identificare le principali sfide per l’area ed evidenzia la necessità di una migliore comprensione e modellizzazione dei fenomeni chiave. La centralità delle attività agricole, in termini di produttività, rilevanza per gli agricoltori e impatti sulla qualità dell’acqua e sulle aree naturali, sottolinea la necessità di studiare questi impatti e le potenziali misure di mitigazione utilizzando specifici modelli agro-idrologici.

Il secondo capitolo si basa sulle principali sfide identificate utilizzando PSDM e propone modelli idrologici consolidati (SWAT) per migliorare

ulteriormente la comprensione e la gestione del WEFE Nexus. In linea con gli obiettivi della ricerca, il modello SWAT è stato utilizzato con i set di dati disponibili per stabilire innanzitutto le condizioni attuali nel bacino idrografico e, in secondo luogo, per sviluppare scenari specifici che rappresentano gli effetti del cambiamento climatico. L'algoritmo Sequential Uncertainty Fitting versione 2 (SUFI-2), parte del pacchetto di strumenti SWAT-CUP, è stato utilizzato per la calibrazione, la convalida e l'analisi della sensibilità. I dati dell'iniziativa EURO-CORDEX includono vari modelli climatici che coinvolgono modelli climatici regionali (RCM) annidati in diversi modelli di circolazione globale (GCM) utilizzati in questo studio. Sono stati selezionati esperimenti storici e proiezioni future (basate sullo scenario peggiore delle emissioni di gas serra RCP 8.5). Le proiezioni climatiche EURO-CORDEX più affidabili sono state selezionate dopo una rigorosa valutazione delle prestazioni di diverse combinazioni ad alta risoluzione (GCM-RCM) sull'area. Questa sezione dello studio ha studiato l'equilibrio idrologico, l'erosione del suolo e la resa dei nutrienti nel bacino idrografico, concentrandosi in particolare sulle pratiche agricole e sugli impatti dei cambiamenti climatici. I risultati dello studio hanno rivelato una significativa perdita di suolo e cambiamenti nella resa totale di azoto (TN) e fosforo totale (TP) negli scenari attuali e futuri, con le pratiche agricole che esacerbano questi problemi. In conclusione, questo capitolo evidenzia la necessità di attuare strategie di gestione efficaci e misure di mitigazione per affrontare queste sfide.

Il terzo capitolo esplora l'implementazione delle Migliori Pratiche di Gestione (BMP) per affrontare gli impatti in loco e fuori sito derivanti dall'erosione del suolo e dall'inquinamento da nutrienti nell'area di studio, una regione suscettibile a queste sfide ambientali a causa del suo clima mediterraneo e dell'intensa attività pratiche agricole. Utilizzando lo strumento di valutazione del suolo e dell'acqua (SWAT), lo studio valuta diverse BMP individuali, come il terrazzamento, l'agricoltura di contorno, la non lavorazione del terreno e la gestione dei residui, nonché la loro combinazione. I risultati sottolineano l'efficacia delle BMP combinate nel ridurre l'erosione e l'inquinamento da nutrienti, con i terrazzamenti che risultano particolarmente efficaci nel ridurre al minimo la perdita di suolo nelle aree calde all’interno dello spartiacque e nel ridurre il carico di sedimenti e nutrienti nel fiume. L’analisi sottolinea l’importanza degli approcci BMP integrati per la gestione sostenibile del suolo e dell’acqua nelle aree agricole, oltre a evidenziare la necessità di strategie di gestione mirate per mitigare gli impatti ambientali e migliorare la qualità dell’acqua.

L’ultimo capitolo si concentra sull’applicazione del PSDM, descrivendo come una transizione dai Causal Loop Diagrams ai modelli quantitativi (stock e flusso) può aiutare a esplorare potenziali traiettorie future del sistema in varie condizioni, con l’obiettivo in particolare di migliorare la sua resilienza. Le parti interessate, compresi i decisori politici e decisionali, sono state coinvolte attivamente nella co-progettazione, analisi e discussione degli scenari rilevanti. Lo studio sottolinea l’integrazione delle conoscenze delle parti interessate con gli sforzi di modellazione tecnica per identificare strategie di gestione sostenibile per le risorse idriche, gli ecosistemi e le pratiche agricole nella regione. Al centro del capitolo c’è lo sviluppo di un modello completo di stock e flussi, abbinato al modello idrologico SWAT, per studiare gli impatti a lungo termine delle pratiche agricole sulle risorse idriche e sulla sostenibilità degli ecosistemi. Questo approccio di modellizzazione integrato consente un’analisi dettagliata di come le strategie di gestione, in particolare quelle che coinvolgono le soluzioni basate sulla natura (NBS), influenzano la quantità, la qualità e la produttività agricola dell’acqua in diversi scenari di cambiamento climatico. Oltre a supportare la comprensione del sistema, l’approccio proposto ha mostrato il potenziale per promuovere il dialogo tra le parti interessate, che è fondamentale per creare consenso sui percorsi di sviluppo sostenibile per l’area. Sono incluse anche le principali sfide metodologiche e le potenziali esigenze di ulteriore innovazione.

CONTENTS

INTRODUCTION/INTRODUZIONE

The management of natural resources is critical to sustaining life, supporting ecosystems, and enabling socio-economic development. According to the recent Intergovernmental Panel on Climate Change (IPCC) assessment report, the Mediterranean region is expected to encounter severe challenges in the near future (Pörtner et al., 2022). These challenges include increasing temperatures, extreme precipitation patterns, and a growing frequency and intensity of extreme weather events. The impacts on natural resources, particularly water resources, are anticipated to be severe, leading to heightened conflicts among various water users and uses (Jury & Vaux, 2007; Pluchinotta et al., 2018; Portoghese et al., 2015). Agriculture is especially important in this context, as it is crucial for socio-economic welfare and food security. However, it consumes a substantial portion of global freshwater (FAO, 2014), raising significant concerns about its sustainability, particularly due to unsustainable practices that affect water resources, food production, energy use, and ecosystem health. Within this framework, it is crucial to recognize that natural resources are intricately interconnected, meaning that any action in one area can significantly impact others (Sharmina et al., 2016). This understanding has led to the growing prominence of Nexus management, which emphasizes the interdependencies among various sectors and resources (Grady et al., 2023; Teutschbein et al., 2023). By examining these connections, Nexus management seeks to identify collaborative benefits and address conflicting demands from multiple perspectives (Estoque, 2023; Hoff, 2011; Pahl-Wostl, 2019; Smajgl et al., 2016), refer to Figure 1. The Water-Energy-Food-Ecosystems Nexus is a key approach that promotes the integrated management of resources to minimize trade-offs, enhance synergies, improve system efficiency, and develop sustainable strategies. This approach necessitates a comprehensive understanding of how human activities and natural processes interact within the same framework (Wu et al., 2021). Despite its increasing recognition in scientific research, Nexus approaches are often overlooked in policy agendas. As a result, decision-makers frequently fail to incorporate the need for integrated and sustainable resource allocation into their planning processes (Baratella et al., 2023; WEF, 2015).

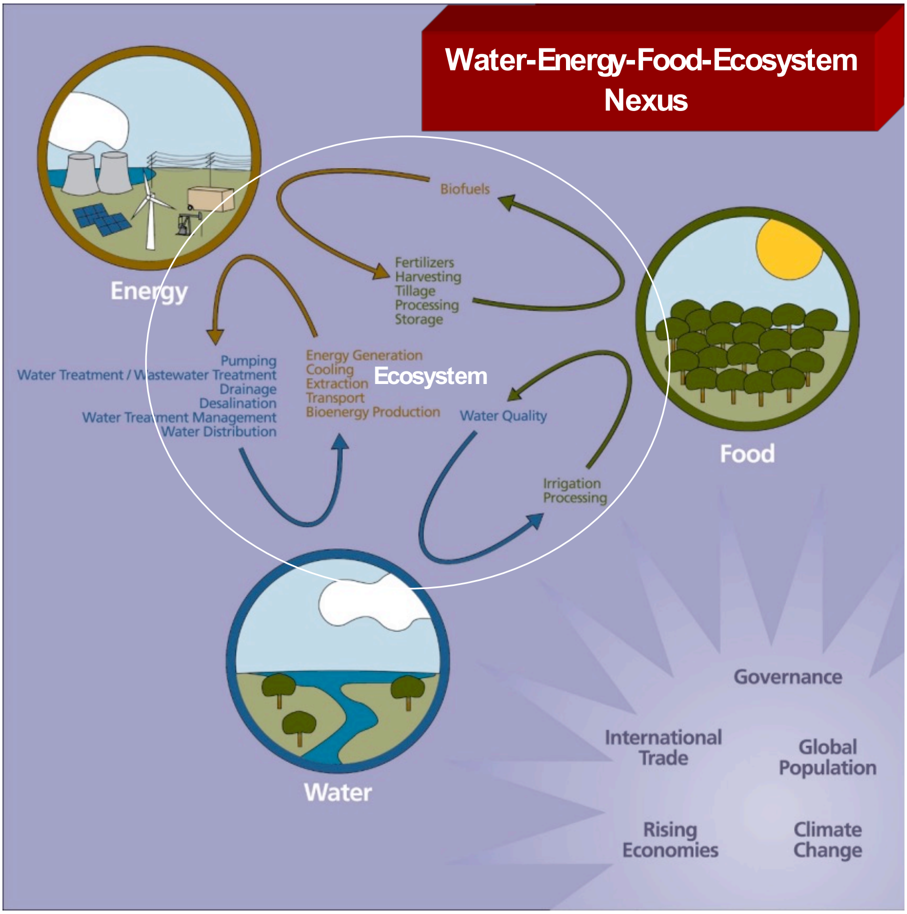


Figure 1 Sectors interactions and influencing factors within the water-energy-food-ecosystem Nexus.

Effective management of sustainable resources requires active participation from stakeholders (Hedelin et al., 2017), which is crucial for the exchange of knowledge and collaborative action, especially when resource limitations lead to conflicts (Egerer et al., 2021; Sušnik & Staddon, 2021). Nexus research advocates for participatory methods to uncover connections and resolve conflicts among varying interests. This involves utilizing advanced modeling tools and communication methods to engage stakeholders and apply systems thinking to reveal the complexities and trade-offs within the Water-Energy-Food (WEF) system (Baratella et al., 2023; Hedelin et al., 2017; Pahl-Wostl et al., 2007; Voinov et al., 2018). This approach not only generates comprehensive system knowledge (Arnold & Wade, 2015; Egerer et al., 2021; Harms et al., 2023; Meadows, 2008), but also enhances collaboration and decision-making by integrating local insights (Coletta et al., 2021; Scrieciu et al., 2021). Studies highlight the importance of this method in reaching consensus on strategies for efficient Nexus management (Martinez-Hernandez et al., 2017; Sušnik et al., 2018; Sušnik & Staddon, 2021). System Dynamics Modeling (SDM) encompasses a set of tools and methods that support system thinking, proving effective in understanding complex socio-environmental systems by examining the interactions among various variables and subsystems within these dynamics (Sterman, 2000). SDM includes both qualitative and quantitative approaches, whose use depends on analysis objectives, employed methodology, and addressed the audience (Brychkov et al., 2022). Qualitative SDM allows the analysis of the system behavior with the help of a conceptual (mental) model, often based on Causal Loop Diagrams (CLDs) which capture how elements in the system are interrelated by depicting cause-and-effect linkages and feedback loops (Sterman, 2000). Qualitative SDM is particularly useful to (i) describe a problem situation and its possible causes and solutions, potential risks and uncertainties, hypotheses and constraints; (ii) ‘capture intricacies of circular causality in ways that aid understanding’; (iii) help people externalize and share their mental models and perceptions; (iv) show people the dynamic system they are part of and to propose solutions (Chen & Wei, 2014; Meinherz & Videira, 2018; Pruyt, 2013). Quantitative simulation models, on the other hand, mainly take the form of stock-and-flow diagrams and a set of simulation equations that quantify linkages between different types of variables. Quantitative SDM enables (i) simulate complex system behavior over time, providing a dynamic view of how systems evolve; (ii) quantify relationships between different variables through mathematical modeling; (iii) forecast future scenarios based on different policy options or changes in system parameters; (iv) perform sensitivity analysis to identify critical variables that influence system outcomes; (v) evaluate the impact of potential interventions, supporting evidence-based decision-making (Azar, 2012; Briscoe et al., 2019; Mirchi, 2013; Pluchinotta et al., 2018). According to Egerer et al. (2021), SDM focuses on the structure and interactions within systems and helps pinpoint areas needing further data. The 'participatory' aspect of SDM is quite common, with PSDM involving stakeholders in various stages of the process. This includes activities such as defining the problem, describing the system, identifying key policy levers, developing the model, and analyzing policies. Stakeholders are engaged to different extents throughout these phases, contributing to a comprehensive system dynamics perspective (Stave, 2010).

SDM facilitates the formation of connections between hydrological and socio-economic processes in Nexus modeling (Francisco et al., 2023; González-Rosell et al., 2020; Halbe et al., 2015; Howarth & Monasterolo, 2016; Langsdale et al., 2009; Pittock et al., 2016; Ramos et al., 2022; Sušnik et al., 2012, 2018; Sušnik & Staddon, 2022). Some challenges still exist, such as the capability of fully describing hydrological processes within these models (Vamvakeridou-Lyroudia et al., 2008). In particular, adding spatial information into SDM and regulating the spatial variability of a system suffers from substantial barriers (Nikolic & Simonovic, 2015; Sušnik et al., 2012). As a result, there is a trend to simplify components in these models (Harms et al., 2023). Some gaps also exist in the use of SDM in a participatory form (referred to in the following as Participatory System Dynamics Modeling - PSDM). The accessibility and quality of data a significant barriers, particularly when soft or qualitative information needs to be taken into account (Pluchinotta et al., 2024). In addition, the integration of data and knowledge from diverse disciplines such as hydrology, social sciences and economics which is central in Nexus approaches is not straightforward due to differences in data sources and methodologies (Cai et al., 2018; Li et al., 2021).

This research concentrated on addressing three fundamental research questions, specifically exploring i) to what extent can the combination of scientific knowledge and input from stakeholders within the CLD enhance our understanding of the Water-Energy-Food-Ecosystems (WEFE) Nexus and address its main challenges , thereby increasing the effectiveness of management policies in intensive agricultural areas?, ii) how does the sectoral (hydrological) model enhance our capability to delve deeper into the challenges of assessing the impact of agriculture on the hydrological balance, while considering climate change influences?, and iii) in the realm of intensive agricultural areas, how does the construction of a stock and flow model, utilizing information from the sectoral (hydrological) model and enriched by insights from stakeholders, contribute to the examination of socio-economic and ecological consequences, alongside the evaluation of diverse strategies for the sustainable management of water resources, ecosystems, and food production?

In addressing these questions, the present study proposes an innovative methodology for Nexus modeling based on the integration between i) qualitative SDM (Causal Loop Diagram), to understand and describe the complex set of interconnections among diverse natural resource systems and uses with the active participation of stakeholders through PSDM, ii) basin-scale agro-hydrological modeling, which helps to focus deeply on the main challenges related to the water sector and agricultural practices, i.e. the use of water (for irrigation), fertilization, and others as well as their impacts on water quantity and quality, considering also the impacts of climate change and potential management options iii) using quantitative SDM (stock and flow model) to identify potential leverage points and design effective actions that support the sustainability transition of the system being analyzed.

The integration of the system dynamics (SD) model with the hydrological model helps investigate key Nexus challenges in agricultural areas while understanding the implications of cropping and land management activities on the environment, ultimately identifying potential actions that contribute to a sustainability transition. The proposed approach aims to show also how stakeholder participation can better enable a transition toward sustainable development, encouraging collaboration across policy domains. Engaging relevant stakeholders, and considering individual requirements and concerns, helps delve more into complex governance matters. This approach boosts collaboration and shared knowledge among specific domains, enabling the co-creation and testing of effective and ‘shared’ management policies. The methodology has been tested in the Tarquinia pilot area (Italy), located north of Rome in the Lazio region, Central Italy. One of the Learning and Action Alliances (LAA, see Baratella et al., 2023) activated within the LENSES project (PRIMA Foundation, GA n. 2041), the area where the role of agriculture is central, yet increasingly vulnerable to climate change and competitive resource use. The area includes Lake Bolsena, where the Marta River originates, and is characterized by flat topography, Mediterranean climate, and intensive agricultural practices, which rely heavily on the river for irrigation. Key concerns for the region include the interplay between agricultural practices, water quality and quantity, and the conservation of ecosystems, all under increasing pressures from climate change. These challenges highlight the need for sustainable resource management and cooperative governance to address the impacts of intensive farming and ensure long-term resilience.

CHAPTER 1

WEFE NEXUS ANALYSIS USING PARTICIPATORY SYSTEM DYNAMICS MODELING IN AN AGRICULTURAL BASIN IN CENTRAL ITALY

CHAPTER 1 WEFE NEXUS ANALYSIS USING PARTICIPATORY SYSTEM DYNAMICS MODELING IN AN AGRICULTURAL BASIN IN CENTRAL ITALY

Summary

The Nexus concept emerged in the last decade as a theoretical approach to natural resources management, which highlights the interconnections and interdependencies among different sectors (typically Water-Energy-Food-Ecosystems, WEFE). It is also seen as an analytical promoter that can drive actions to support sustainability transitions, overcoming sectoral perspectives and conflicts that often hinder such processes. There is a need for developing participatory approaches, as the involvement of stakeholders is widely acknowledged as a key leverage to activate sustainability transitions. In this context, the present work presents an approach to WEFE Nexus understanding and management based on the use of Participatory System Dynamics Modelling (PSDM). The PSDM allows mapping the Nexus in a participatory way, helping stakeholders achieve consensus on the main challenges of the study area, where a strong interdependency (and conflict) exists between agriculture and the state of the environment.

1.1 Context and Background

In the upcoming years, the Mediterranean region is expected to face severe challenges, including increasing temperature, extreme precipitation patterns, and an increasing frequency and magnitude of extreme events (Pörtner et al., 2022). Severe impacts are foreseen on the state of natural resources and, in particular, on water resources which are also characterized by a relevant level of conflict among different water users and uses (Jury & Vaux, 2007; Pluchinotta et al., 2018; Portoghese et al., 2015). The role of irrigated agriculture is central in this context since it is crucial for the socio-economic well-being and for guaranteeing food security but, at the same time, it exploits around 70% of global freshwater (FAO, 2014). Its sustainability is therefore increasingly questioned mainly due to the unsustainable use of resources it relies on such as water, soil, ecosystem state, and energy (de Vito et al., 2017, 2019).

Within this framework, it is vital to remember that natural resources are tightly interlinked, meaning that any action in one area might have significant implications in others (Sharmina et al., 2016). In this direction, the concept of "Nexus" management is gaining increasing attention (see e.g., Grady et al., 2023; Teutschbein et al., 2023). It emphasizes the mutual interdependencies among different sectors and resources (Smajgl et al., 2016), to understand the connections, collaborative benefits, and conflicting demands among resources at diverse perspectives (Estoque, 2023; Hoff, 2011; Pahl-Wostl, 2019). The Water-Energy-Food-Ecosystems (WEFE) Nexus is a conceptual approach that focuses on the integrated management of resources, aiming to reduce trade-offs, promote synergies, increase system efficiency, and seek strategies for sustainable development. Therefore, it requires an improved understanding of Nexus systems, which often integrates human (e.g., economy, energy, land use, etc.) and natural components (e.g., hydrology, biology, etc.) in the same framework (Wu et al., 2021). Despite increasing attention in scientific research, the policy agenda frequently ignores Nexus approaches and, as a result, decision-makers are unable to adequately address the need for an integrated and sustainable allocation of scarce resources in their plans (Enayati et al., 2021; Herrera-Franco et al., 2023).

When it comes to sustainable resources management, involving stakeholders is viewed as an invaluable opportunity (Hedelin et al., 2017). Their involvement not simply gives opportunities in terms of knowledge exchange, but also permits collective action in instances when conflicts develop owing to restrictions in resource domains (Egerer et al., 2021; Liu et al., 2018; Sušnik & Staddon, 2021). For this purpose, Nexus research is encouraging the use of participatory approaches with the aim of uncovering interdependencies and finding suitable solutions in the face of various conflicting interests. Suitable modelling tools and efficient methods of communication need to be used for facilitating stakeholder involvement (Hedelin et al., 2017; Pahl-Wostl et al., 2007; Voinov et al., 2018) and the use of System Thinking is becoming increasingly acknowledged in Nexus studies for revealing interdependencies and possible trade-offs of the intricate reality of the WEF system (Laspidou et al., 2020). Besides originating knowledge on the whole system (Arnold & Wade, 2015; Egerer et al., 2021; Harms et al., 2023; Meadows, 2008), it is essential for fostering collaboration and providing decision-making assistance by incorporating local information and insights of the investigated problem, as a result acting as a tool to support in making decisions and designing strategies (Coletta et al., 2021; Scrieciu et al., 2021). Several studies have proven how this might be crucial for impactful Nexus management, particularly when finding agreement on potential strategies is the ambition (Martinez-Hernandez et al., 2017; Sušnik et al., 2018; Sušnik & Staddon, 2021).

System Dynamics Modeling (SDM) comprises a set of tools and methods that are usable for supporting System Thinking and has shown its effectiveness in facilitating the thorough comprehension of complex socio-environmental systems, taking into account the interactions among different variables and subsystems in dynamic complexities (Sterman, 2000). Following e.g. Egerer et al. (2021), focusing on understanding system structure and the interactions between components, SDM also aims to assist in identifying areas that require additional information. Specifically, qualitative SDM (e.g. Causal Loop Diagrams – CLDs) hold value for stakeholders as they provide a structured and comprehensive overview of multifaceted problems and can also effectively capture their viewpoints (Sedlacko et al., 2014).

Within this framework, the present study proposes the PSDM approach for Nexus modelling to understand and describe the complex set of interconnections among diverse natural resource systems and uses with the active participation of stakeholders. The CLDs help investigate key Nexus challenges in agricultural areas and identify potential actions that contribute to a sustainability transition. The proposed approach aims to show also how stakeholder participation can better enable a transition toward sustainable development, encouraging collaboration across policy domains. Engaging relevant stakeholders, and considering individual requirements and concerns, helps delve more into complex governance matters. This approach boosts collaboration and shared knowledge among specific domains, enabling the co-creation and testing of effective and 'shared' management policies. The methodology has been tested in the Tarquinia pilot area (Italy), one of the Learning and Action Alliances (LAA, see Baratella et al. 2023) activated within the LENSES project (PRIMA Foundation, GA n. 2041), an area where the role of agriculture is central, yet increasingly vulnerable to climate change and competitive resources use.

1.2 Overview of SDM and PSDM use in Nexus studies.

SDM includes both qualitative and quantitative approaches, whose use depends on analysis objectives, employed methodology, and addressed audience (Brychkov et al., 2022). Basically, qualitative SDM allows the analysis of the system behavior with the help of a conceptual (mental) model, often based on CLDs which capture how elements in the system are interrelated by depicting cause-and-effect linkages and feedback loops (Sterman, 2000). Quantitative simulation models mainly are in the form of stock-and-flow diagrams and a set of simulation equations that quantify linkages between different types of variables.

Qualitative SDM is particularly useful to (i) describe a problem situation and its possible causes and solutions, potential risks and uncertainties, hypotheses and constraints; (ii) 'capture intricacies of circular causality in ways that aid understanding'; (iii) help people externalize and share their mental models and perceptions; (iv) show people the dynamic system they are part of and to propose solutions. A few limitations obviously exist as well, such as (i) the limited level of detail of the analysis; (ii) the limited estimation of the scale or speed of change of key items; (iii) the low level of trust in feedback based insights and qualitative models (Chen & Wei, 2014; Meinherz & Videira, 2018; Pruyt, 2013).

The ’participatory’ component of SDM is not unusual, and PSDM refers to the use of a system dynamics perspective in which stakeholders participate to some degree in different stages of the process, including problem definition, system description, identification of policy levers, model development and/or policy analysis (Stave, 2010). Several researchers, in the last few years, have proposed the use of PSDM in the WEFE sectors individually or using a Nexus approach, aiming to better inform decision-makers and facilitate stakeholder participation (Baratella et al., 2023; Bastan et al., 2017; D’Odorico et al., 2018; Fernández & Selma, 2004; Harms et al., 2023; Hassanzadeh et al., 2014; Jeong & Adamowski, 2016; Kotir et al., 2017; Mirchi et al., 2012; Saysel et al., 2002; Sušnik et al., 2018; Sušnik & Staddon, 2021; Voinov & Bousquet, 2010; Winz et al., 2009). Several recent studies specifically focused on the use of SDM in Nexus-related problems. Among the others, (Wu et al., 2021) worked with CLDs to integrate human (e.g., economy, energy, land use, etc.) and natural systems (e.g., hydrology, biology, etc.) in the same framework, ultimately analyzing resources security (Gallagher et al., 2020). The authors combined participatory CLD development, scenario modeling, and a new resilience analysis method to identify and test anticipated WEF risks, showing expected trade-offs between sectors. An intervention protocol, based on PSDM, for supporting sustainability transformations relying on the WEF approach was proposed by Kimmich et al. (2019). The authors employed a procedure based on the use of CLDs that involves stakeholders selecting essential variables, developing cause-effect connections between them, and then simulating the development of these relationships into the future through scenario analysis. SDM has been used by (Sušnik et al., 2018) to support a quantitative Nexus analysis, based on the qualitative description provided by a conceptual diagram of the major nexus components relevant to the Sardinia case study (Italy). The model structure was consolidated in consultation with local stakeholders, and model outputs were discussed with local case study experts. Purwanto et al. (2019) developed a qualitative CLD (map) of the Water-Energy-Food security Nexus in a pilot area in Indonesia, with the aim of elucidating to local stakeholders the complexity of the system without recourse to a complicated modeling and data collection exercise. Qualitative and quantitative SDM was used with local stakeholders to validate model structure, data, and results, as well as to gather information on Latvian policy objectives and implement them in the model as potential future policies by Sušnik & Staddon (2021). Specific attention has been given to the potential role of cross-sectoral implications in Nexus management. Alizadeh et al. (2022) used SDM for an integrated socio-economic and environmental analysis of a complex human-water system under different climate change scenarios. The model combines the fundamental aspects of climate, hydrology, agriculture, economy and society and is built upon an integrated Physical/participatory System Dynamics Model.

1.3 Description of the Study Area

The study area is the Tarquinia plain (90 kilometers north of Rome in the Lazio region, Central Italy) which - from the hydrological point of view - mainly includes the Marta River watershed. It has an area of 1,047.62 km^2, including Lake Bolsena which covers 114 km^2, through which Marta River originates with a length of 49 km. It runs past the city of Tuscania and is connected by a tributary initiating from the Cimini Hills. Then, it passes through the municipality of Tarquinia before reaching the Tyrrhenian Sea near Lido di Tarquinia.

The key locations, boundaries and topological characteristics of the area are represented in Figure 2. It is historically a highly productive area, and the agricultural sector has a central role in the local economy. The agricultural area is characterized by intensive farming, including both rain-fed and irrigated crops (about 72,584 ha in total, 13,322 ha irrigable). The water for irrigation mainly comes from the Marta River and is managed by the Water User Association (WUA) called “Consorzio di Bonifica Litorale Nord”.

In addition, the study area is characterized mainly by a flat topography with elevation fluctuating between 2 m a.s.l. and 983 m a.s.l.; a soil categorized by two basic types: Eutric Cambisols and Mollic Andosols with a clay-loam and loam soil texture respectively; and an arid, and sub-humid environment. The main crops in the area include non-irrigated arable crops (Winter wheat cereals) which comprise 49.23 % of the area, followed by broad-leaved forest at 13.93 %, and olive groves at 7.02 %. Positioned within the Mediterranean region, this area perceives a total annual precipitation of 656.39 mm, a total annual potential evapotranspiration (PET) rate of 1282.92 mm and an average annual temperature range from 10.6°C (January) to 21.9°C (August).

There are increasing concerns about the impacts of intensive practices, which have led to approximately 85% of the area being recognized as a Nitrate-Vulnerable Zone (NVZ), resulting in significant environmental issues in this region affecting both surface and groundwater sources. Among these, there are significant issues related to both water quality and quantity limiting the allowable loads of crop nutrients.

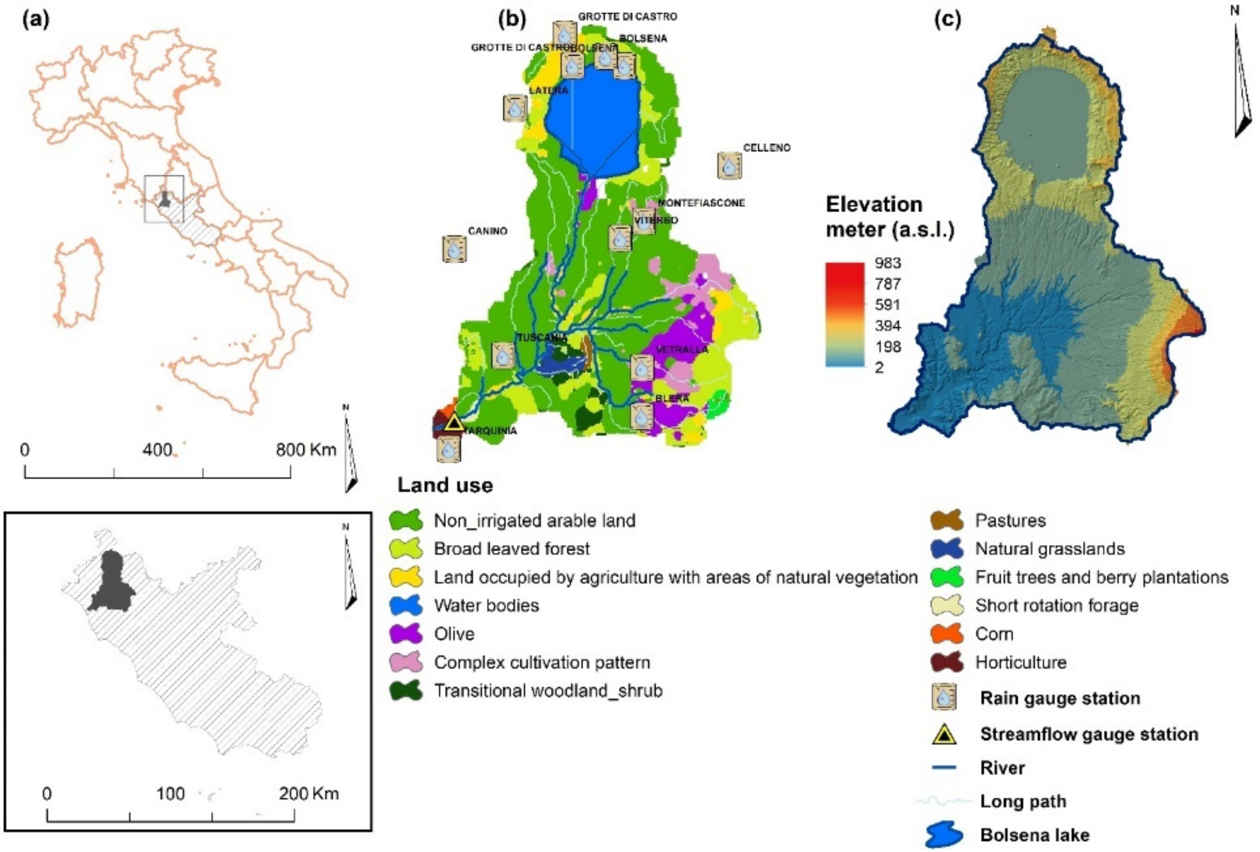


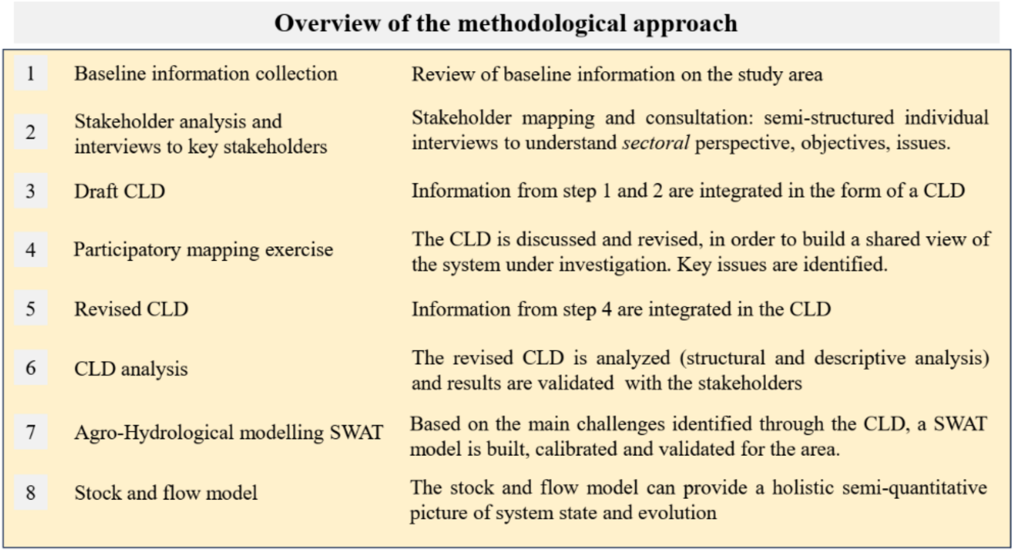
Figure 2. Marta River watershed: (a) Geographical location; (b) Land use spatial distribution and hydrological details; (c) Digital elevation model.

Tarquinia plain is also considered a hotspot for biodiversity and includes high-value ecosystems, such as the “Saline di Tarquinia" Natural Reserve which consists of a former salt pan that currently hosts rare species of avifauna such as the pink flamingo and the little egret and halophytic flora. Due to its biodiversity, the area is a Site of Community Importance (SIC) and a Special Protection Area (SPA), thus forming part of the EU “Natura 2000” network.

A key concern for the area is therefore the interplay between agricultural activities, water resources quality/quantity and protection of ecosystems, under increasing stresses caused by climate change. Finding a sustainable transition pathway for the area is not straightforward, and a dialogue among multiple stakeholders involved needs to be activated. In this direction, an attempt to facilitate the development of a (unique) cooperative governance structure in the area is the ‘River, Lake and Coastal Contract’ (Altamore & De Leo, 2023).

1.4 Method

The present work proposes the use of the PSDM approach for WEF Nexus understanding and modeling, aiming to support active stakeholder participation. This approach is used in the form of CLDs, to increase the understanding of the interconnections among WEF sectors, considering sectoral objectives, while working to build a consensual view of the system as a whole. A structured analysis of the CLD then results in the identification of the key challenges to tackle and, consequently, in the identification of a suitable ‘in-depth’ modeling approach. Figure 3 proposes an overview of the whole process, while each step is detailed afterward.



Overview of the methodological approach

1	Baseline information collection	Review of baseline information on the study area
2	Stakeholder analysis and interviews to key stakeholders	Stakeholder mapping and consultation: semi-structured individual interviews to understand *sectoral* perspective, objectives, issues.
3	Draft CLD	Information from step 1 and 2 are integrated in the form of a CLD
4	Participatory mapping exercise	The CLD is discussed and revised, in order to build a shared view of the system under investigation. Key issues are identified.
5	Revised CLD	Information from step 4 are integrated in the CLD
6	CLD analysis	The revised CLD is analyzed (structural and descriptive analysis) and results are validated with the stakeholders
7	Agro-Hydrological modelling SWAT	Based on the main challenges identified through the CLD, a SWAT model is built, calibrated and validated for the area.
8	Stock and flow model	The stock and flow model can provide a holistic semi-quantitative picture of system state and evolution

Figure 3. Overview of the methodological approach.

Step 1. Baseline information collection

The first step aims to provide a basic characterization of the study area and is mainly based on the information included in a Baseline description, which includes a review of previous studies carried out in the area, reports and relevant scientific and technical documents. Bilateral meetings have been also performed at the beginning of the process with pilot leaders, to get further insights into the main Nexus challenges and strategic objectives for the area according to their knowledge. The main purpose of this step is to set the context of the analysis, based on a retrospective review of information and the evidence from previous projects and activities.

Step 2. Stakeholder analysis and interviews with key stakeholders

Based on the results of Step 1, preliminary stakeholder mapping is performed. It is worth mentioning that the mapping is updated throughout the project duration using a snowballing technique (Reed et al., 2009) ensuring that all relevant sectors are represented in a balanced way. Key stakeholders are involved in semi-structured individual interviews, focused on sectoral Nexus domains (i.e. water, food, ecosystems) for i) the identification of main variables/indicators; ii) the identification and analysis of the main cause-effect chains. Going a bit further into details, the rationale of the interviews is to identify critical connections between the sectoral security level, and the level of satisfaction of the main needs expressed by the stakeholders, identifying all the most influential processes (both natural and anthropic) with their barriers and drivers. The analysis is mainly focused on the current system state ('Business-as-usual').

Step 3. Draft CLD development

The outcome of this step is the development of a draft CLD, which accounts for the information obtained in Step 1, but also includes the stakeholder knowledge coming from Step 2. The CLD basically provides a holistic picture of the whole system, that reflects the sectoral perspectives provided by individual stakeholders, ultimately creating a shared understanding (or diagnosis) of the current system state.

Step 4. Participatory Mapping Exercise

A Workshop is then organized to bring stakeholders together, starting the 'Nexus dialogue' and using the CLD as a supporting tool for this purpose. Besides asking for a revision of the key variables/indicators, stakeholders are asked to co-define Nexus interactions, reflecting on causal connections already represented in the CLD and focusing specifically on those that have cross-sectoral interdependencies. An element of innovation that helps to feed the debate and overcome the limited capacity of CLDs to represent spatial information, is the use of printed geographical maps, where stakeholders can place cards representing the main variables included in the CLD (Figure 4a).

Step 5. Revised CLD

The model developed in Step 3 is revised (variable names, connections and polarity, potential delays) according to the validation achieved in Step 4. Although the CLD must be considered as a highly dynamic tool to be updated throughout the process, this version should represent a shared (and consensual) view of the system under investigation.

Step 6. CLD analysis

This step aims to get structured information on the system under investigation, mainly based on the description of the CLD structure, its current state and potential evolution under variable conditions (including potential policy actions). Although CLDs only include qualitative information, their analysis can help deconstruct system interactions and better understand behaviors that might often be unpredictable and counterintuitive (Murphy & Jones, 2021). Two intertwined activities can be performed for this purpose, which can be broadly identified as a ‘descriptive’ and ‘structural’ analysis of the CLD. The former relates to the analysis of the main dynamics that affect the state and potential evolution of relevant variables (mainly based on the identification and description of key feedback loops). The latter is based on the use of graph theory measures: by measuring network structure (e.g., how densely coupled variables are, or how central a node is) important information about the nature of the network as a whole can be inferred (Murphy & Jones, 2020). The combination of the descriptive and structural analysis allows the identification of Nexus challenges (i.e. key intersectoral issues affecting the Nexus sustainability that need to be addressed across sectors in an integrated way), and supports the screening of potential leverage points, i.e., points in the system where local intervention could have large impacts at system scale (Abson et al., 2017; Birney, 2021; Egerer et al., 2021; Meadows, 1997). Full details on the rationale of this step are included in the work by (Giordano et al., under review).

Step 7. Agro-hydrological modeling

To respond more in detail to the key challenges identified through the analysis of the CLD, the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 2012; Neitsch et al., 2011) was suggested for implementation in the area. It is widely used worldwide for supporting agro-hydrological modeling (Abbaspour et al., 2015; Bieger et al., 2017; Nkwasa et al., 2020). SWAT components cover hydrology, atmospheric conditions, land use, vegetative growth, erosion, nutrients, and different management practices. The model was implemented, and the details are presented in Chapters 2 and 3.

Step 8. Stock and flow model

The last step of the proposed approach is beyond the purpose of the present work. It is basically centered on the development of a stock and flow model, which integrates the information from the CLD and from sectoral models (with particular regard to the SWAT models) to provide support to policymakers in the identification of potential sustainability pathways for the study area. The model was implemented with the details provided in Chapter 4.

1.5 Results

A preliminary version of the CLD for the Tarquinia area has been built based on background information (technical reports and evidence from previous projects) according to Step 1. It has been then revised and updated (Steps 2 and 3) following a preliminary round of interviews with the key stakeholders (11, covering all WEF sectors) that helped understanding sectoral perspectives in the study area. It has been later presented during the stakeholders' workshop (WS) that was organized in May 2022 in Tarquinia and used to support the Nexus dialogue. During the workshop stakeholders were asked to:

- Identify and locate on a geographical map the main elements that characterize the area (using a predefined set of cards representing some key elements that were selected as activities, resources, pressures, and impacts.
- Draw and characterize the main interconnections and interdependencies between such elements, thus identifying cause-effect chains. Stakeholders were asked to provide information on the strength/weight of the main interconnections and to explain their meaning/relevance.

The following pictures (Figure 4a and Figure 4b) were taken during the above phases of the WS and refer respectively to the geographical mapping exercise and the 'conceptual' mapping activity (Step 4).

Figure 4. (a) Participatory mapping; (b) Participatory conceptual modeling in the Tarquinia pilot.

The final version of the CLD (Step 5, built in Kumu, see https://kumu.io/ for further info) is presented in the Figure 5. A 'descriptive' analysis of the CLD is provided afterward.

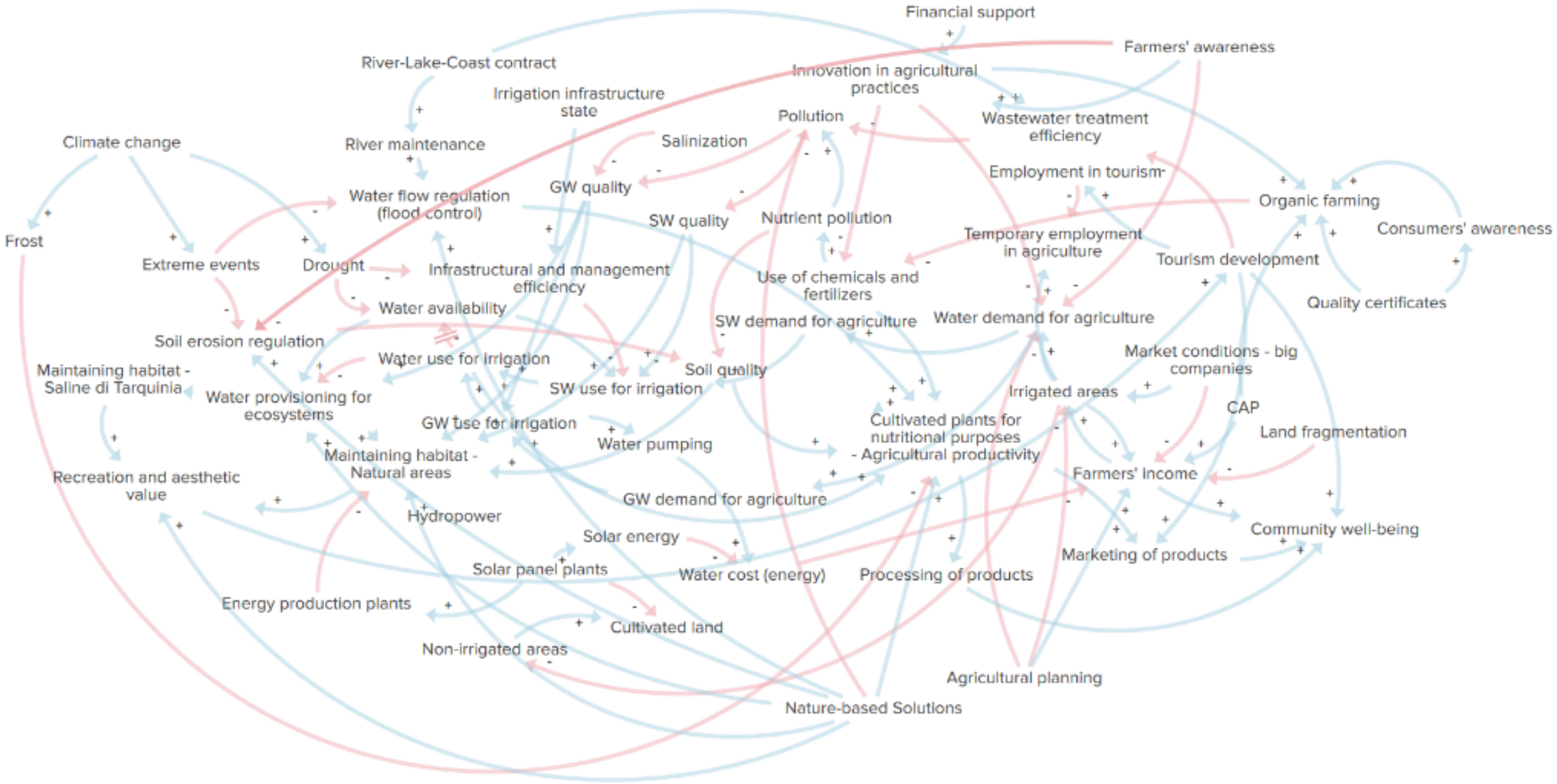


Figure 5. Participatory conceptual modeling for the Tarquinia pilot. Blue lines identify (+) connections, red lines identify (-) connections.

One of the key natural elements for the area is the Marta River, which is crucial for satisfying drinking and agricultural water demand but also represents the destination of non-point source pollutants (including soil erosion and nutrient load) related to agricultural practices. Water is still rather abundant in the area, but climate change is causing increasing concerns due to the increased frequency and magnitude of droughts, as well as the impacts of flood events and winter frost. Despite the availability of surface water, some concerns relate to the inefficiency of the water supply system, as a poor level of service (low pressure) is acknowledged in specific areas particularly during peak irrigation periods (mainly July and August). The increasing concerns about water availability also reflect increasing concerns about the ecological flow and the impacts it might have on the ecosystems. However, to date, the key perceived issue in the water sector is related to water quality (both for surface water and groundwater), which is heavily impacted by chemicals and fertilizers used in agriculture, as well as by the heavy load of urban wastewater treatment plants during summer.

Historically, the area is fertile and therefore devoted to agriculture, which is a crucial socio-economic asset for the local population. However, there are increasing concerns about the sustainability of agricultural practices, heavily driven by market conditions, both in terms of environmental impacts and in terms of profitability for the local communities. A low level of farmers' awareness on the impacts of agricultural practices is significantly threatening the soil quality and creating issues to the soil erosion regulation. The sustainability of agricultural activities (mainly in terms of profitability for farmers) is being deeply conditioned by several issues, which include: i) the farm size, as small farms (approximately below 20 ha, a heritage of the land reform in the 1950s) are currently not able to safely sustain their business; ii) the market conditions, as the presence of large retailers and their demand for agricultural products is both an economic opportunity for the area and a limit (mainly for small farms); iii) the very limited effectiveness of subsidies such as the Common Agricultural Policy (CAP). The impacts of unsustainable agricultural practices are threatening the whole ecosystem, which is also characterized by several hotspots, including the saltworks area (‘Saline di Tarquinia’ natural park, part of the Natura 2000 network) and several natural reserves. Because of agricultural overexploitation, a wide area is currently a Nitrate Vulnerable Zone (NVZ).

Several initiatives and actions are being currently oriented to improve agricultural productivity and sustainability over the long term, particularly for smaller farms, ultimately guaranteeing the achievement of ‘food security’. A strong coordination among different actors, mainly farmers associations (FA) and cooperatives is being supported with initiatives such as the ‘Tavolo Verde’ (supported also by the Tarquinia municipality) and the ‘Biodistretto MET - Maremma Etrusca e monti della Tolfa’ (an eco-region which includes four municipalities) to promote a transition in the agricultural sector towards organic farming. In summary, the transition towards environmental-friendly agricultural productions (e.g. organic farming) is seen as highly relevant for the area and for the socio-economic well-being, although currently characterized by very limited policy and economic support. One key ongoing initiative is the ‘Contratto di Lago-Fiume-Costa’, i.e. a participatory planning and management initiative that involves approximately 12 municipalities along with several local associations, to pursue an integrated sustainable and integrated management of the whole hydrological system from upstream (Lago di Bolsena) to downstream (coastal area). A statement of intent-document has been already signed to support this initiative which is central to the ‘ecosystem security’ of the area.

A ‘structural’ analysis has been also performed on the CLD, using graph theory measures. Following Giordano et al. (under review) reference is made to the centrality degree to locate the local connectors/hubs, and thus used for the identification of the key challenges. Particular attention has been given to high-degree variables that have also multi-sectoral impacts/dependencies, as they can help identify Nexus challenges. The analysis confirms that a key challenge for the Tarquinia plain mainly relates to the role of agricultural activities and its interdependencies with the water sector and with the socio-economic conditions of the area. Among the high-ranked variables in terms of Centrality Degree, the analysis highlights the role of ‘Irrigated Areas’ (Degree centrality 8, Betweenness centrality 0.112), ‘Agricultural productivity’ (Degree centrality 9) and ‘Farmers’ income’ (Degree centrality 8, Betweenness centrality 0.110). This means that there is a strong interconnection between water and agriculture, as the impacts of irrigated agriculture on the availability and state of natural resources is high, but agriculture is also relevant for the well-being of the farmers’ community. This also emerges from the high centrality of ‘Water demand for agriculture’ (Degree of centrality 6) and Water quality’ (Degree of centrality 5, Betweenness centrality 0.120). It is worth considering that, although (to date) the water availability over the area has never been a relevant issue, there are increasing concerns mainly due to the impacts of climate change (note: some interviews have been performed after a rather long – and quite uncommon - dry period in the area). Conversely, there are impacts on GW quality due to the massive use of chemicals in agriculture in many irrigated areas. A relevant interconnection between human activities (mainly agriculture) and the environment is also evident, as highlighted by the centrality of ‘Maintaining habitat – Natural areas’ and ‘Water provisioning for ecosystems’ (Degree centrality 6 and 5 respectively, Betweenness centrality 0.106 and 0.09 respectively, Eigenvector centrality 0.078 and 0.066 respectively), ‘Pollution’ (Degree centrality 5, Betweenness centrality 0.150) and ‘Recreation and aesthetic value’ (Betweenness centrality 0.150, Eigenvector centrality 0.088). A central issue is also the ‘Wastewater treatment efficiency’ (Betweenness centrality 0.120, Eigenvector centrality 0.044), which significantly affects the state of water bodies and natural areas, in particular in case the pollution load is extremely high. The analysis also shows the potential central role of some measures that might be considered for improving system state (e.g. ‘Organic farming’ and ‘Innovation in agricultural practices’ with Centrality degree 5) and, particularly, ‘Nature-based Solutions’ (Centrality degree 7) positively affecting multiple sectors/dimensions. A summary of the main Nexus challenges and related centrality measures is provided in the following Table 1.

Table 1. Nexus challenges for the Tarquinia plain case study.

Nexus challenges	Centrality measures
Agricultural productivity	High centrality degree
Water quality	High centrality degree; high betweenness centrality
Maintaining habitat – Natural areas	High centrality degree; High betweenness centrality; High eigenvector centrality
Wastewater treatment efficiency	High betweenness centrality; high eigenvector centrality
Farmers' income	High centrality degree; high betweenness centrality

The closeness centrality is then used to identify elements that can easily affect most of the network and usually have a high impact on what is happening across the system (i.e. potential leverage points). The variable characterized, by far, by the highest value of closeness centrality is 'Nature-based Solutions', showing the high potential of a series of combined measures (mainly, the adoption of sustainable agro-ecological practices) to affect the state and potential evolution of the system, targeting many of the main challenges. The variables characterized by the highest closeness centrality are all related to the agricultural sector, which thus has a lot of potential leverage points to act on the state of the system. Those variables – besides the 'Irrigated areas' (0.198) - include 'Innovation in agricultural practices' (0.193), 'Agricultural planning' (0.179), 'Farmers' awareness' (0.175), 'CAP' (0.171) and 'Use of chemicals and fertilizers' (0.159). The analysis thus suggests that acting on the agricultural sector with technical and/or financial measures might have a significant impact on the system, affecting multiple dimensions including the profitability/sustainability of agricultural activities, the state of water resources and water bodies and, consequently, the state of natural areas. A summary of the results of the leverage analysis is provided in Table 2.

Table 2. Results of the leverage analysis for the Tarquinia plain case study.

Nexus challenges	Potential leverage points
Agricultural productivity	Innovation in agricultural practices Agricultural planning Farmers’ awareness Common Agricultural Policy (CAP) Use of chemicals and fertilizers Nature-based Solutions
Water quality	Innovation in agricultural practices Farmers’ awareness Use of chemicals and fertilizers River-Lake-Coast contract Nature-based Solutions
Maintaining habitat – Natural areas	Nature-based Solutions Innovation in agricultural practices
Wastewater treatment efficiency	River-Lake-Coast contract Tourism development
Farmers’ income	Innovation in agricultural practices Agricultural planning CAP Market conditions – big companies

The analysis of the CLD helped identify in a structured way the main challenges/issues for the area, but also contributed to highlighting the need for an improved understanding and modeling of key phenomena. In particular, the centrality of agricultural activities over the area (in terms of productivity and relevance for the farmers, but also in terms of impacts on water quality and state of the natural areas) suggested the need for investigating in depth the impacts of such activities over the area, as well as the potential associated with mitigation measures. For this reason, the need to develop a detailed hydrological model (SWAT) over the area emerged.

1.6 Discussion

The use of qualitative PSDM (CLDs) can help overcome silo-thinking, supporting stakeholders in the analysis of a complex study area using a Nexus approach. The visualization potential of CLDs ultimately supports mapping the interdependencies among WEFE sectors, highlighting the complexity of the system being investigated. Although there is literature on the use of CLDs in Nexus studies, the present work proposes a twofold innovation. First, the process is based on the participation of stakeholders throughout the modeling process, -through both individual activities and group exercises oriented to CLD building, revision, analysis and validation. One innovative element in the approach, considering the available literature on PSDM, is the development of a structured approach to how to get insights from CLDs, which includes both a 'descriptive' and a 'structural' analysis based on graph theory metrics. The value added of the approach is that it allows a robust and replicable approach to CLD analysis, facilitating the identification – and formulation – of challenges, of the key variables and the main potential points of intervention. This is also a relevant result in the direction of facilitating the achievement of consensus in Nexus studies, which is often not a trivial task, and in raising awareness on the complexity of the process of identification of suitable and effective policies. The first step of analysis thus helps also in the identification of the key issues that need to be further investigated, to produce actionable knowledge that can be used by policy- and decision-makers.

In the case study considered in the present work, one of the central issues is the impact of agricultural practices on water resources and the state of the environment. The need for detailed agro-hydrological modeling therefore suggested quantitatively investigating the causal loops connecting agricultural practices to the environmental quality related to water bodies and agro-ecological conservation.

The proposed approach also values the role of stakeholders and their participation, encouraging collaboration across domains and supporting a collective identification of the main challenges and potential solutions. As already detailed, stakeholders are not just data/information providers, rather they directly contribute to all modeling activities. This actually may increase the sense of ownership of modeling results and may contribute to the commitment of decision- and policymakers towards the implementation of the selected actions.

CHAPTER 2

IMPACT STUDY OF CLIMATE CHANGE

CHAPTER 2 IMPACT STUDY OF CLIMATE CHANGE

Summary

Agricultural practices exert profound impacts on water availability and quality, particularly in the context of climate change. Assessing the response of hydrological balance and diffuse pollutant loads in a watershed under the impacts of intensive agricultural activities and climate change requires suitable modeling tools, such as the soil and water assessment tool (SWAT). Focusing on the Tarquinia case study and the Marta River watershed, monthly streamflow monitoring data of discharge, nitrate nitrogen (NO_3^-), and total nitrogen (TN) from gauge stations were utilized to calibrate and validate the hydrological model for the period 2006-2020. A SUFI-2 approach in the SWAT-CUP program was used to calibrate, validate, and perform uncertainty analysis of the hydrological model. Subsequently, the calibrated hydrological model has been forced by the three most important surface variables to human activity and the hydrological cycle of EURO-CORDEX climate models combinations (daily precipitation, daily minimum surface temperature, and daily maximum surface temperature) after rigorous evaluation of all available EURO-CORDEX combinations over Marta River watershed. The linear regression bias correction method has been also implemented for the best climate models to mitigate their potential uncertainty. Monthly simulation during the calibration and validation period of the hydrological model showed a positive model performance for streamflow. The calibrated model can be utilized to assess the long-term impacts on the study watershed and water quality from various management strategies designed to mitigate ecosystem impacts and conserve water resources. By simulating different management practices, such as sustainable agriculture techniques and improved land-use planning, the model can predict potential improvements in watersheds from pollutant loads and water quality over time.

2.1 Context and Background

Nowadays climate change has huge attention from the scientific and policy-makers especially for water resources (qualitative/quantitative dimensions) (Duran-Encalada et al., 2017; Ahmed et al., 2020) and agricultural sectors (Kim, 2010; FAO, 2016; Straffelini and Tarolli, 2023). It has a huge effect on shaping the hydrological cycle with substantial influences on agriculture (Li et al., 2022; Wang & Liu, 2023). Garnier et al. (2015) and Badrzadeh et al. (2022) stated that agriculture services as a primary source of non-point source pollution and are harshly influenced by extreme events related to climate change, particularly, global warming in the near future (Allen & Ingram, 2002; Loaiciga et al., 1996; Sinn, 2008; Zhang et al., 2004), which have been attributed to the natural variability or human influence (Lange, 2020). Rising temperature can change precipitation patterns (Dore, 2005; Mani et al., 2018; Piao et al., 2010; Trenberth, 2011), leading to frequent and extreme rainfall events (Trenberth, 2005; Westra et al., 2014) as well as worsen nutrient loss dynamics inside agricultural lands through intensifying the discharging and cycling of nutrients (nitrogen and phosphorus) (Aggarwal, 2008; Ba et al., 2020; Carpenter et al., 2018; de Senerpont Domis et al., 2013; Jeppesen et al., 2011; Lesk et al., 2022; Rabalais et al., 2010; Sinha et al., 2017). Raised availability of nutrients leads to deteriorating water quality, and can make water bodies more susceptible to eutrophication (Ansari et al., 2011; Khan & Mohammad, 2014; Nazari-Sharabian et al., 2018; Yang et al., 2008). This intensified precipitation joined directly with changed hydrological cycles, increase in the rates of soil erosion resulting in degradation of water resources quality (Borrelli et al., 2020; Issaka & Ashraf, 2017; Lal, 2015; Latocha et al., 2016; Li & Fang, 2016; Nearing et al., 2004; Ramos et al., 2019; Schröder et al., 2024; Tarigan, 2022; Ziadat & Taimeh, 2013; Zucca et al., 2021). The complicated relationship among weather patterns, inflow/outflow dynamics and land characteristics significantly impact external nutrient influxes and erosion rates, further complicating the management of water quality (Alley et al., 1999; Atique & An, 2020; Garnier et al., 2015; Kasat, 2006).

In this regard, the development of robust and detailed hydrological models to evaluate water resources in quantitative/qualitative dimensions is needed. SWAT is a widely employed agro-hydrological model (Arnold et al., 2012; Neitsch et al., 2011), built at the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) to estimate the potential effects of various land management activities on water quality and quantity, particularly agricultural chemical yields, and sediment in wide-range and complex watersheds differentiated by varied land uses, soil properties, and management activities across extended periods (Krysanova & White, 2015; Omran, 2019; Zhao et al., 2024). This semi-distributed watershed model can operate within different time intervals, starting from sub-daily to yearly scales. SWAT requires accurate data on meteorological conditions, soil features, terrain characteristics, vegetation cover, and land management practices in a certain watershed (Abbaspour et al., 2015; Mekuriaw, 2019).

The best way to predict the future changes (near-future and far-future) of watershed hydrological components is to run the hydrological model developed for a study area with the variables of climate models. Global circulation models (GCMs) come with coarse resolution, but the resolution of these climate models can be improved through regional climate models (RCMs). The EURO-CORDEX initiative includes many combinations between GCMs and RCMs, with some models having different performances in different areas and for variable scales. Evaluating the performance of the climate models for the study area is therefore crucial.

The use of climate change scenarios in hydrological models such as SWAT by using climate models has recently gained a lot of attention. El-Khoury et al. (2015) assessed land use projections and climate change scenarios by integrating them with a hydrological model to estimate the relative impact of climate and land use projections on a suite of water quality and quantity endpoints for a Canadian watershed. Čerkasova et al. (2021) evaluated future changes to the stream flow of the Nemunas River watershed situated in the Baltic Sea basin regarding hydrologic regime, sediment (SS), total nitrogen (TN) and total phosphorus (TP) load from the river to the Curonian Lagoon under different climate change scenarios using high-resolution modeling. Cousino et al. (2015) used data from four Coupled Model Intercomparison Project Phase 5 (CMIP5) models in a calibrated SWAT model of the Maumee River watershed to determine the effects of climate change on watershed yields. Lee et al. (2018) evaluated the impacts of climate variability on two adjacent watersheds in the Coastal plain of the Chesapeake Bay Watershed using the SWAT model. Jayakody et al. (2014) investigated climate change impacts on sediment and nutrient transport and the efficiency of best management practices in the Upper Pearl River Watershed in Mississippi. Bi et al. (2018) examined the responses of total nitrogen and total phosphorus loads to different climate scenarios over the Luanhe River Basin in north-eastern China. Thang et al. (2018) investigated the impact of climate change on streamflow and water quality in the upper Dong Nai River Basin using the SWAT model. Li et al. (2018) used SWAT to simulate water budget and nutrient loads for landscape patterns representing a 30-year progression of urbanization in a watershed near the Tianjin metropolis. Jha et al. (2015) evaluated the long-term changes in annual water yield and nitrogen load in the Upper Mississippi River Basin using the SWAT model with mid-century (2046–2065) climate change projections as predicted by the ensemble of ten general circulation models. Coppens et al. (2020) used a combined modeling approach that included the catchment model SWAT and the lake model PCLake to study the possible effects of several climate scenarios on a shallow lake in semi-arid central Anatolia, Turkey. Kim et al. (2020) designed and evaluated a coupled model, SWAPX, using SWAT and APEX-paddy models for enhancing the current watershed modeling approach in paddy-dominant watersheds, the impacts on future hydrologic and water quality were assessed by applying ten GCMs outputs under RCP 8.5 of CMIP5. Ba et al. (2020) used four climate change scenarios during 2040–2044 and two agricultural management scenarios were input into the SWAT model to quantify the effects of climate change and agricultural management on solvents and solutes of pollutants in the Lower Kaidu River Basin of China. Marcinkowski et al. (2017) assessed the effect of projected climate change on water quantity and quality in two lowland catchments (the Upper Narew and the Barycz) in Poland in two future periods (near future: 2021–2050, and far future: 2071–2100) by using SWAT forced by climate data from an ensemble of nine bias-corrected General Circulation Models—Regional Climate Models (GCM-RCM) from EURO-CORDEX. Almeida et al. (2018) investigated the effect of different scenarios due to climate change in the hydrological regime of the Sorraia River Basin in Portugal. Nazari-Sharabian et al. (2019) Used the RCP4.5 and RCP8.5 scenarios of the Beijing Normal University Earth System Model, forcing both SWAT and System Dynamics model (SDM) to investigate the combined impacts of climate change scenarios upstream of the Mahabad Dam reservoir in Iran. Čerkasova et al. (2019) assessed climate change Impacts on streamflow, sediment and nutrient loadings of the Minija River in Lithuania. Li & Kim (2019) analyzed the impact of climate change on non-point source (NPS) pollution loads on a large spatial scale in the Saemangeum watershed in South Korea under RCP climate change scenarios for 81 years (2019–2099) by applying the SWAT model. Feng & Shen (2021) used SWAT which was forced by two RCMs under two climate scenarios over the Miyun Reservoir watershed in China. Evaluation of future river runoff in the Baltic Sea region conducted by Tamm et al. (2018) at a basin scale to analyze the separate and combined impacts of climate and land use change using the SWAT hydrological model. Different scenarios were generated utilizing two different RCMs from the EURO-CORDEX under RCP 4.5 scenario and two assumed maps of land use change, to understand how potential variations in climate and land use might influence the river hydrology in the far future (2071–2100) to aid policymakers in enhancing decisions related to land and water management across the study region.

Based on previous investigations, most of the impact studies of climate change did not perform performance evaluation for climate models against reference datasets to decide which model is most appropriate for the study area.

Simultaneously, only a limited number of studies on climate change impact analysis on hydrological balance components have been implemented in central Italy. Accordingly, there is a need for a study that accurately evaluates climate models to identify the best-suited model for the area and variables needed to drive hydrological models. Additionally, fully understanding the dynamics of these hydrological components under the influence of climate change is of great importance to gather insights and frame effective management strategies and policy interferences.

2.2 Method

2.2.1 Performance evaluation of climate models

The performance evaluation of climate models concerning ground observations is a complex and challenging task, due to the highly nonlinear and dynamic nature of the climate system, the large spatial and temporal scales involved, and the complexity of the physical processes that govern the system. The evaluation process can be used also to diagnose and identify model strengths and weaknesses. Moreover, by evaluating the historical period and choosing the best-performing climate model, one may assume that such a model would be the best option for future projections.

In this study EURO-CORDEX initiative high-resolution models (0.11°) have been used, the three most important variables for human activity (daily precipitation, daily maximum surface temperature and daily minimum surface temperature) have been extracted, three climate indices for spatiotemporal analysis have been considered during evaluation performance of all available climate models combinations (GCMs-RCMs) over the watershed; annual total precipitation (PRCP), annual mean of daily minimum temperature (TNmean) and annual mean of daily maximum temperature (TXmean). Climate models in general suffer from bias and uncertainty, and to use them directly to force hydrological models is not recommended, therefore performance evaluation of all available climate models against reference datasets is a crucial task before any impact study. The best method for performance evaluation of climate models is by comparing the observation data with historical simulation of climate models.

After choosing the best climate model for the historical period, the future projection of the mentioned model will be used to force the hydrological model. In general bias correction is required for the climate model which is eventually used as an input for the hydrological model, to minimize the uncertainty which eventually this uncertainty will accumulate with the uncertainty of the hydrological model.

In this study all the available model combinations (GCMs-RCMs) of the EURO-CORDEX initiative have been evaluated over the study area which has daily precipitation, daily minimum temperature and daily maximum temperature, for the purpose of performance evaluations of the combinations of all three variables, the Aras diagram (Izzaddin et al., 2024) has been utilized, which allows for visual assessments of the correspondence between model outputs and reference data in terms of total error, correlation, as well as bias and variability ratios through an easy-to-interpret 2-dimensional plot, allowing for proper weighting of different model features. For details of the climate models evaluation over the watershed, refer to Figure 46.

After selecting the best model for each variable, bias corrections have been implemented using the Linear Scaling (LS) method with the aid of CMhyd software (Rathjens et al., 2016).

2.2.2 SWAT model

2.2.2.1 Model description

SWAT is a widely used agro-hydrological model (Gassman et al., 2014), developed by the United States Department of Agriculture (USDA)-Agricultural Research Service (ARS). It operates continuously using a semi-distributed, process-based method, applicable from local watersheds to large river basins (Arnold et al., 2012), to estimate the impacts of land management and climate on watershed dynamics including water, sediment, and agrochemical yields using spatial data on topography, land use, soil, climate and management practices (Neitsch et al., 2009). It is highly flexible for simulating agricultural basins (Marek et al., 2020) and various management scenarios.

Inside ArcGIS, SWAT presents an interface to delineate watershed hydrological characteristics. This enables the watershed partition into multiple sub-basins for detailed spatial simulations. Subsequently, these sub-basins are further subdivided into hydrological response units (HRUs) based on unique combinations of land cover, soil type, and related slope. The operation of the SWAT model includes different processes intended for different watershed levels while simulating the hydrology of the watershed through two main phases (Rathjens et al., 2015): the land phase, estimating daily water balance, sediment discharge, and nutrient yield at the HRU level; and the stream phase, managing water, sediments, and nutrients in the stream network to the watershed outlet (Neitsch et al., 2011). As a fundamental component, the water balance equation (1) is used by the hydrological model to simulate the key hydrological processes within the soil profile, including precipitation, surface runoff, infiltration, evapotranspiration, stream and channel transmission losses, water storage changes, lateral flow, and percolation, detailed information on all components is provided in (Arnold et al., 1998; Neitsch et al., 2011).

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right) \qquad (1)$$

where SW_t is the final soil water content (mm H_2O), SW_o is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

The estimation of surface runoff from HRUs is done through the soil conservation service (SCS) curve number approach (Rallison & Miller, 1981). In this approach, precipitation excess/surface runoff is estimated by considering factors, comprising the cumulative depth of precipitation, permeability of the soil and land cover, and antecedent soil water conditions (soil moisture level before the precipitation event), as defined in the equation (2). SCS defines three antecedent moisture conditions: I – dry (wilting point), II – average moisture, and III – wet (field capacity).

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \tag{2}$$

In which, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is the retention parameter (mm), which varies spatially because of changes in slope, land use and their management, and it varies temporally because of changes in soil water content, as described in equation (3).

$$S = 25.4\left(\frac{100}{CN} - 10\right) \tag{3}$$

The potential evapotranspiration (PET) is estimated utilizing Penman-Monteith method (Monteith, 1965). This method integrates components addressing the energy required to keep evaporation, the effectiveness of the mechanism needed for water vapor removal, and factors related to aerodynamic and surface resistance, as described in the equation (4).

$$\lambda E = \frac{\Delta.(H_{net} - G) + P_{air}.C_P.[e_z^0 - e_z]/r_a}{\Delta + \gamma.(1 + r_c/r_a)} \tag{4}$$

where λE is the latent heat flux density (MJ/m²/d), E is the evaporation rate (mm/d), Δ is the slope of the saturation vapor pressure-temperature curve, de/dT (kPa/◦C), H_{net} is the net radiation (MJ/m²/d), G is the heat flux density to the ground (MJ/m²/d), P_{air} is the air density (kg/m³), C_p is the specific heat at constant pressure (MJ/kg/◦C), e_z^0 is the saturation vapor pressure of the air at height z (kPa), e_z is the water vapor pressure of the air at height z (kPa), γ is the psychrometric constant (kPa/◦C), r_c is the plant canopy resistance (s/m), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s/m). For sufficiently watered crops in conditions of neutral atmospheric stability as well as pretending logarithmic wind profiles (Jensen, 1990), the equation of Penman-Monteith can be described in equation (5).

$$\lambda E_t = \frac{\Delta.(H_{net} - G) + \gamma.K_1.(0.622.\lambda.P_{air}/P).(e_z^0 - e_z)/r_a}{\Delta + \gamma.(1 + r_c/r_a)} \tag{5}$$

Where λ is the latent heat of vaporization (MJ/kg), E_t is the maximum transpiration rate (mm/d), K_1 is a dimensionless coefficient needed to ensure the two terms in the numerator have the same units, and *P* is the atmospheric pressure (kPa).

In SWAT, the erosion resulting from runoff within HRUs is predicted using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995). MUSLE is a variation of the Universal Soil Loss Equation (USLE), maintaining a similar structure but replacing the rainfall energy factor with a runoff factor, as described in the equation (6).

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad (6)$$

Where sed is the sediment yield on a given day (t), and Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is peak runoff rate (m^3/s), $area_{hru}$ is the area of HRU (ha), K_{USLE} is the USLE soil erodibility factor [0.013 t m^2 hr/ (m^3 - t cm)], C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and $CFRG$ is the coarse fragment factor. Figure 6 illustrates the hydrological system using the SWAT model.

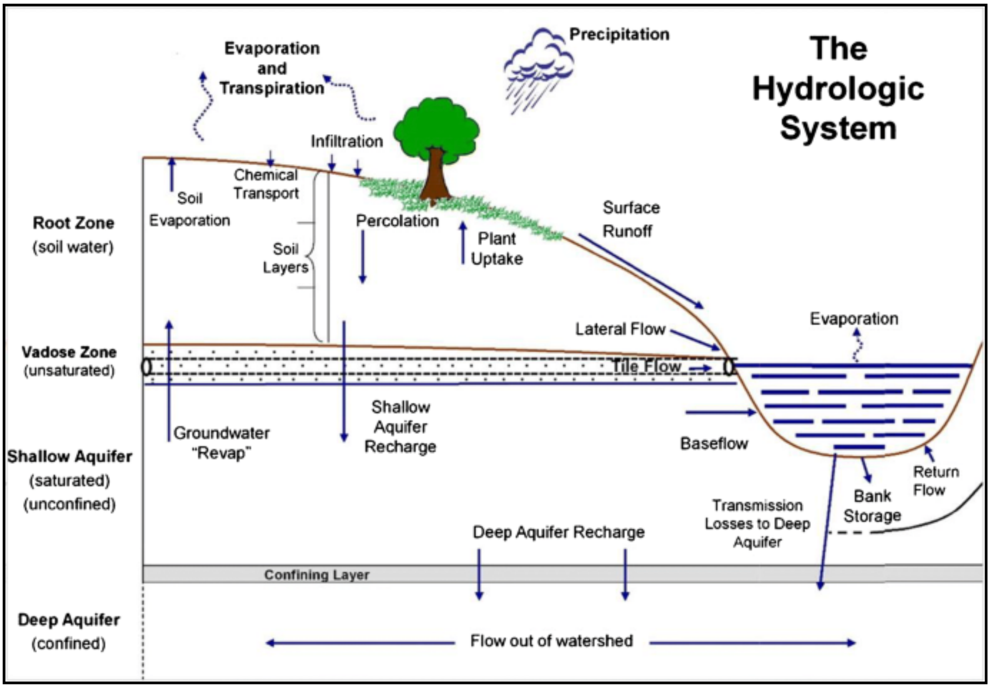


Figure 6. Diagram of the hydrological cycle and the processes simulated by the SWAT model (Neitsch et al., 2011). Sourced from (Nasiri et al., 2020).

2.2.2.2 Model input and setup.

The setup of the hydrological model involves defining key input data, such as weather, topography, land use, soil, and management operations. The weather data, such as daily precipitation, maximum and minimum daily air temperatures measured by 14 selected rain gauges obtained from (L'Agenzia Regionale per lo Sviluppo e l'Innovazione dell'Agricoltura del Lazio-ARSIAL), solar radiation, relative humidity, and wind speed data from E-OBS daily gridded dataset (https://www.ecad.eu/download/ensembles/download.php) covering the period from 2004 to 2020. The digital elevation model (DEM) data was sourced from the (Shuttle Radar Topography Mission-SRTM) (USGS, 2020), and Land-use data from the (GlobCorine given by the European Space Agency) (CLC, 2018). A gridded soil data was obtained from the (FAO/UNESCO global soil map) (FAO, 1988). Measured data regarding management practices including actual planting, harvesting, tillage, irrigation and fertilizer application for various crops were acquired from the local farmers of the study area and the (Consorzio di bonifica "Litorale Nord"). Measured hydrological data including flow discharge, total nitrogen (TN), and nitrate (NO_3^-) are sourced from the (Regione Lazio - AGENZIA REGIONALE DI PROTEZIONE CIVILE and Arpa Lazio). Further details on data collection for the hydrological model construction are shown in Table 3.

Table 3. Input data descriptions and sources utilized for the hydrological model.

Data type	Scale/Resolution	Source
Digital Elevation Model (DEM)	30m	Shuttle Radar Topography Mission (SRTM) https://earthexplorer.usgs.gov/
Soil	500 m	FAO/UNESCO global soil map https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
Landuse	100 m	Corine Land Cover/ European Environment Agency (EEA) https://land.copernicus.eu/en/products/corine-land-cover/clc2018
Weather data	14 stations 0.11° grid	- L'Agenzia Regionale per lo Sviluppo e l'Innovazione dell'Agricoltura del Lazio (ARSIAL) https://www.arsial.it/ - European daily gridded meteorological data (E-OBS) https://www.ecad.eu/download/ensembles/download.php
River discharge	1 station, Monthly ($m^3 s^{-1}$)	Regione Lazio - AGENZIA REGIONALE DI PROTEZIONE CIVILE https://www.meteomarta.altervista.org/portale/il-livello-attuale-del-fiume-marta-tarquinia
Total nitrogen (TN) **Nitrate (NO_3^-)**	1 station, Monthly ($mg\ l^{-1}$)	Arpa Lazio https://www.arpalazio.it/web/guest/ambiente/acqua

Agricultural management practices	Planting Fertilization Irrigation Harvesting Tillage	Consorzio di bonifica "Litorale Nord"

The development of the hydrological model based on the current conditions in the watershed (baseline scenario) was initiated by delineating the watershed using Arc-SWAT an interface within Arc-GIS version (10.6). Figure 7 provides an overview of the SWAT model components, methodology, and framework. A delineation process is supported by employing the specified DEM dataset. This study utilized an automated approach for the watershed delineation to evaluate basin morphology. Primarily, the DEM was re-projected to the appropriate coordinate system and mosaicked to cover the study area. Then, a filling operation was performed to correct depressions, and flow direction and accumulation grids were analyzed. Each sub-basin's stream network and outlet are delineated by applying a standardized threshold value. Finally, the watershed exit point (new outlet) was manually selected on the stream near Tarquinia station as the outlet of the watershed. Following the delineation process, the watershed boundary and its area, with a total of 28 sub-basins, were identified for the Marta River watershed, which has an area of 1047.62 km^2. The hydrological model construction was completed through the definition of spatially unique HRUs within sub-basins separately utilizing land use, soil and slope data as an input to the model. Regarding the land use (CLC) map, certain areas inside the watershed were updated with new land use classifications based on the information provided by local authorities and study area specialists. Subsequently, the categories defined in the Land Cover (CLC) database undergo reclassification to align with the definitions provided in the global SWAT database (Arnold et al., 2013) and are divided into thirteen classes (see Figure 8a and Table 4). The obtained gridded soil data from (FAO/UNESCO global soil map) database was imported into the model by editing the default database of (usersoil). The process outcome created two distinct soil classes, as demonstrated in Figure 8b. The slope map was derived from the DEM during the process of watershed delineation. Utilizing the (multiple slopes) option, the maximum allowable range for five slope classes was defined, as presented in Figure 8c, with a specific threshold percentage established for each land use, soil and slope. Eventually, the hydrological model generated a total of 277 HRUs inside the watershed. Weather data including maximum and minimum daily temperature (°C), precipitation (mm), solar radiation (MJ/m^2), relative humidity, and wind speed (m/s) were then incorporated into the model. To more accurately simulate the real conditions that exist in the study area, information regarding management activities, including plantation, fertilization, irrigation and other operations were analyzed on a single HRU and scheduled during specific dates using a date-based scheduling method (Arnold et al., 2010). Regarding irrigation operations, SWAT can identify potential sources of irrigation such as rivers, reservoirs, shallow aquifers, deep aquifers, or unlimited sources outside the catchment. In this study, the reach as the source of irrigation was selected for the lower watershed irrigated areas, which was in the sub-basin-27, while the shallow aquifer was chosen for the upper and middle watershed areas. The irrigation water volume was defined in the model for different crops based on the average amount applied in the field for each month from May to August. The irrigation system utilized is a sprinkler method with irrigation efficiency (efficiency of irrigation system to deliver water to the proposed crops) of 75% was set in the model, considering both conveyance and application losses. The model construction ended with running a simulation covering 17 years from 2004 to 2020 considering the first two years as a warm-up period to precisely reflect watershed behavior by diminishing the unidentified initial condition effects (Fuka et al., 2016; Ghadei et al., 2018).

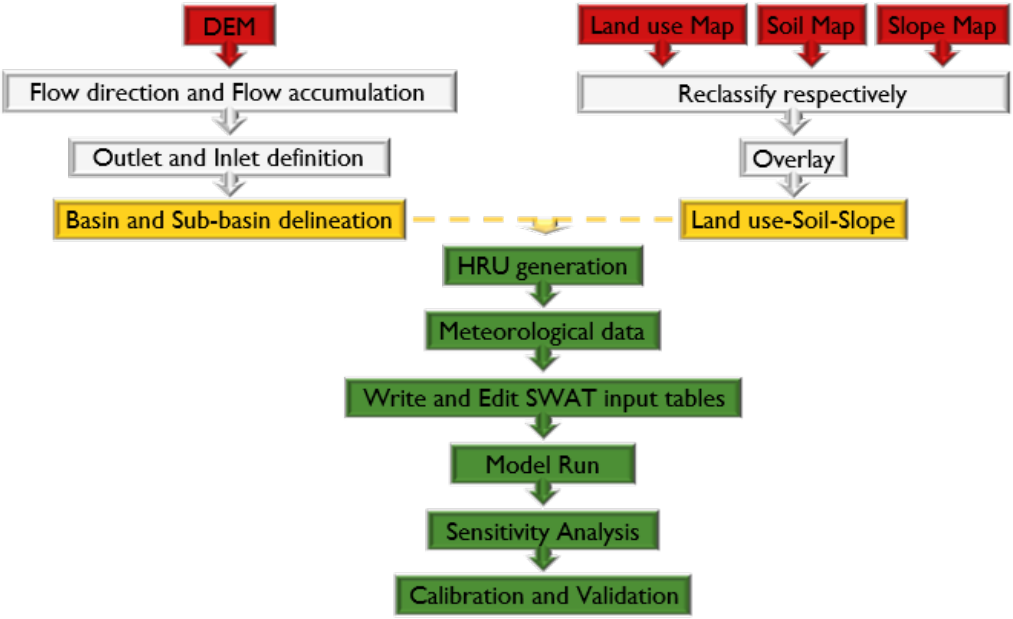


Figure 7. The general framework of hydrological modeling (SWAT).

Table 4. Land use classes at a watershed level using the SWAT Model.

Land use classes	**Area (km^2)**	**Watershed area (%)**
Complex cultivation pattern	49.07	4.68
Land principally occupied by agriculture with areas of natural vegetation	69.62	6.65
Corn	0.09	0.01
Broad-leaved forest	145.93	13.93
Short rotation forage	4.69	0.45
Olive groves	73.55	7.02
Pasture	3.32	0.32
Transitional woodland-shrub	21.53	2.05
Natural grassland	11.21	1.07
Fruit trees and berry plantation	3.70	0.35
Horticulture	6.05	0.58
Water	143.11	13.66
Winter wheat cereal	515.75	49.23

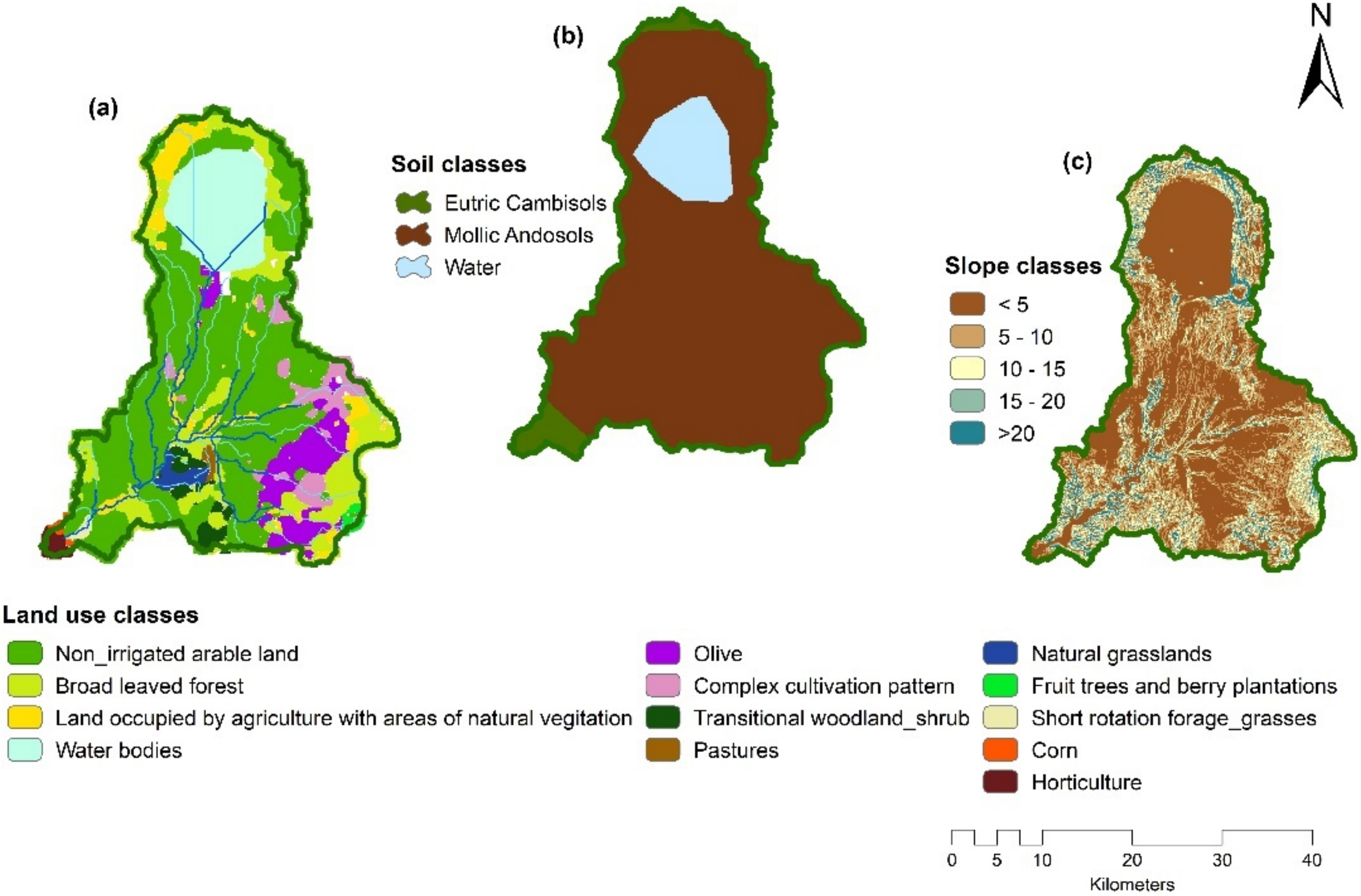


Figure 8. SWAT model spatial inputs: (a) land use map; (b) soil map; (c) slope map.

2.2.2.3 The SWAT calibration and uncertainty analysis

Considering the specificities and needs of the study area as well as the availability of measured data, the calibration of the hydrological model focused on flow discharge, TN, and NO_3^- utilizing monthly measurements covering the period from 2004 to 2020. The first two years (2004-2005) were considered as a warm-up period to reduce the unidentified initial condition effects, then a portion of the dataset covering the years from 2006 to 2020 was designated for calibration, with the remaining portion for validation (Abbaspour et al., 2015; Almeida et al., 2018). The period of simulation for the calibration of flow discharge was from 2006 to 2015 and for validation was from 2016 to 2020. For the estimation of TN and NO_3^-, the period of simulation for calibration was 2013-2018, while for validation was 2018-2019 and 2018-2020, respectively.

The calibration, validation and sensitivity analysis were conducted for the constructed hydrological model utilizing the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) software package. The Sequential Uncertainty Fitting algorithm version 2 (SUFI-2) was selected among the optimization procedures that are available in the SWAT CUP package. Initially, the sensitivity analysis was carried out for numerous common sensitive hydrological parameters to identify the most influential and sensitive hydrological parameters for every single sub-basin utilizing the global sensitivity analysis (GSA) procedure in SWAT-CUP (Abbaspour et al., 2015; Tuo et al., 2016). This procedure can change input parameters systematically within reasonable ranges and observe resulting changes in model outputs utilizing statistical measures such as p-values and t-statistics (t-stat). The t-stat assesses the significance of calibration parameters in the model, a higher t-stat absolute value indicates that the corresponding parameter has a significant effect on the model output. The p-value determines the statistical significance of the calibration parameters, a p-value usually lower than 0.05 indicates that the parameter is statistically significant. Following the sensitive parameters and their initial ranges identified in this analysis, the models underwent 4 iterations. The initial parameters were set within physically acceptable ranges based on literature and SWAT documentation. In each iteration, 1000 simulations were conducted. Following each iteration, adjustments were made to the parameter ranges, typically narrowing them down. This modification considered both the feedback given by the program for new parameters and physical constraints (Abbaspour et al., 2004, 2007, 2015). Therefore, the final iteration has the best ranges for the parameters and the best simulation of the final iteration presents the best-performing parameter set.

Numerous metrics are reported in the literature for model performance assessment. In this study, we adopt the methodology proposed by Abbaspour et al. (2015), which utilized SUFI-2 for evaluating the reliability and accuracy of the hydrological model simulations. This algorithm supports model calibration, validation, sensitivity, and uncertainty analysis through an iterative process. It involves mapping uncertainties associated with input data, model parameters, observed data and simulated models onto parameter ranges. The main goal is to encompass most of the observed data within the 95% prediction uncertainty interval (95PPU) of the model. The 95PPU is calculated based on the 2.5% and 97.5% levels of the cumulative distribution of an output variable. This distribution is generated by propagating the parameter ranges or uncertainties using Latin hypercube sampling (Abbaspour et al., 2015). To achieve the optimal range for each parameter, the 95PPU must bracket most of the observed data, while keeping band thickness as small as possible. Therefore, the prediction uncertainties are assessed using the P-factor and R-factor (Abbaspour, 2015; Abbaspour et al., 2004). The P-factor represents the fraction of observed data bracketed by the 95% prediction uncertainty (95PPU) band, with value ranges from 0 to 1, with 1 being optimal, signifying that all observed data fall within the prediction uncertainty range. The R-factor measures the thickness of the 95PPU band, defined as the ratio between the average width of this band and the standard deviation of the observed data. An ideal model simulation is indicated by a P-factor of 1 and an R-factor of 0 in which the predictions align perfectly with the observed data. As achieving a higher P-factor necessitates an increased R-factor, it is essential to maintain a balance between these two indices. A P-factor higher than 0.7 and an R-factor lower than 1.5 are considered satisfactory regarding flow discharge prediction uncertainty and it varies based on the scale of the project and the quality of the input and calibration data, recommended by (Abbaspour et al., 2004, 2015). SUFI-2 uses several objective functions: coefficient of determination (R^2) (Krause et al., 2005), Nash-Sutcliffe Efficiency (NSE) (Nash & Sutcliffe, 1970), Kling-Gupta Efficiency (KGE) (Gupta et al., 2009), Root Mean Square Error to Standard Deviation Ratio (RSR) (Moriasi et al., 2007) and percent bias (PBIAS) (Yapo et al., 1996) to evaluate the performance of the hydrological model, the equations for each objective functions are demonstrated below, equations (7), (8), (9), (10), and (11). R^2 and KGE both range from zero to one, with zero representing a poor fit and one indicating a perfect fit (optimal model performance) (Moriasi et al., 2007). NSE spans from minus infinity to one and assesses how closely the observed data matches the simulated data. RSR is determined by the ratio of RSME to the standard deviation of observed data (SD_{obs}). A lower RSR indicates a lower RMSE and good model simulation performance. The ideal Percent Bias value is zero, with low magnitude values signifying accurate model simulations. Negative percent bias values suggest model overestimation, while positive values suggest underestimation (simulated values are lower than observed values) (Moriasi et al., 2007). The model simulation is deemed satisfactory if the NSE, R^2 and KGE value exceeds 0.5, PBIAS is within ±25%, and RSR is lower than 0.7 (Moriasi et al., 2007; Santhi et al., 2001). Table 5 presents the detailed hydrological model performance rating on a monthly scale.

$$R^2 = \frac{\left(\sum_{i=1}^{n}\left(O_i - O_{avg}\right) - \left(S_i - S_{avg}\right)\right)^2}{\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2 \ \sum_{i=1}^{n}\left(S_i - S_{avg}\right)^2} \tag{7}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2} \tag{8}$$

$$KGE = 1 - \sqrt{(CC-1)^2 + \left(\frac{cd}{rd} - 1\right)^2 + \left(\frac{cm}{rm} - 1\right)^2} \tag{9}$$

$$RSR = \frac{RMSE}{SD_{obs}} = \frac{\sqrt{\sum_{i}^{n}(O_i - S_i)^2}}{\sqrt{\sum_{i}^{n}\left(O_i - O_{avg}\right)^2}} \tag{10}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100 \tag{11}$$

Where, S_i represents the simulated and O_i represents the observed data (in terms of discharge, TN, and NO_3^-), S_{avg} denotes the mean value of simulated and O_{avg} denotes the mean value of observed data, and *n* is the number of recorded data. CC, cm, rm, cd and rd are the Pearson correlation coefficient value, average of simulated values, average of observed values, standard deviation of simulated values and standard deviation of observation values, respectively.

Table 5. Model performance rating on a monthly scale.

KGE	R^2	NSE	RSR	PBIAS	Performance rating
$0.9 \le KGE \le 1$	$0.75 < R^2 \le 1$	$0.75 < NSE \le 1$	$0 \le RSR \le 0.5$	$PBIAS < \pm 10$	**Very good**
$0.75 \le KGE < 0.9$	$0.65 < R^2 \le 0.75$	$0.65 < NSE \le 0.75$	$0.5 < RSR \le 0.6$	$\pm 10 \le PBIAS < \pm 15$	**Good**
$0.5 \le KGE < 0.75$	$0.5 < R^2 \le 0.65$	$0.5 < NSE \le 0.65$	$0.6 < RSR \le 0.7$	$\pm 15 \le PBIAS < \pm 25$	**Satisfactory**
$KGE < 0.5$	$R^2 \le 0.5$	$NSE \le 0.5$	$RSR > 0.7$	$PBIAS \ge \pm 25$	**Unsatisfactory**

2.3 Results and Discussion

2.3.1 Selecting the best climate models for the study area

This study evaluated all the available combinations of the highest resolution of EURO-CORDEX combinations (0.11°) for three variables over the watershed. Three indices have been chosen for the variables: annual total precipitation (PRCP), annual mean of daily minimum surface temperature (TNmean), and annual mean of daily maximum surface temperature (TXmean), for the purpose of the performance evaluation the Aras diagram (Izzaddin et al., 2024) has been utilized.

The first index is PRCP spatiotemporal analysis (both spatial climatological pattern and interannual temporal analysis), which has been considered (see Figure 9), The best combination over the watershed is MPI-M-MPI-ESM (GCM) drives RACMO22E (RCM), which overestimated both the mean and the variability, which has a bias-variability error of 25%.

Regarding performance evaluation of daily minimum surface temperature, the majority of the models have similar skills (see Figure 10), In general, the combinations have higher performance when compared with precipitation, most of the models underestimated the mean and the variability, and the best combination over the basin is MOHC-HadGEM2-ES drives CNRM-ALADIN63.

Finally, the last variable that has been evaluated over the watershed is daily maximum surface temperature, 14 combinations overestimated the mean, and overall, surface temperature performed better than precipitations over the watershed, the best combination over is MPI-M-MPI-ESM-LR drives SMHI-RCA4 as seen in Figure 11.

After choosing the best model combinations, to observe the change of surface maximum temperature from 1950 to 2100, considering the worst-case scenario for CO_2 emission, it shows a positive trend with 6 °C higher than the baseline (see Figure 12). Details of the combinations that have been evaluated over the watershed are shown in Figure 46.

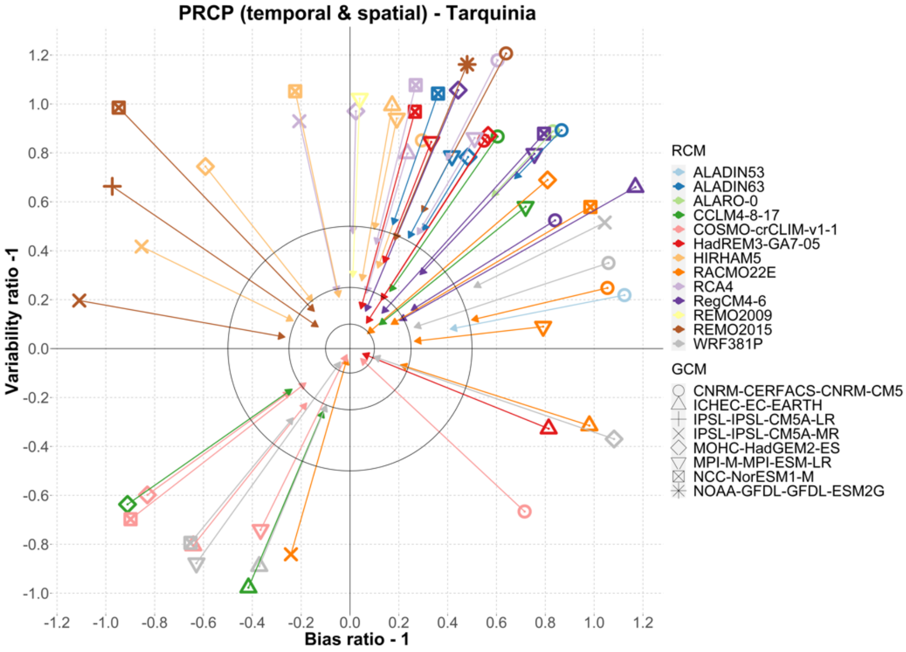


Figure 9. The Aras diagram for performance evaluation of EURO-CORDEX combinations (GCMs-RCMs) of annual total precipitation (PRCP) over the Tarquinia basin.

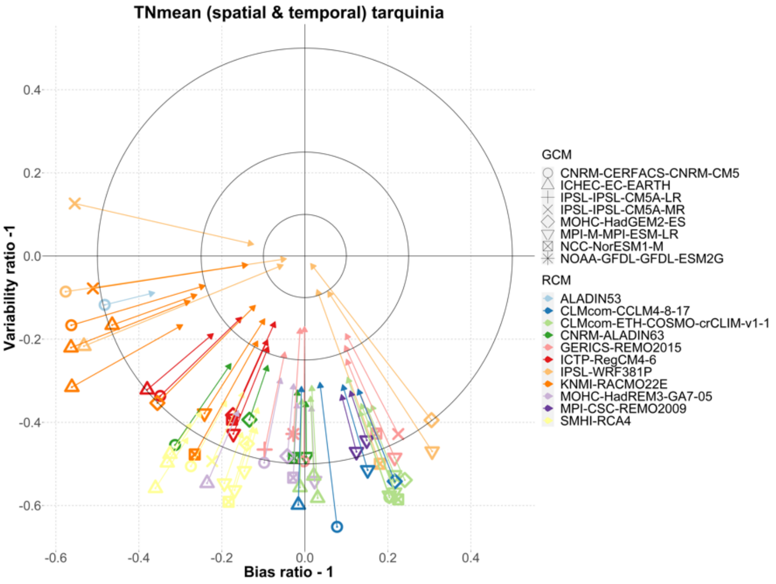


Figure 10. The Aras diagram for performance evaluation of EURO-CORDEX combinations (GCMs-RCMs) of an annual mean of daily minimum surface temperature over the Tarquinia basin.

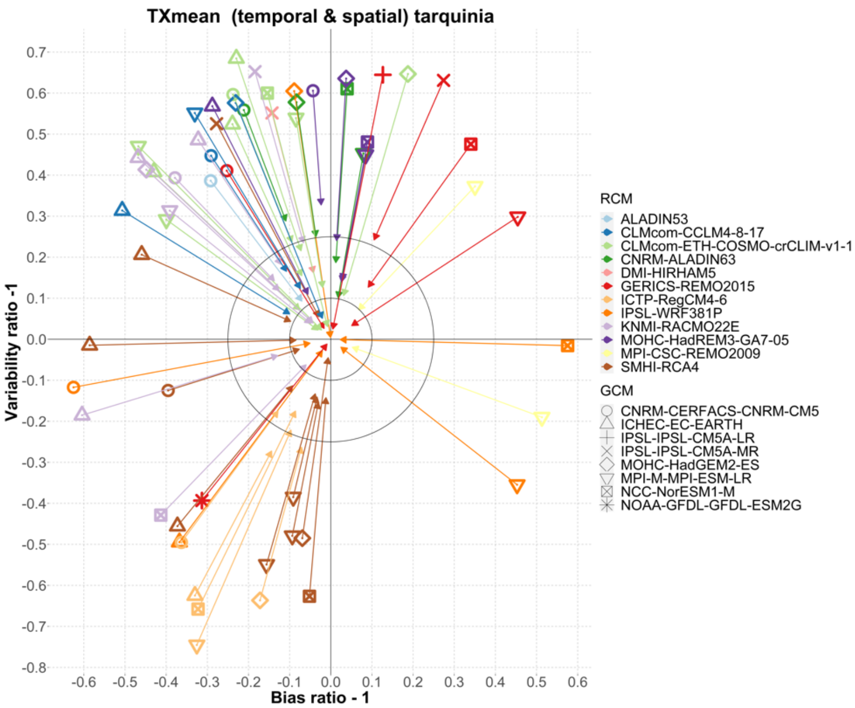


Figure 11. The Aras diagram for performance evaluation of EURO-CORDEX combinations (GCMs-RCMs) of an annual mean of daily maximum surface temperature over the Tarquinia basin.

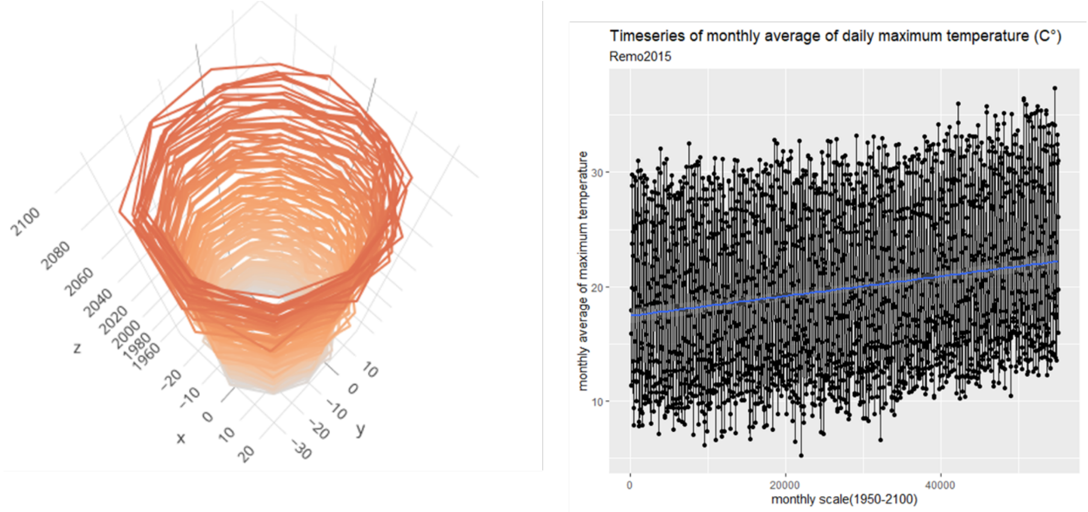


Figure 12. Time series of monthly average daily maximum temperature (°C) extracted from the best combination over Tarquinia watershed (left and right plots are same with different views).

2.3.2 Agro-hydrological (SWAT) model performance

Table 6 presents a detailed evaluation of performance metrics for flow discharge, NO_3^- and TN modeling, during calibration and validation periods. The subsequent (Figure 13 - Figure 15) display the long-term evaluation and Figure 16 illustrates the relationship between observed and simulated data for flow discharge, NO_3^- and TN, respectively.

2.3.2.1 Stream flow

The evaluation metrics demonstrated that the model calibration and validation for flow discharge at the Tarquinia gauge effectively replicates the hydrological processes in the watershed, as evidenced by the goodness-of-fit objective function results (see Table 6). During the calibration period, the NSE, KGE, RSR and PBIAS are rated as good model performance, with 0.7, 0.77, 0.55 and 14.1 %, respectively. For validation, the NSE and RSR demonstrated good performance, with values of 0.66 and 0.58, respectively, while the KGE was 0.62 and PBIAS was 2.6 %, rated as satisfactory and very good model performance, respectively. The performance metrics demonstrated that the model configuration handles stream flow effectively. Nevertheless, the slight increase in PBIAS and the decrease in KGE metrics highlight a limitation in accurately simulating certain peak and low flows. Despite this, the PBIAS value is within ±30 %, which is considered the upper threshold for river discharge model performance (Moriasi et al., 2015; Pulighe et al., 2019). The predictions of the model for flow discharge at the Tarquinia gauge showed a high coefficient of determination (R^2) with the observed data during both calibration and validation period, which indicates a good correlation between measured and observed data points and the data points align closely with the 1:1 line, which indicates a good fit, with the value of 0.72 and 0.71 for calibration and validation, respectively (see Figure 16a and Figure 16b). Furthermore, the model's performance was further assessed by utilizing the percentage prediction uncertainty analysis to provide a more comprehensive assessment of the model’s performance. The study outputs demonstrated that the observed flow consistently fell within the 95PPU bounds during both calibration and validation periods, as seen in Figure 13. During calibration, the P-factor was 0.7 which indicates that 70% of the measured data points fall within the 95PPU band and the R-factor of 1.02. For the validation, the P-factor and R-factor were 0.68 and 0.64, respectively.

2.3.2.2 Nitrate (NO_3^-)

The simulation outcomes indicated that the model used can accurately replicate the water quality parameter (NO_3^-) and their changes over time at the Tarquinia gauge station, as demonstrated in Figure 14. The NSE for NO_3^- during both the calibration and validation period received a good rating for model performance, with a value of 0.7 during calibration and 0.74 during validation. The KGE and RSR were 0.75 and 0.56, showed a good performance during calibration, respectively, while PBIAS was evaluated as a satisfactory performance with a value of 18.5%, as seen in Table 6. Nitrate received a rating of good performance during validation for both KGE and PBIAS, with values of 0.82 and 10.3%, respectively and a high rating for the RSR with 0.47. The high peaks of NO_3 are attributed to high runoff events. Like the flow discharge, the nitrate simulation exhibited fewer uncertainties, with P-factor and R-factor values of 0.67 and 0.95 during calibration, and 0.45 and 1.23 during validation, respectively. The simulation model outputs also showed a strong relationship exists between measured and simulated nitrate data points, with R^2 of 0.82 and 0.78 during calibration and validation, respectively (see Figure 16c and Figure 16d).

2.3.2.3 Total nitrogen (TN)

Regarding TN, the high values of NSE confirmed that the SWAT model simulated TN within acceptable levels of precision during the calibration and validation periods with values of 0.87 and 0.79, respectively. The KGE, RSR and PBIAS exhibited high performance, with values 0.9, 0.37 and 6.4% during calibration, and 0.76, 0.46 and 13.8 during validation, respectively, as demonstrated in Table 6. The uncertainty analysis outputs showed that the measured TN data is bracketed by the 95PPU, with a P-factor of 0.65 and 0.43 and an R-factor of 0.97 and 1.42 during calibration and validation, respectively (see Figure 15). The R^2 of 0.93 and 0.81 revealed a strong relationship between the measured and simulated TN, as demonstrated in Figure 16e and Figure 16f.

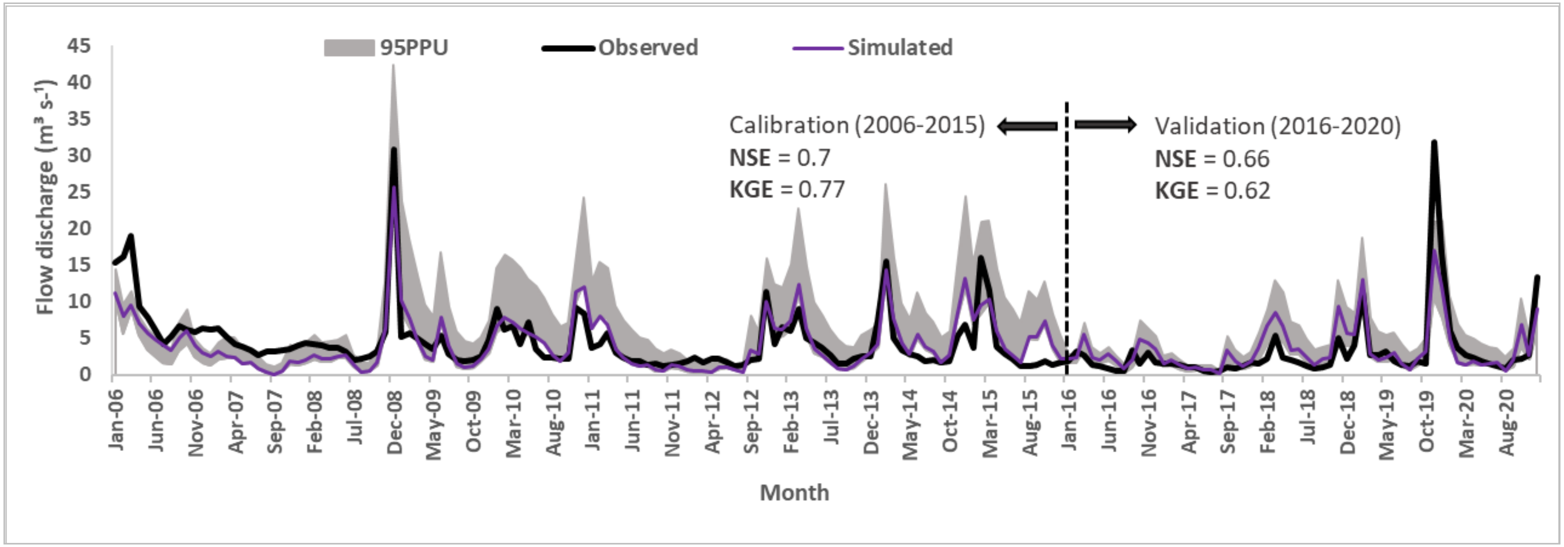


Figure 13. Hydrological model performance for flow discharge during the calibration period (2006-2015) and validation period (2016-2020).

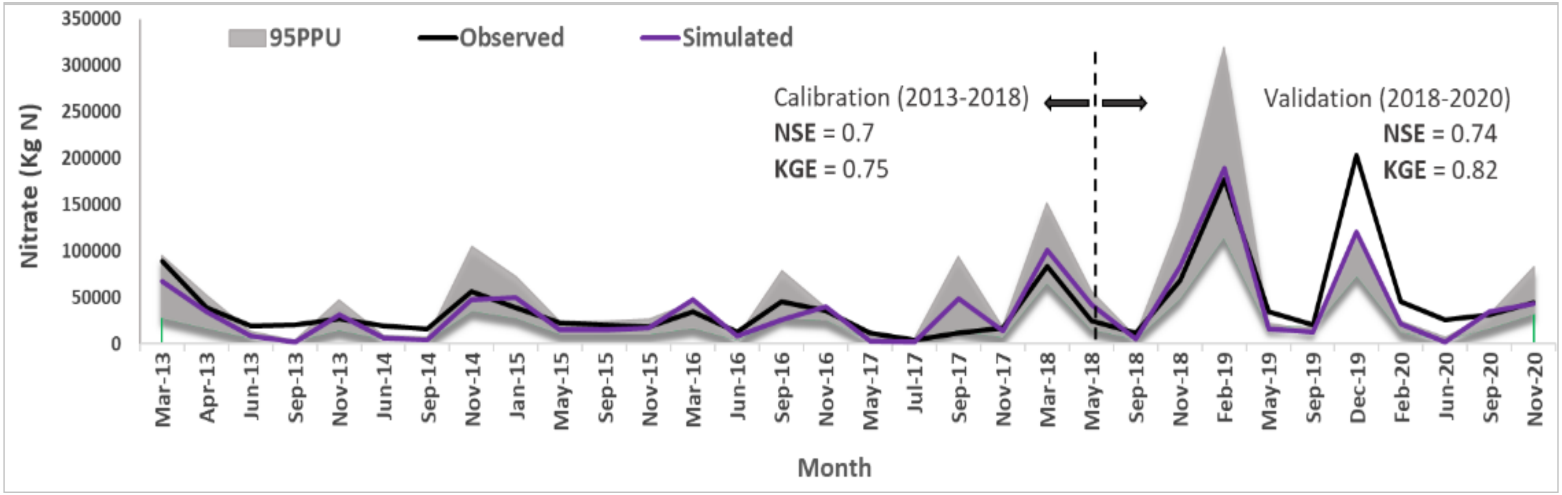


Figure 14. Hydrological model performance for nitrate (NO_3^-) during the calibration period (2013-2018) and validation period (2018-2020).

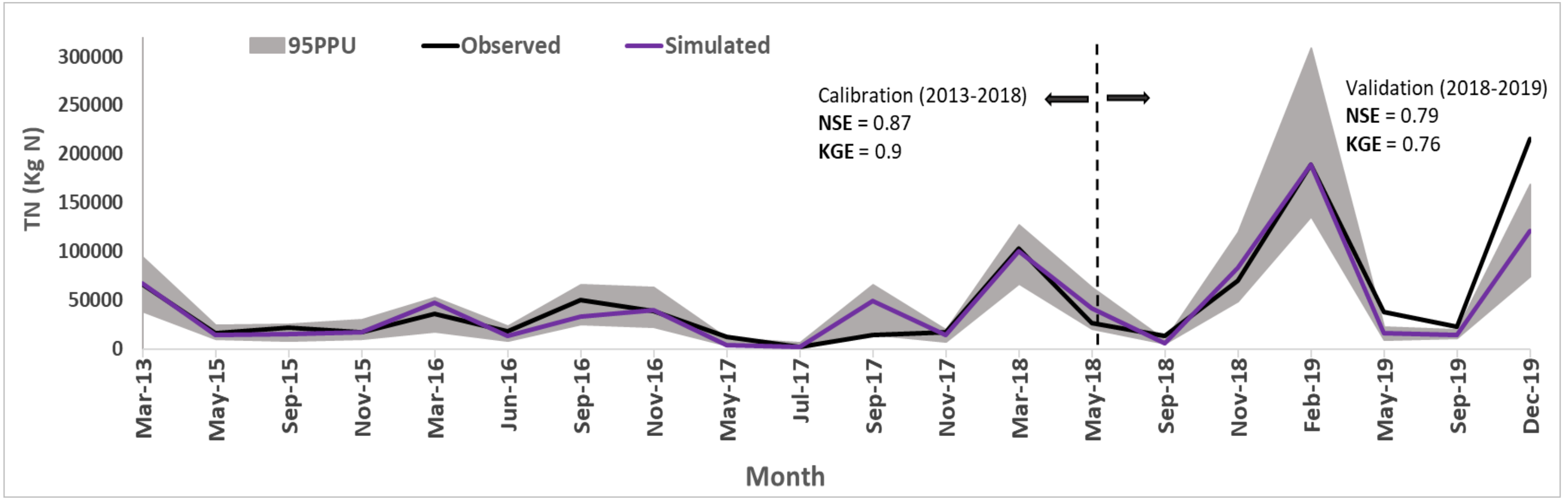


Figure 15. Hydrological model performance for total nitrogen (TN) during the calibration period (2013-2018) and validation period (2018-2019).

Table 6. Evaluation of performance metrics for flow discharge, NO_3^- and TN modeling during calibration and validation.

Tarquinia station	**Calibration**					**Validation**				
	KGE	**R^2**	**NSE**	**RSR**	**PBIAS**	**KGE**	**R^2**	**NSE**	**RSR**	**PBIAS**
Flow Discharge	0.77	0.72	0.7	0.55	14.1	0.62	0.71	0.66	0.58	2.6
Nitrate	0.75	0.82	0.7	0.56	18.5	0.82	0.78	0.74	0.47	10.3
Total nitrogen	0.9	0.93	0.87	0.37	6.4	0.76	0.81	0.79	0.46	13.8

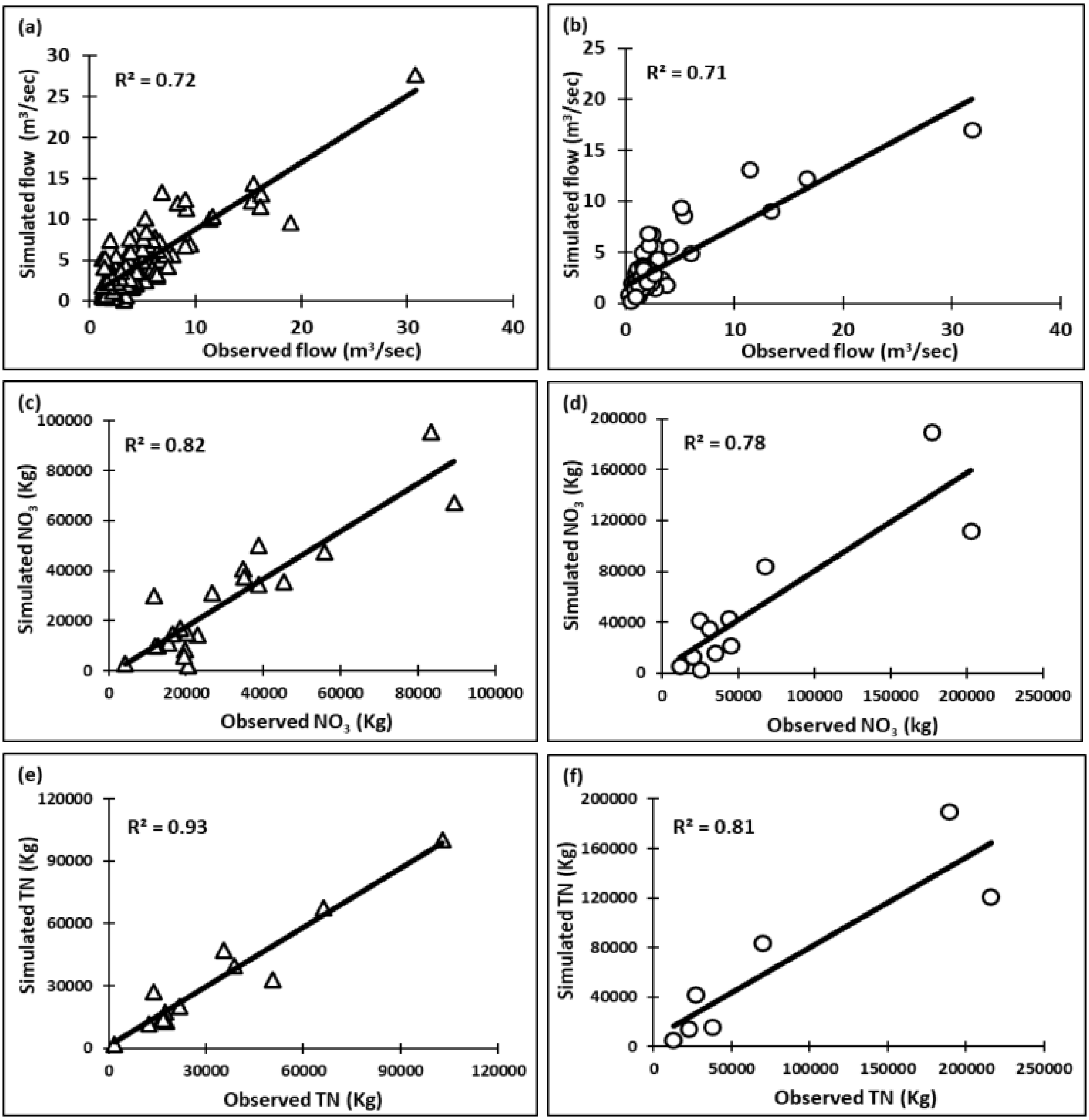


Figure 16. Scatter plots displaying the relationship between observed and simulated monthly flow discharge during, a) calibration, b) validation; monthly NO_3^- load during, c) calibration, d) validation; and monthly TN load during, e) calibration, f) validation; with the straight line shows 1:1 reference line.

2.3.3 Sensitivity analysis

Table 7 displays a total of 30 common sensitive hydrological parameters selected for the model calibration utilizing SWAT_CUP, along with corresponding descriptions, methods, units, initial ranges and fitted values. Sixteen parameters were selected for flow and fourteen parameters were selected for nitrogen (nitrate and total nitrogen) during the hydrological model calibration and validation. Figure 17 presents the sensitivity analysis of hydrological model parameters using P-value and T-statistics. The p-value determines the statistical significance of the calibration parameters, a p-value usually lower than 0.05 indicates that the parameter is statistically significant. The t-stat assesses the significance of calibration parameters in the model. The model simulation outputs revealed that the most sensitive parameters to flow include moist bulk density (SOL_BD), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), average slope length (SLSUBBSN), threshold depth of water in the shallow aquifer for "revap" to occur (REVAPMN), soil evaporation compensation factor (ESCO), groundwater delay (GW_DELAY), groundwater "revap" coefficient (GW_REVAP), plant uptake compensation factor (EPCO), available water capacity of the soil layer (SOL_AWC), saturated hydraulic conductivity (SOL_K), and Manning's "n" value for the main channel (CH_N2), as they had P-values near to zero ($P<0.05$) and high T-statistics. The critical parameters identified through the sensitivity analysis are vital for accurately simulating and managing the hydrological balance within the watershed (Li et al., 2021). The sensitivity of SOL_BD, SLSUBBSN, and CH_N2 indicate that these parameters significantly impact soil loss within the watershed by affecting surface runoff, soil erodibility, and streamflow velocity, respectively (Cerdà et al., 2021; Fu et al., 2019; Neitsch et al., 2011; Przewoźna, 2014). Sensitive parameters like GWQMN and REVAPMN show a considerable influence on runoff generation and groundwater recharge rates (Guyo et al., 2024). Partitioning of rainfall into infiltration and evaporation, thereby influencing both runoff and groundwater recharge, is affected by ESCO (Omollo & Kiptala, 2022). In addition, sensitivity in both parameters, ESCO and EPCO indicates that they govern the rates of soil evaporation and vegetation transpiration, respectively, impacting evapotranspiration processes within the watershed (Neitsch et al., 2011; Rajib et al., 2018). On the other hand, the highly sensitive parameters to NO_3^- and TN include denitrification threshold water content (SDNCO), denitrification exponential rate coefficient (CDN), soluble nitrogen concentration (SOLN_CON), and organic N in the baseflow (LAT_ORGN), which exhibited P-values < 0.05 and high T-statistics. Sensitive parameters related to NO_3^- and TN play a critical role in understanding nitrogen dynamics within the study watershed. Sensitive SDNCO represents the level at which denitrification becomes significant, affecting how much nitrogen can be removed from the system, while CDN directly impacts the rate of denitrification, influencing the efficiency of nitrogen removal from water bodies (Moriasi et al., 2013; Wen et al., 2024). Sensitive SOLN_CON signifies the availability of nitrogen for denitrification (Yen et al., 2016), which along with LAT_ORGN, controls denitrification rates and the total nitrogen balance (Jiang et al., 2023; Ren et al., 2022).

Table 7. Optimizing hydrological model calibration: Initial parameter ranges and their fitted values.

Parameter	Extension	Method	Definition	Unit	Initial range		Fitted value
					Min	Max	
			Flow sensitive parameter				
SOL_AWC	.sol	Relative	Available water capacity of the soil layer	mm/mm	-0.2	0.2	-0.049
SOL_K	.sol	Relative	Saturated hydraulic conductivity	mm/hr	-0.2	0.2	-0.135
SOL_BD	.sol	Relative	Moist bulk density	gm/cm³	-0.5	0.5	0.363
CN2	.mgt	Relative	SCS runoff curve number	—	-0.25	0.25	-0.188
ESCO	.hru	Replace	Soil evaporation compensation factor	—	0	1	0.771
HRU_SLP	.hru	Replace	Average slope steepness	m/m	0	1	0.622

SLSUBBSN	.hru	Replace	Average slope length	m	10	150	41.550
EPCO	.hru	Replace	Plant uptake compensation factor	—	0	1	0.474
OV_N	.hru	Replace	Manning's "n" value for overland flow	—	0.01	1	0.182
GWQMN	.gw	Replace	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	0	5000	536.703
REVAPMN	.gw	Replace	Threshold depth of water in the shallow aquifer for "revap" to occur	mm	0	500	300.728
GW_REVAP	.gw	Replace	Groundwater "revap" coefficient	—	0.02	0.2	0.116
GW_DELAY	.gw	Replace	Groundwater delay	days	0	500	191.341
ALPHA_BF	.gw	Replace	Baseflow alpha factor	days	0	1	0.620
CH_K2	.rte	Replace	Effective hydraulic conductivity in main channel alluvium	mm/hr	-0.01	500	84.559
CH_N2	.rte	Replace	Manning's "n" value for the main channel	—	-0.01	0.3	0.182
			Nitrogen sensitive parameter				
LAT_ORGN	.gw	Replace	Organic N in the baseflow	mg/l	0	30	6.300
RCN	.bsn	Replace	Concentration of nitrogen in rainfall	mg N/l	0	3	1.322
N_UPDIS	.bsn	Replace	Nitrogen uptake distribution parameter	—	0	30	17.499
NPERCO	.bsn	Replace	Nitrogen percolation coefficient	—	0	0.3	0.093
CMN	.bsn	Replace	Rate factor for humus mineralization of active organic nitrogen	—	0.001	0.003	0.002
CDN	.bsn	Replace	Denitrification exponential rate coefficient	—	0	3	0.020
SDNCO	.bsn	Replace	Denitrification threshold water content	—	0	1	0.995

FIXCO	.bsn	Replace	Nitrogen fixation coefficient	—	0	1	0.692
RCN_SUB_BSN	.bsn	Replace	Concentration of nitrate in precipitation	ppm	0	2	0.922
BC3_BSN	.bsn	Replace	Rate constant for hydrolosis of organic nitrogen to ammonia	1/day	0.02	0.4	0.289
BC3	.swq	Replace	Rate constant for hydrolysis of organic N to NH_4 in the reach	1/day	0.2	0.4	0.199
RS4	.swq	Replace	Rate coefficient for organic N settling in the reach	1/day	0.001	0.1	0.036
ERORGN	.hru	Replace	Organic N enrichment ratio	—	0	4	1.462
SOLN_CON	.hru	Replace	Soluble nitrogen concentration	—	0	10	8.133

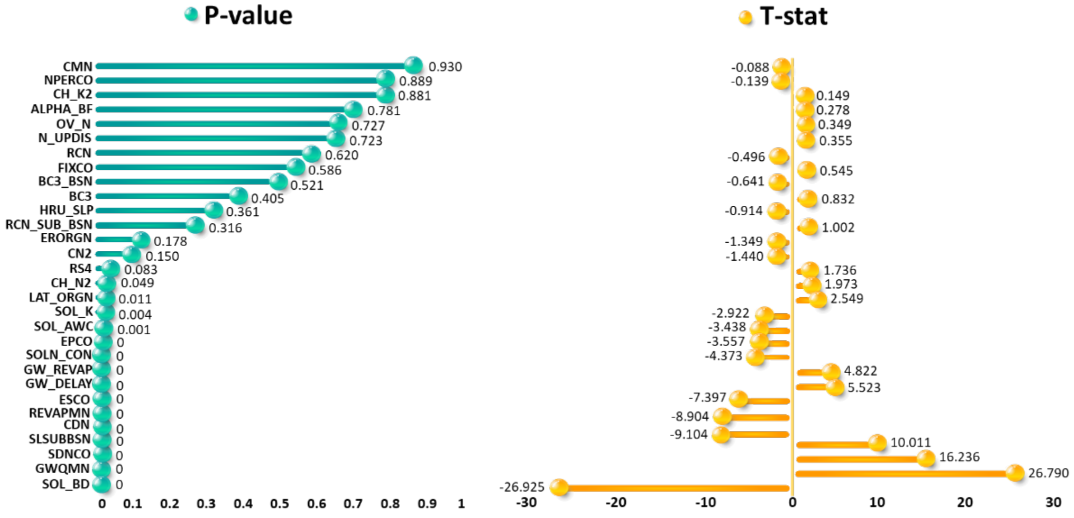


Figure 17. Sensitivity analysis of the hydrological model parameters.

2.3.4 Comparative assessment of hydrological balance under baseline and future climate change scenarios

2.3.4.1 Hydrological balance assessment under the baseline scenario

The monthly averages of water balance components over the 15-year simulation period within the Marta River watershed are shown in Table 8. The simulation outcomes revealed that in the annual precipitation of 656.4 mm, about 68 % constitutes evapotranspiration with 447.7 mm year^{-1}, which is considered the predominant outflow component, highlighting large portion of water is lost to the atmosphere through evaporation and plant transpiration; however, the annual potential evapotranspiration was 1282.9 mm. These results are supported by findings from (De Girolamo & Lo Porto, 2012; Ravelli, 2009). Around 25% of the annual precipitation contributes to the water yield of 163.3 mm, which is the water discharged into the channels and supports maintaining the streamflow and groundwater recharge, this result aligns closely with the outcome obtained by De Girolamo & Lo Porto (2012). The annual lateral flow and surface runoff were 109 mm and 23 mm, respectively. The surface runoff rates varied considerably each month, with peaks in November, having a value of 5.32 mm, and December with 4.35 mm. These peaks align with the rainy season brought about by the Mediterranean precipitation pattern, and result in relevant soil and nutrient losses (Pulighe et al., 2019). During the summer months, June and July exhibited relatively high runoff with values of 2.6 mm and 1.3 mm, respectively. May to August was the period during which the irrigation applications were implemented across different areas of the watershed. During these months, the irrigation may lead to increased surface runoff by raising soil moisture and surpassing the infiltration capacity of the soil. The water yield levels indicated a decreasing trend during the summer months, especially in August, which emphasizes the dry conditions and the transition to an ephemeral state in most river channels during the dry summer months. Utilizing both surface and groundwater as sources of irrigation during the summer period contributed to maintaining some level of flow in the river, as evidenced by the surface runoff and water yield values during June (Khan et al., 2009). The monthly lateral flow levels also indicated an obvious seasonal trend, with elevated levels in the winter months and significantly lower values during the summer. The reduction in lateral flow during the summer months further confirmed the reduced water availability and the ephemeral state of river channels.

Table 8. Average monthly values of water balance components within Marta River watershed under baseline conditions.

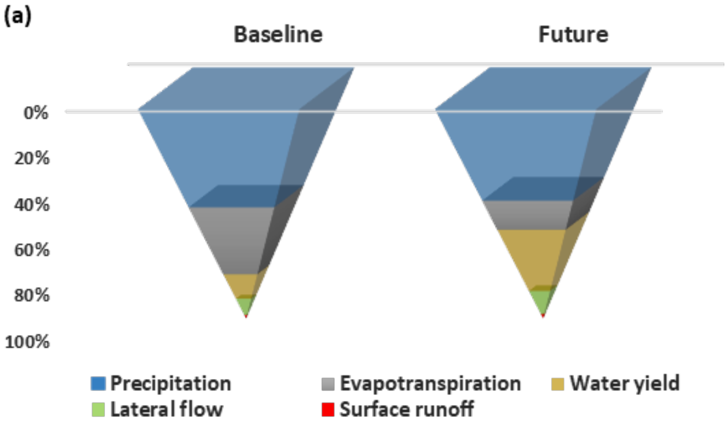
Month	Precipitation (mm)	Surface runoff (mm)	Lateral flow (mm)	Water yield (mm)	ET (mm)	PET (mm)
January	52.03	1.75	11.90	17.69	19.68	43.31
February	65.75	2.60	12.84	18.97	22.70	47.29
March	62.28	1.91	13.34	18.79	38.68	87.66
April	36.59	0.03	8.30	11.40	41.94	104.54
May	32.98	1.10	5.70	9.59	48.53	122.30
June	31.57	2.69	5.92	10.94	54.95	158.97
July	14.59	1.34	4.03	7.45	46.83	187.58
August	16.49	0.63	2.99	5.35	33.23	191.87
September	75.74	0.65	6.40	8.75	48.51	133.91
October	72.01	0.65	8.13	10.67	44.02	100.41
November	112.01	5.32	13.34	20.83	27.30	58.13
December	84.35	4.35	16.05	22.92	21.37	46.95

2.3.4.2 Hydrological balance assessment under the impacts of climate change

The projected monthly averages, the percentage distribution comparison and the comparison of an annual average of water balance components between the baseline and the future are shown in Table 9, Figure 18a, and Figure 18b, respectively. The 30-year hydrological simulation outputs from the most reliable climate model indicated that the precipitation experiences an annual increase to 741.3 mm, compared to its baseline value (see Figure 18b), with an increasing rate of 13 %, with the rainfall peaks notably higher in November and December (see Table 9). In future projections, the evapotranspiration rate is expected to be lower compared to the baseline, approximately 32% of the annual precipitation constitutes the evapotranspiration with 235.8 mm (see Figure 18a and Figure 18b). This is probably the result of the higher atmospheric CO_2 concentrations and land cover dynamics alterations. This finding strongly aligns with the result of Kruijt et al. (2008). A raised CO_2 level may cause stomata in plants to close resulting in a physiological response that lowers transpiration rates. Plants can ensure adequate CO_2 uptake at higher CO_2 levels by minimizing water loss by closing stomata (Cox et al., 2004). Furthermore, alterations in the land cover can impact both surface properties and surface energy balance (Mahmood et al., 2014). Changes in the land cover can lessen vegetation cover, leading to reduced transpiration rates and consequently lowering evapotranspiration rates (Li et al., 2007). The findings showed that the water yield increased compared to the baseline, having an annual average value of 495 mm. When evapotranspiration decreases, less water is lost to the atmosphere, leaving more water available in the soil and for runoff, which can lead to an increase in water yield (Liu et al., 2008). Under the high-emission scenario (RCP 8.5), there are intensified precipitation patterns and more frequent and intense rainfall events. On the other hand, Intensive irrigation practices simultaneously may increase soil moisture and infiltration rates, enhancing groundwater recharge. A rise in the projected surface runoff of up to 35 mm annually could also be a contributing factor to higher water yield levels.

Table 9. Average monthly values of water balance components within Marta River watershed under climate change impacts.

Month	Precipitation (mm)	Surface runoff (mm)	Lateral flow (mm)	Water yield (mm)	ET (mm)	PET (mm)
January	56.23	0.81	22.47	56.08	8.36	21.56
February	55.80	1.77	16.21	46.83	10.23	26.21
March	81.37	5.53	18.53	54.71	16.84	45.38
April	43.56	1.01	15.62	44.70	19.75	54.33
May	49.92	3.67	14.28	43.45	26.65	76.27
June	15.74	1.46	9.13	27.36	33.38	124.09
July	32.45	2.28	6.66	20.78	34.53	148.40
August	51.01	3.44	7.88	22.52	30.66	125.60
September	69.29	4.08	10.98	28.53	23.24	79.66
October	82.06	3.04	15.67	36.94	16.57	46.95
November	111.08	5.16	22.67	51.57	9.33	24.56
December	92.81	3.34	27.18	61.60	6.34	16.44



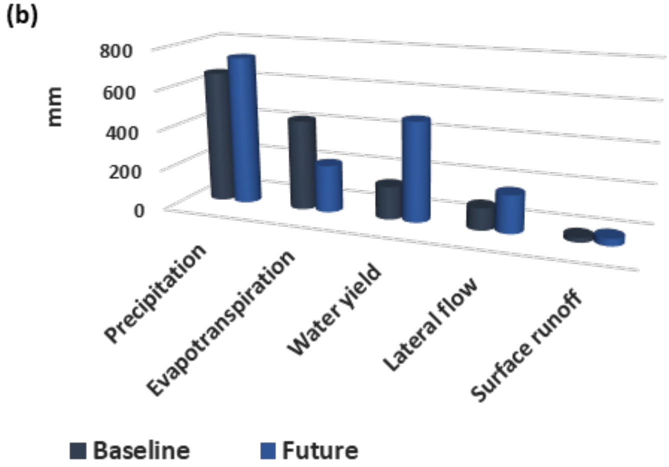


Figure 18. Projected changes in hydrological cycle components compared to the baseline scenario, a) percentage distribution b) annual average.

2.3.5 Evaluation of the impacts of intensive agriculture and climate change on soil erosion and nutrient yield

2.3.5.1 Soil loss under the baseline scenario

Figure 20 represents the spatial distribution of the average annual soil loss (expressed in [tons ha^{-1} y^{-1}]) at the HRU level under 'baseline' conditions over the period 2006-2020. Utilizing 15-year simulation outcomes from the calibrated SWAT model over the Marta River watershed area enabled the detection of zones categorized by extensive soil loss. These determinations were based on the calculation of average annual soil loss within sub-basins separately and the whole watershed, Figure 19 proposes an overview of the organization of the watershed into sub-basins.

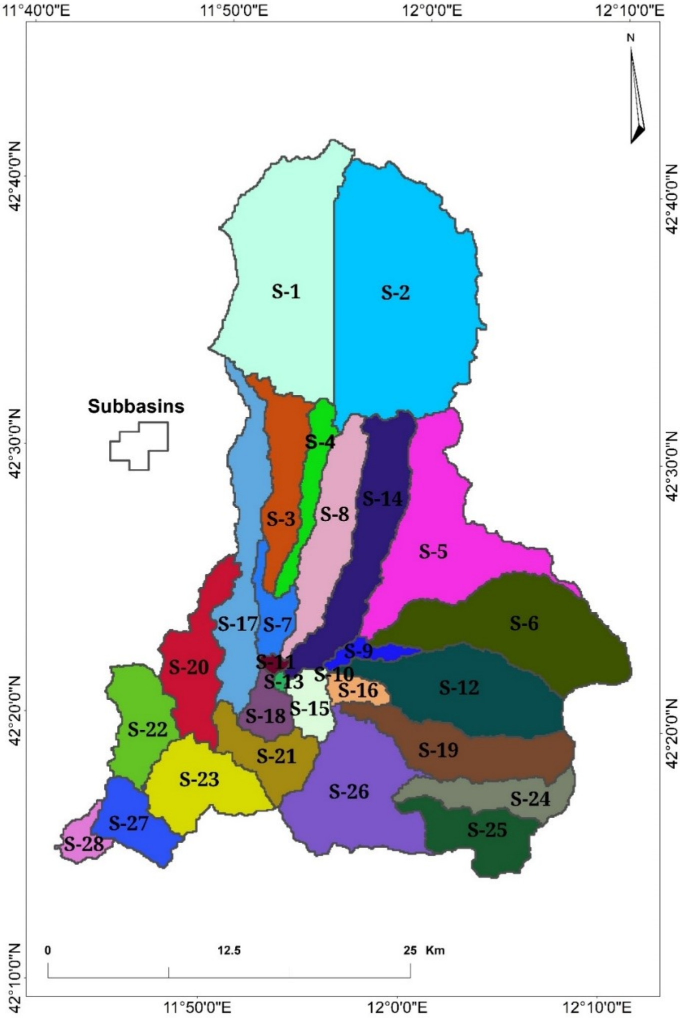


Figure 19. Sub-basins of Marta River watershed.

The rate of soil loss within different sub-basins showed a significant range, varying from 0.25 to 21.05 t ha^{-1} y^{-1} with an average soil loss of 9.24 t ha^{-1} y^{-1} at a watershed level. Various rates of soil loss generated by different land uses, 7.03 t ha^{-1} y^{-1} for winter wheat cereals from non-irrigated arable land, 81.9 t ha^{-1} y^{-1} for corn, 4.24 t ha^{-1} y^{-1} for short rotation forage, 0.09 t ha^{-1} y^{-1} for olive groves, 6.12 t ha^{-1} y^{-1} for fruit trees and berry plantations, 0.18 t ha^{-1} y^{-1} for horticulture, 1.04 t ha^{-1} y^{-1} for pastures, 0.83 t ha^{-1} y^{-1} for transitional woodland-shrubs, 1.02 t ha^{-1} y^{-1} for natural grasslands, 15.23 t ha^{-1} y^{-1} for complex cultivation pattern, 72.76 t ha^{-1} y^{-1} for land principally occupied by agriculture with areas of natural vegetation, and 0.04 t ha^{-1} y^{-1} for broad-leaved forest (see Figure 21). Generally, extensive soil losses are detected in land uses where agricultural practices like irrigation and fertilization are intensively applied including complex cultivation patterns, land principally occupied by agriculture with areas of natural vegetation, short rotation forage, winter wheat cereals, corn, fruit trees and berry plantations. Soil erosion is not just affected by geological and ecological factors but also by land-use type and agricultural activities (García-Ruiz, 2010). Regular irrigation is frequently needed for these land uses to nurture crop growth which results in heightened susceptibility to erosion during the irrigation period which usually occurs during May to August. Cornland occupies a very small area (one HRU) in a watershed with a notable soil loss, while short-rotation forage and pastures were lower than that rate, these results align with the findings of Panagopoulos et al. (2011). Furthermore, land uses like land principally occupied by agriculture with areas of natural vegetation and complex cultivation patterns presented higher soil loss rates. These raised soil loss can be associated with extreme cultivation practices together with the susceptibility characteristic of loamy soil (which covers the largest portion of the watershed) to erosion (O'geen et al., 2006). In areas with complex cultivation categorized by various cropping systems, improper tillage practices may result in extensive soil losses through persistent soil disorder (Jin et al., 2021). On the other hand, the rainfall intensity throughout the wet months, especially in winter followed by irrigation practices during the dry months (May to August) facilitated erosion processes within the study watershed. Additionally, incomplete vegetative cover between planting cycles and the field slope (length and steepness) affects the susceptibility of finer particles of soil to erosion and rising sediment mobilization during precipitation events (Ahmed et al., 2022). The study findings revealed that sub-basins 1, 6, 7, 9, 14, 23, 25 and 28 suffered from greater rates of soil erosion mainly as they have a steeper slope in some areas owing to increased runoff and soil losses. Land use also greatly affects the process of soil erosion, as well as the practices adopted (Meng et al., 2021). A summary of the soil loss rate generated by different hotspot areas and the related land uses is proposed in Table 10.

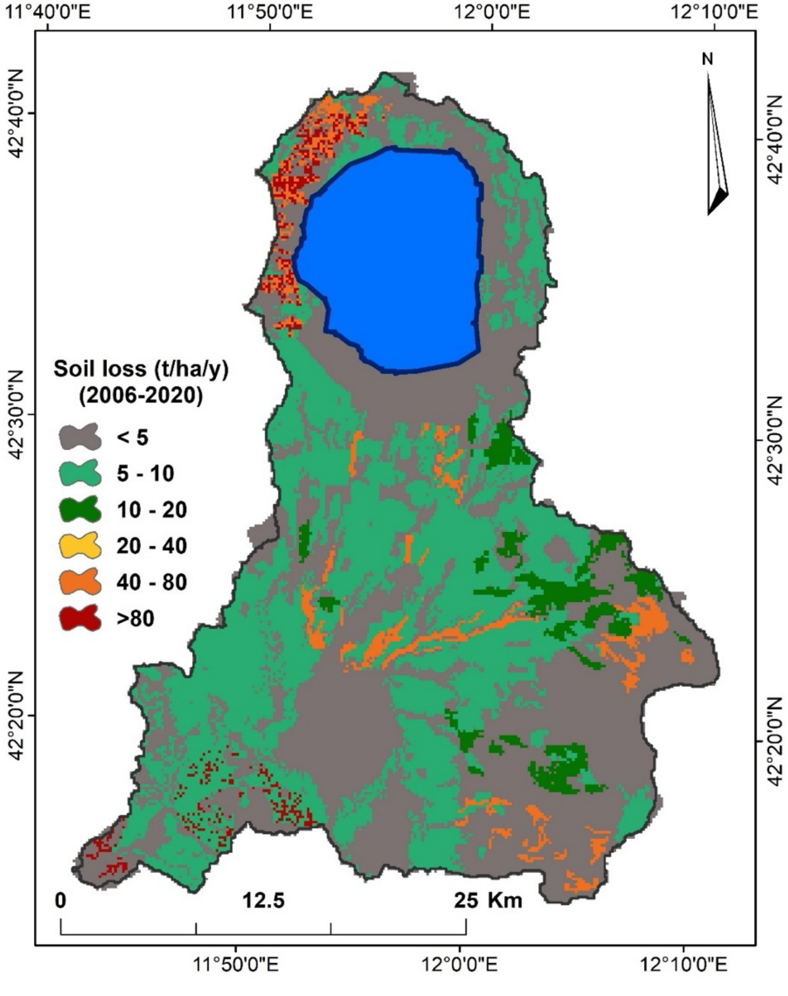


Figure 20. Spatial distribution of soil loss of Marta River watershed under the baseline scenario.

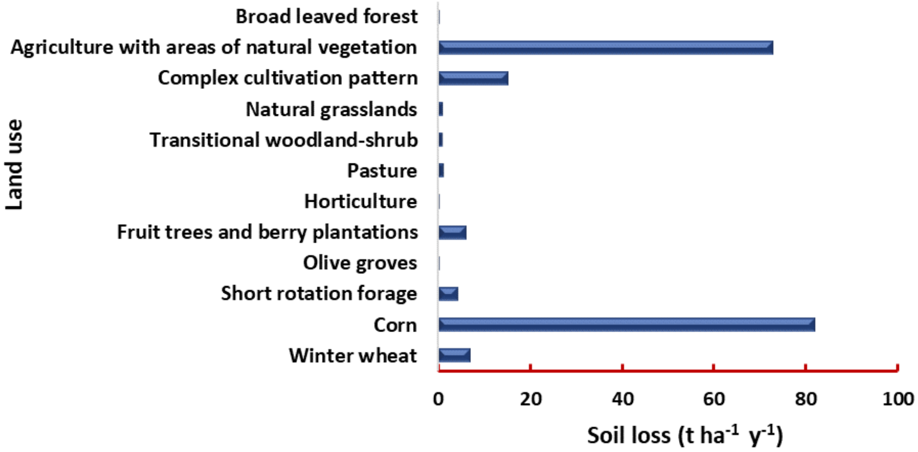


Figure 21. Comparative soil loss across different land use types at a watershed scale under the baseline scenario.

Table 10. Soil loss (t ha^{-1} y^{-1}) of hotspot areas across different spatial scales under the baseline scenario.

Spatial scale	Soil loss (t ha^{-1} y^{-1})
Watershed	9.24
Sub-basin	
Sub-basin-1	18.01
Sub-basin-6	18.22
Sub-basin-7	21.05
Sub-basin-9	14.86
Sub-basin-14	16.01
Sub-basin-23	18.55
Sub-basin-25	16.22
Sub-basin-28	20.68
Land use	
Winter wheat	6.89
Corn	81.9

Horticulture	0.18
Olive	0.09
Complex cultivation pattern	15.18
Land occupied by agriculture with areas of natural vegetation	73.95
Broad-leaved forest	0.04

2.3.5.2 Soil loss under the impacts of climate change

Figure 22a and Figure 22b present the spatial distribution of the average annual soil loss in [tons ha^{-1} y^{-1}] at the HRU level under the RCP 8.5 scenario to show the potential impacts of climate change over the period 2021-2050 comparing with the baseline scenario to highlight the changes. Regarding the adopted climate scenario (RCP 8.5), the simulated future soil loss outputs at both watershed and sub-basin levels have shown a rise in the rate of loss compared with those of the baseline conditions. The rate of soil loss within sub-basins was estimated to vary from 0.4 to 28.27 t ha^{-1} y^{-1} with an average value of 13.93 t ha^{-1} y^{-1} at the watershed level. A similar trend was detected across different land uses, with each land use losing a higher soil rate compared with the baseline scenario, full details can be found in Table 11. The rate of losing was 12.94 t ha^{-1} y^{-1} for winter wheat cereals, 84.33 t ha^{-1} y^{-1} for corn, 4.82 t ha^{-1} y^{-1} for short rotation forage, 0.19 t ha^{-1} y^{-1} for olive groves, 10.28 t ha^{-1} y^{-1} for fruit trees and berry plantations, 0.43 t ha^{-1} y^{-1} for horticulture, 2.14 t ha^{-1} y^{-1} for pasture, 0.95 t ha^{-1} y^{-1} for transitional woodland-shrubs, 1.5 t ha^{-1} y^{-1} for natural grasslands, 15.34 t ha^{-1} y^{-1} for complex cultivation pattern, 98.9 t ha^{-1} y^{-1} for land principally occupied by agriculture with areas of natural vegetation, and 0.07 t ha^{-1} y^{-1} for broad-leaved forest (see Figure 23). Regarding the upper and middle part of the watershed, as for the same baseline scenario, the highest values of soil loss were observed in (sub-basin-1 and sub-basin-7) with values of 25.97 t ha^{-1} y^{-1}, 28.27 t ha^{-1} y^{-1}. The rate of soil loss within these two sub-basins is expected to increase by around 44% and 34% in the near future compared to the baseline values. The highest loss of soil in the lower watershed was observed in (sub-basin-23) with 23.52 t ha^{-1} y^{-1}, this means a 26% increase in the rate of soil loss compared with the baseline value of 18.55 t ha^{-1} y^{-1}. Table 11 presents the soil loss generated by different hotspot areas and the related land uses under the impacts of climate change and determines the rate of change compared to the baseline scenario. A significant increase in soil loss and sediment transport within different areas is to some extent explained by the increase in precipitation amounts and intensity as well as the increase in runoff rates. The precipitation from 2021 to 2050 ranges from 442.7 to 1048.5 mm y^{-1} with an average of 741.32 mm y^{-1}. The predicted future precipitation amount is higher compared to the baseline scenario (2006-2020) with a range of 344 to 987 mm y^{-1} and an average of 656.39 mm y^{-1}. On the other hand, the application of irrigation practices adds disorders to the natural hydrological balance of soil and can result in raised saturation and consequent runoff.

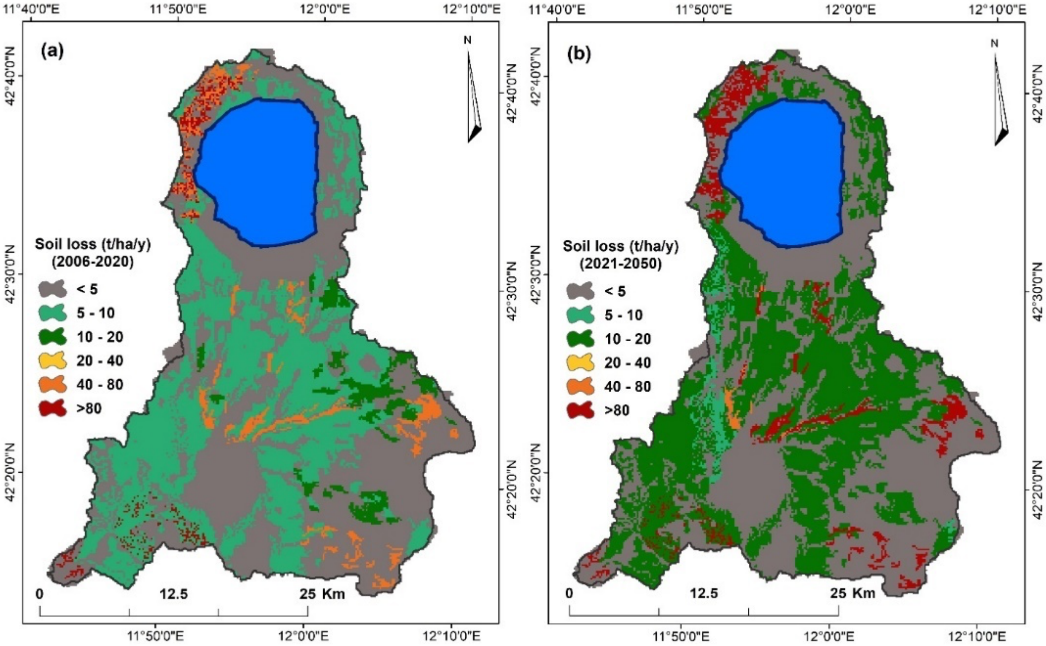


Figure 22. Spatial distribution of soil loss of Marta River watershed: (a) baseline scenario; (b) future scenario.

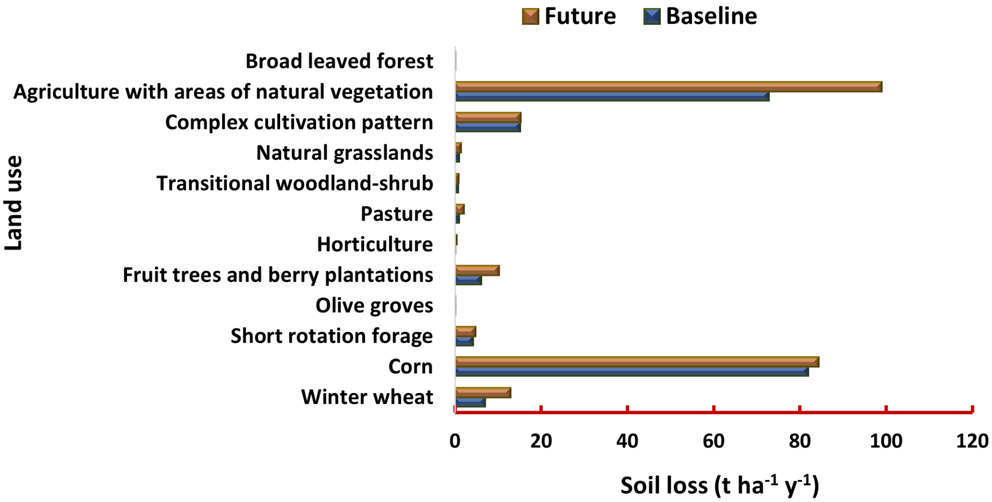


Figure 23. Comparative soil loss across different land use types at a watershed scale under baseline and future scenarios.

Table 11. Soil loss (t ha^{-1} y^{-1}) of baseline and future scenarios in hotspot areas across different spatial scales.

Soil loss (t ha^{-1} y^{-1})				
Spatial scale	**Baseline**	**Future**	**Change (%)**	**Contribution rate against total change (%)**
Watershed	9.24	13.93	50	—
Sub-basin				
Sub-basin-1	18.01	25.9	43	—
Sub-basin-6	18.22	24.07	32	—
Sub-basin-7	21.05	28.27	34	—
Sub-basin-9	14.86	23.06	55	—
Sub-basin-14	16.01	24.54	53	—
Sub-basin-23	18.55	23.52	26	—
Sub-basin-25	16.22	22.89	41	—
Sub-basin-28	20.68	21.47	3	—
Land use				
Winter wheat	6.89	12.61	82	26.99
Corn	81.9	84.33	3	0.009
Horticulture	0.18	0.34	88	0.04
Olive	0.09	0.12	25	0.03
Complex cultivation pattern	15.18	15.86	4	0.59
Land occupied by agriculture with areas of natural vegetation	73.95	100.44	35	72.25
Broad-leaved forest	0.04	0.07	75	0.07

2.3.5.3 Total nitrogen (TN) yield under the baseline scenario

Figure 24 presents the spatial distribution of annual average TN yield [expressed in (kg h^{-1} y^{-1})] at the HRU scale, providing detailed insights on environmental protection and public health. The 15-year average annual TN from the hydrological model outputs was evaluated at the HRU, sub-basin and watershed scales. The TN yield covered a wide range from 1.22 kg ha^{-1} y^{-1} to 18.91 kg ha^{-1} y^{-1}, with an average of 2.91 kg ha^{-1} y^{-1} at the watershed. Considering the variations in watershed characteristics across different areas, these results align with those detected in the Mediterranean area. For example, the study conducted by De Girolamo et al. (2019) in Canale d'Aiedda Basin (SE Italy), calculated the mean annual total nitrogen contribution per unit area of the riverine export at a watershed scale with a value of 2.8 kg ha^{-1} y^{-1}, while the finding of Carvalho-Santos et al. (2016) in the Mediterranean watershed (Portugal) lower than our output at a watershed scale, which is valued at 1.04 kg ha^{-1} y^{-1}. The small total nitrogen loss rates in the area are due to groundwater being the primary receptor of NO_3-N leached from fractured soils, according to Pulighe et al. (2019). The Figure 24 are highly informative in multiple aspects, particularly highlighting the southern watershed, certain areas exhibited high export rates, with TN up to 18 kg ha^{-1} y^{-1} (sub-basin-28), while in the northern and middle part of the watershed, the TN reached 1.6 kg ha^{-1} y^{-1} (sub-basin-1) and 5.4 kg ha^{-1} y^{-1} (sub-basin-18), respectively. The study results demonstrated that certain areas within the northern (sub-basin-1) and southern (sub-basin-28) parts of the watershed with higher TN levels also exhibited higher soil loss rates. This finding confirms the existing relationship between nutrients and sediment transportation, nutrients attach to soil particles and are transported along with sediments during runoff events. This finding points out the role of soil erosion in the mobilization of TN within agricultural areas and aligns with the finding of Pulighe et al. (2019).

At a watershed scale, various land use types contributed to TN yield, each with specific rates, for example, winter wheat contributed at a rate of 2.97 kg ha^{-1} y^{-1}, corn contributed at a rate of 23.7 kg ha^{-1} y^{-1}, short rotation forage with a rate of 2.85 kg ha^{-1} y^{-1}, olive with a rate of 1.54 kg ha^{-1} y^{-1}, horticulture with a rate of 17.3 kg ha^{-1} y^{-1}, pasture with 1.73 kg ha^{-1} y^{-1}, fruit trees and berry plantations with 1.91 kg ha^{-1} y^{-1}, transitional woodland-shrub with 5.45 kg ha^{-1} y^{-1}, natural grasslands with 5.6 kg ha^{-1} y^{-1}, complex cultivation pattern with 4.33 kg ha^{-1} y^{-1}, land principally occupied by agriculture with areas of natural vegetation with 5.2 kg ha^{-1} y^{-1}, and broad-leaved forest with 4.37 kg ha^{-1} y^{-1}, as demonstrated in Figure 25. All land uses contribute to TN load, with corn and horticulture crops being particularly significant. This is primarily due to the intensive fertilization required for these crops, leading to higher nitrogen inputs. The irrigation practices in this case can be a key factor in transporting nutrients, as water applied to the fields dissolves fertilizers and transports them throughout the area. These practices can also displace nutrient-rich topsoil into nearby water sources. Consequently, the combination of fertilizer and intensive irrigation application in agricultural areas can jointly result in greater nutrient losses (Brown et al., 2011; Domagalski et al., 2008). The study findings identified that sub-basins 13, 18, 23 and 28 experienced higher TN levels. Table 12 summarizes the TN yield rates generated by different hotspot areas and the related land uses.

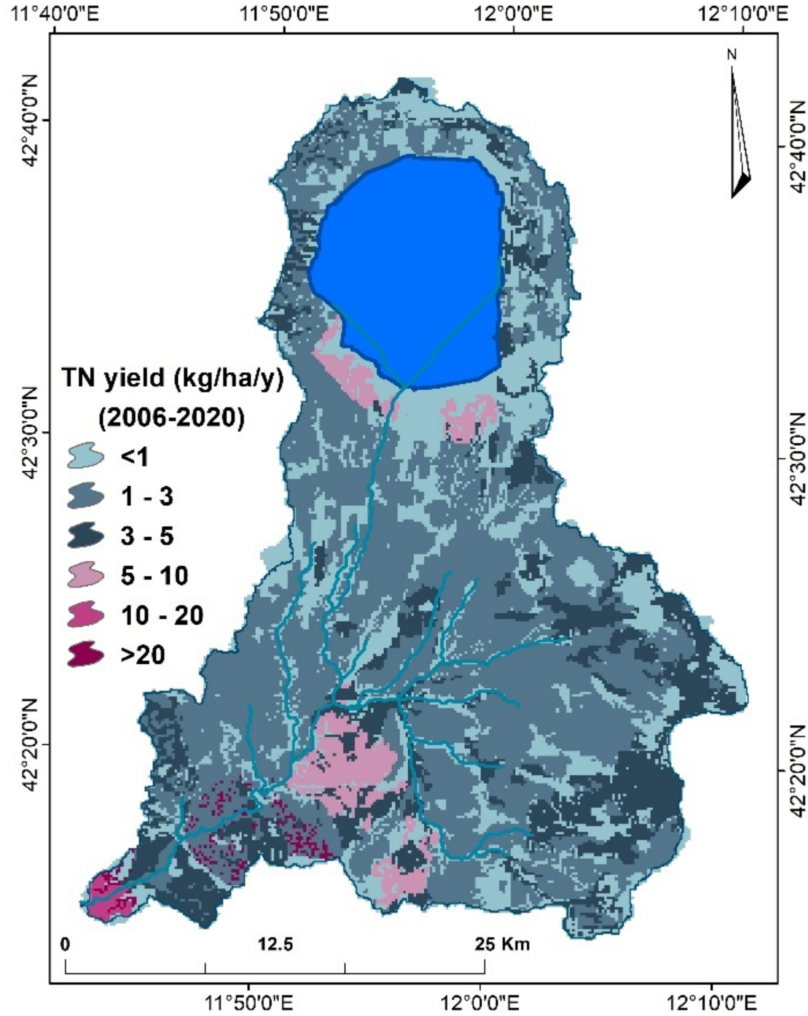


Figure 24. Spatial distribution of total nitrogen (TN) of Marta River watershed under the baseline scenario.

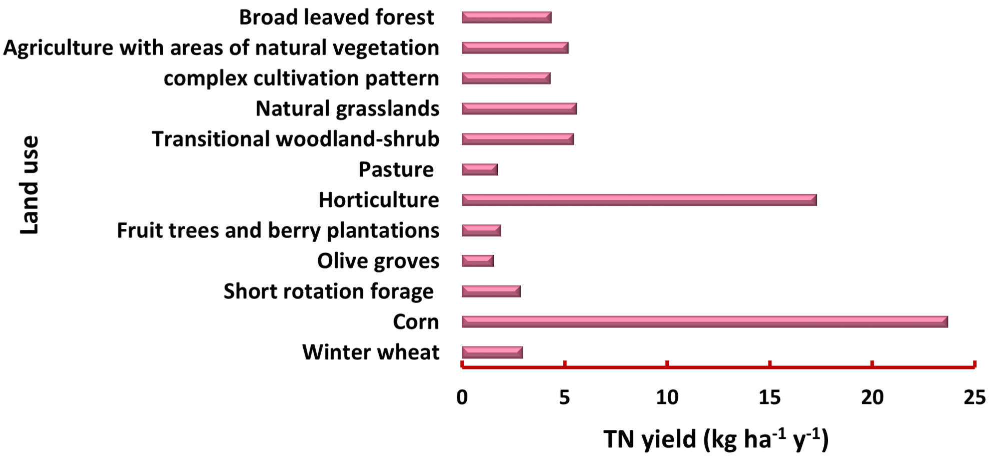


Figure 25. Comparative total nitrogen (TN) yields across different land use types at a watershed scale under the baseline scenario.

Table 12. Total nitrogen (TN) yield (kg ha^{-1} y^{-1}) of hotspot areas across different spatial scales under the baseline scenario.

Spatial scale	TN yield (kg ha^{-1} y^{-1})
Watershed	2.91
Sub-basin	
Sub-basin-13	5.3
Sub-basin-18	5.4
Sub-basin-23	7.94
Sub-basin-28	18.91
Land use	
Winter wheat	2.46
Corn	23.7
Horticulture	17.3
Land occupied by agriculture with areas of natural vegetation	20.46
Transitional woodland-shrub	5.45

Natural grasslands	5.6
Broad-leaved forest	4.55

2.3.5.4 Total nitrogen (TN) yield under the impacts of climate change

Regarding the implemented climate scenario, the simulated future TN yield outputs at the watershed level over the period 2021-2050 have shown a rise in the annual average TN yield compared with the baseline scenario (see Figure 26), with the value being 3.36 kg ha^{-1} y^{-1}. The TN yield across different sub-basins ranged from 1.3 kg ha^{-1} y^{-1} to 8.62 kg ha^{-1} y^{-1}. Generally, the TN yield has shown a rise in most of the sub-basins, and some additional sub-basins have become TN hotspot areas, while some sub-basins have shown a decrease in the TN, as detailed further in Table 13. At the upper part of the watershed, the higher yield was observed at (sub-basin-1) with 1.71 kg ha^{-1} y^{-1}, while at the middle and lower watershed parts were detected at (sub-basin-3) and (sub-basin-28) with 5.6 kg ha^{-1} y^{-1} and 8.62 kg ha^{-1} y^{-1}. Concerning the TN yield within various land uses at the watershed level, except for the winter wheat, which covers the largest portion of the watershed, showed an increase in the TN, while all other land use types demonstrated a decrease in the TN. The TN yield was 5.15 kg ha^{-1} y^{-1} for winter wheat, 17.24 kg ha^{-1} y^{-1} for corn, 0.48 kg ha^{-1} y^{-1} for short rotation forage, 0.9 kg ha^{-1} y^{-1} for olive groves, 1.11 kg ha^{-1} y^{-1} for fruit trees and berry plantations, 5.74 kg ha^{-1} y^{-1} for horticulture, 1.08 kg ha^{-1} y^{-1} for pasture, 1.44 kg ha^{-1} y^{-1} for transitional woodland-shrubs, 1.4 kg ha^{-1} y^{-1} for natural grasslands, 4.26 kg ha^{-1} y^{-1} for complex cultivation pattern, 2.95 kg ha^{-1} y^{-1} for land principally occupied by agriculture with areas of natural vegetation, and 1.27 kg ha^{-1} y^{-1} for broad-leaved forest (see Figure 27). The rise in the TN in certain areas of the watershed may be explained by the increase in precipitation amounts and intensity in the near future, which intensifies runoff rates, leading to the yield and transportation of nutrients throughout the area (Kalkhoff et al., 2016). Additionally, these raised TN yields can be also associated with extreme agricultural practices together with the susceptibility characteristic of loamy soil (which covers the largest portion of the watershed) to erosion and transporting larger amounts of nutrients (O'geen et al., 2006).

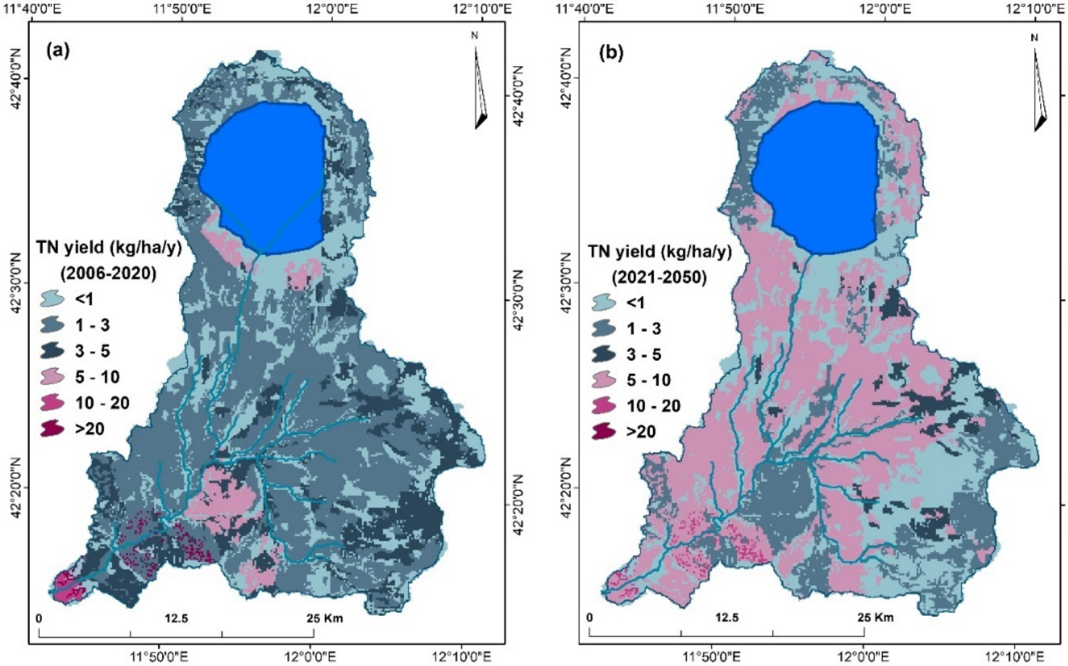


Figure 26. Spatial distribution of total nitrogen (TN) of Marta River watershed a) baseline, b) future scenarios.

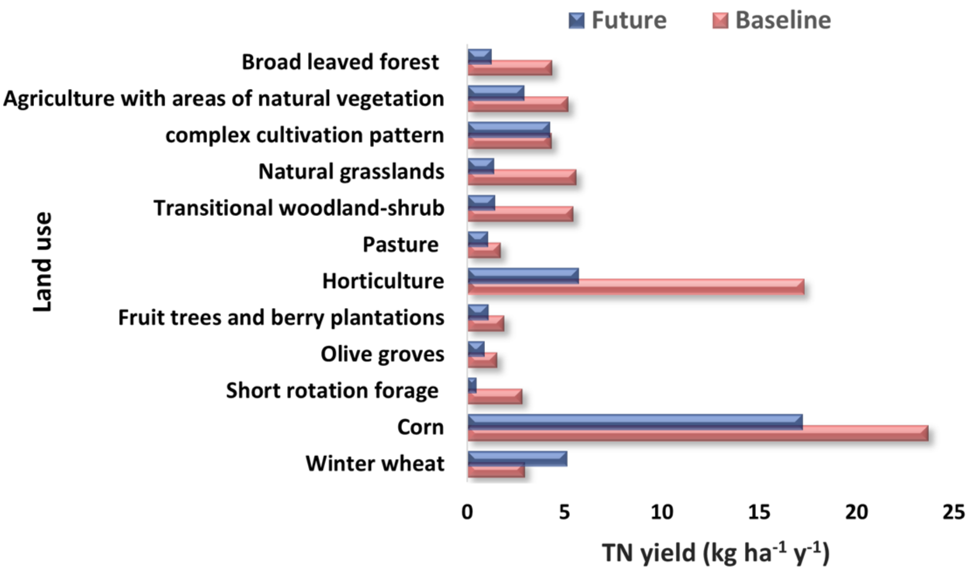


Figure 27. Comparative TN yield across different land use types at a watershed scale under baseline and future scenarios.

Table 13. TN yield (Kg ha^{-1} y^{-1}) of baseline and future scenarios in hotspot areas across different spatial scales.

Spatial scale	Baseline	Future	Change %	Contribution rate against total change (%)
	TN yield (Kg ha^{-1} y^{-1})			
Watershed	2.91	3.36	+15	–
Sub-basin				
Sub-basin-3	2.95	5.6	+89	–
Sub-basin-5	2.82	5.03	+78	–
Sub-basin-8	2.76	4.95	+79	–
Sub-basin-13	5.3	1.37	-74	–
Sub-basin-17	2.8	5.13	+83	–
Sub-basin-18	5.4	2.02	-62	–

Sub-basin-20	2.74	5.1	+86	—
Sub-basin-23	7.94	5.14	-35	—
Sub-basin-27	3.22	5.73	+78	—
Sub-basin-28	18.91	8.62	-54	—
Land use				
Winter wheat	2.58	5.1	+97	72.7
Corn	23.7	17.24	-27	1.5
Horticulture	17.3	5.74	-66	8.2
Short rotation forage	2.85	0.48	-83	1.3
Complex cultivation pattern	4.33	4.67	+8	0.6
Land occupied by agriculture with areas of natural vegetation	20.46	10.61	-48	6.9
Transitional woodland-shrub	5.45	1.44	-73	2.2
Natural grassland	5.6	1.41	-75	1.5
Broad-leaved forest	4.55	1.32	-71	4.7

(+) marks an increase in the rate; (-) marks a decrease in the rate.

2.3.5.5 Total phosphorus (TP) yield under the baseline scenario

Figure 28 shows the spatial distribution of annual average TP yield [expressed in (kg h^{-1} y^{-1})] at the HRU scale. The 15-year annual average TP from the hydrological model outputs was calculated at the HRU, sub-basin and watershed scales. The TP yield ranges from 0.31 kg h^{-1} y^{-1} to 5.22 kg h^{-1} y^{-1}. At the watershed level, the TP yield estimation obtained was 2.84 kg h^{-1} y^{-1}, which is higher than the results reported by Carvalho-Santos et al. (2016), De Girolamo et al. (2019), and Pulighe et al. (2019) from studies conducted in Mediterranean areas. Certain areas in the southern part of the watershed exhibited high TP, with values reaching up to 3.81 kg h^{-1} y^{-1} (sub-basin-23). In the northern and middle areas of the watershed, higher TP levels were observed in sub-basin-1 and sub-basin-7, with values of 2.16 kg h^{-1} y^{-1} and 5.22 kg h^{-1} y^{-1}, respectively. The study findings demonstrated that areas with high soil erosion rates also tend to have higher total phosphorus (TP) losses, this is because phosphorus in the soil is often bound to eroded particles (Thomas Sims & Pierzynski, 2005). When rainfall or irrigation occurs, these particles are dislodged and carried away by surface runoff, leading to increased phosphorus movement into nearby water bodies. As a result, areas with significant soil erosion contribute more to phosphorus loading into the rivers (Alewell et al., 2020). The combination of poor soil structure, land use type, and improper land management practices in these regions exacerbates both soil loss and phosphorus transportation, ultimately increasing the risk of water pollution and eutrophication (Issaka & Ashraf, 2017). At a watershed scale, each land use contributes to a distinct level of TP (see Figure 29), winter wheat contributed at a rate of 4.02 kg ha^{-1} y^{-1}, corn contributed at a rate of 2.72 kg ha^{-1} y^{-1}, short rotation forage with a rate of 2.51 kg ha^{-1} y^{-1}, olive with a rate of 0.17 kg ha^{-1} y^{-1}, horticulture with a rate of 0.18 kg ha^{-1} y^{-1}, Pasture with 1.25 kg ha^{-1} y^{-1}, fruit trees and berry plantations with 4.73 kg ha^{-1} y^{-1}, transitional woodland-shrub with 0.89 kg ha^{-1} y^{-1}, natural grasslands with 1.17 kg ha^{-1} y^{-1}, complex cultivation pattern with 5.84 kg ha^{-1} y^{-1}, land principally occupied by agriculture with areas of natural vegetation with 7.56 kg ha^{-1} y^{-1}, and broad-leaved forest with 0.1 kg ha^{-1} y^{-1}. The study findings identified that sub-basins 3, 5, 6, 7, 8, 9, 14, 16, 17, 20, 23, and 26 experienced higher TP levels. Table 14 proposes a summary of the TP yield rates generated by different hotspot areas and the related land uses.

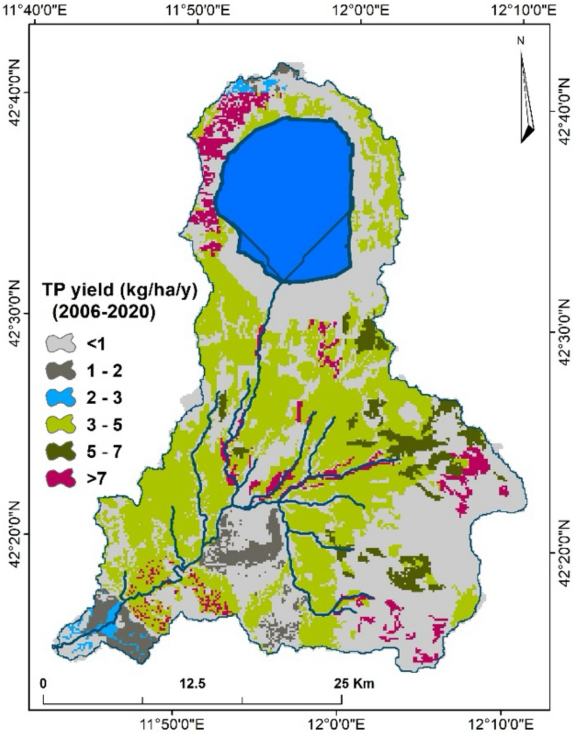


Figure 28. Spatial distribution of total phosphorus (TP) of Marta River watershed under the baseline scenario.

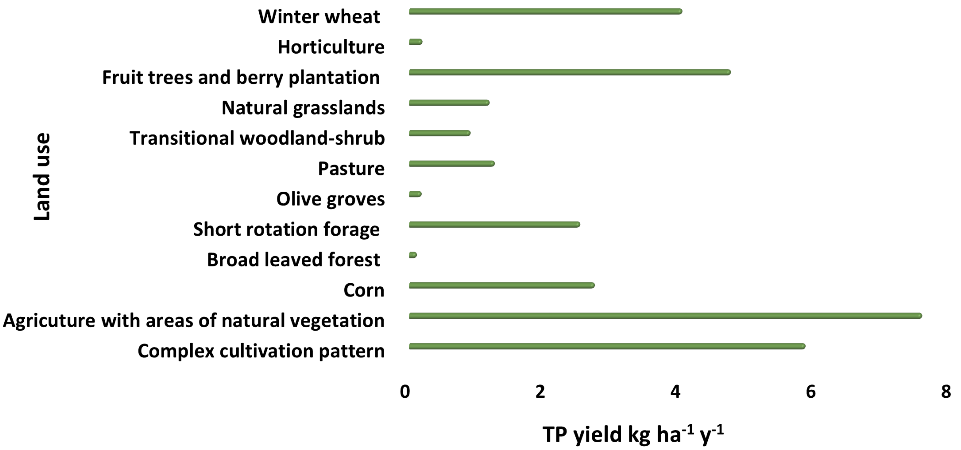


Figure 29. Comparative total phosphorus (TP) yields across different land use types at a watershed scale under the baseline scenario.

Table 14. Total phosphorus (TP) yield (kg ha^{-1} y^{-1}) of hotspot areas across different spatial scales under the baseline scenario.

Spatial scale	TP yield (kg ha^{-1} y^{-1})
Watershed	2.84
Sub-basin	
Sub-basin-3	3.55
Sub-basin-5	4.71
Sub-basin-6	3.93
Sub-basin-7	5.22
Sub-basin-8	4.19
Sub-basin-9	4.18
Sub-basin-14	3.62
Sub-basin-16	3.47
Sub-basin-17	4.13
Sub-basin-20	4.14
Sub-basin-23	3.81
Sub-basin-26	3.06
Land use	
Winter wheat	4.12
Olive	0.16
Complex cultivation pattern	5.84
Land occupied by agriculture with areas of natural vegetation	7.66
Transitional woodland-shrub	0.92
Broad-leaved forest	0.1

2.3.5.6 Total phosphorus (TP) yield under the impacts of climate change

The average future total phosphorus (TP) yield in the watershed under the implemented climatic scenario revealed a decrease compared to baseline conditions, with a value of 2.43 kg ha^{-1} y^{-1} as opposed to 2.84 kg ha^{-1} y^{-1} under baseline conditions, as demonstrated in Figure 30. The TP rates from different sub-basins ranged from 0.58 kg ha^{-1} y^{-1} to 4.03 kg ha^{-1} y^{-1}. The future TP yield in most of the sub-basins decreased, except for sub-basins 10, 13, 15, 18, and 21, which showed an increase compared to the baseline conditions. Regarding different land uses at a watershed level, some showed a decrease in the TP yield rate, while others showed an increase compared to the baseline conditions, further details are shown in Figure 31. The TP yield was 3.62 kg ha^{-1} y^{-1} for winter wheat, 1.54 kg ha^{-1} y^{-1} for corn, 0.69 kg ha^{-1} y^{-1} for short rotation forage, 0.33 kg ha^{-1} y^{-1} for olive groves, 5.77 kg ha^{-1} y^{-1} for fruit trees and berry plantations, 0.35 kg ha^{-1} y^{-1} for horticulture, 1.93 kg ha^{-1} y^{-1} for pasture, 1.59 kg ha^{-1} y^{-1} for transitional woodland-shrubs, 1.25 kg ha^{-1} y^{-1} for natural grasslands, 3.8 kg ha^{-1} y^{-1} for complex cultivation pattern, 5.29 kg ha^{-1} y^{-1} for land principally occupied by agriculture with areas of natural vegetation, and 0.18 kg ha^{-1} y^{-1} for broad-leaved forest. Table 15 shows the TP yield of baseline and future scenarios in hotspot areas across different spatial scales.

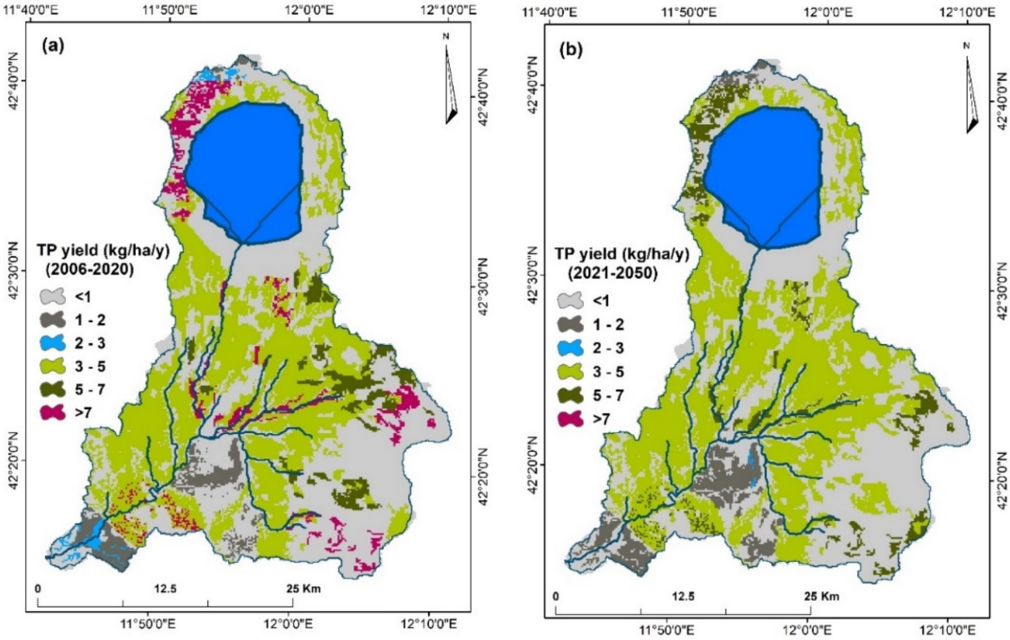


Figure 30. Spatial distribution of total phosphorus (TP) of Marta River watershed a) baseline, b) future scenarios.

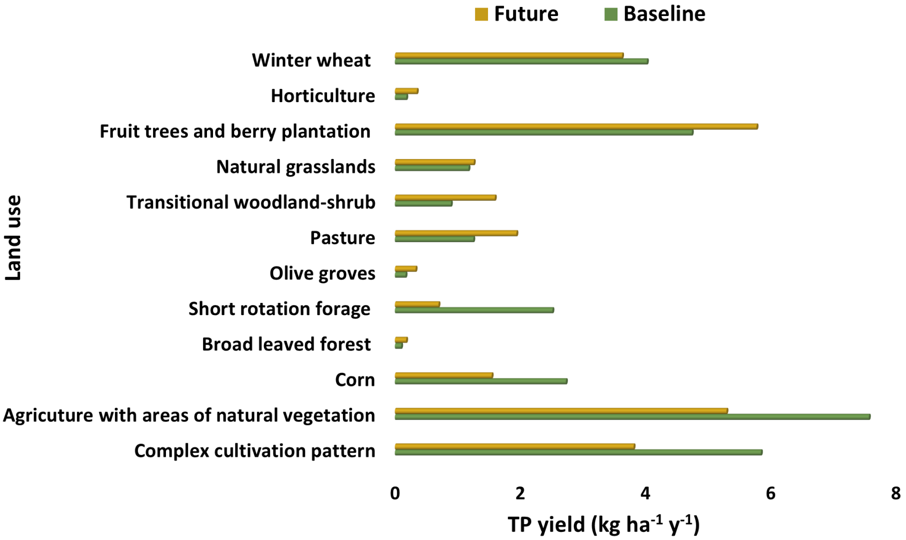


Figure 31. Comparative TP yield across different land use types at a watershed scale under baseline and future scenarios.

Table 15. TP yield (kg ha^{-1} y^{-1}) of baseline and future scenarios in hotspot areas across different spatial scales.

TP yield (kg ha^{-1} y^{-1})				
Spatial scale	**Baseline**	**Future**	**Change %**	**Contribution rate against total change (%)**
Watershed	2.84	2.43	-14	—
Sub-basin				
Sub-basin-3	3.55	3.23	-9	—
Sub-basin-5	4.71	3.96	-16	—
Sub-basin-6	3.93	2.97	-24	—
Sub-basin-7	5.22	4.03	-22	—
Sub-basin-8	4.19	3.80	-9	—
Sub-basin-9	4.18	3.56	-14	—
Sub-basin-14	3.62	3.04	-16	—
Sub-basin-16	3.47	3.19	-8	—
Sub-basin-17	4.13	3.76	-8	—
Sub-basin-20	4.14	3.77	-9	—
Sub-basin-23	3.81	3.21	-15	—
Sub-basin-26	3.06	2.89	-5	—
Land use				
Winter wheat	4.12	3.73	-9	46.4
Olive groves	0.16	0.3	+87	0.5
Complex cultivation pattern	5.84	3.8	-34	24.4
Land occupied by agriculture with areas of natural vegetation	7.66	5.38	-29	24.9
Transitional woodland-shrub	0.92	1.64	+78	2.2
Broad-leaved forest	0.1	0.18	+80	1.3

2.4 Key Findings and Implications

The agro-hydrological model was developed, calibrated and validated using detailed data from the Tarquinia gauge station in the northwestern section of the Lazio region, Italy. The model parameters were determined, and the objective functions were calculated for the monthly discharge, NO_3^-, and TN using the sequential uncertainty fitting algorithm (SUFI-2) in the SWAT Calibration Uncertainties Program (SWAT-CUP). The study findings demonstrated that the model accurately reflected the spatial and temporal variability of flow regimes, and nutrient fluxes in the river system. Subsequently, the SWAT model has been forced by the three most important surface variables of EURO-CORDEX climate model combinations (daily precipitation, daily minimum surface temperature, and daily maximum surface temperature), which are highly influencing the hydrological balance of the basin, before forcing the SWAT model with the climate models, all available combinations of the EURO-CORDEX have been evaluated over the watershed using the Aras diagram, the best model combination has been chosen for each variable, and bias corrections have been implemented utilizing the Linear Scaling (LS) method. Eventually, the bias corrected variables forced the SWAT model. The 30-year hydrological simulation outputs from the most reliable climate model indicated a significant increase in annual precipitation relative to the baseline scenario. The water balance simulations from the baseline scenario confirmed that evapotranspiration was the main outflow component, while surface runoff was particularly significant during the winter months. During summer, especially June and July exhibited a relatively high runoff, as May to August was the period during which the irrigation practices were implemented across different areas of the watershed. However, in the future, the evapotranspiration rate is expected to decrease due to higher CO_2 levels and land cover changes, while increased precipitation and intense rainfall events are projected to raise surface runoff. The research results revealed that the soil loss rates vary considerably within different areas, with some areas observing high soil loss rates that are significantly influenced by variations in slope, vegetative cover and soil characteristics. On the other hand, irrigation practices across different watershed areas contributed to significant sediment movement, as the findings indicated extensive soil loss in areas where agricultural practices, such as irrigation and fertilization were intensively applied. Raised future precipitation (in terms of frequency and intensity) had a substantial impact on increasing soil loss rates. The future simulations revealed an increase in soil loss across the watershed and various land uses. Regarding nutrient yield under baseline conditions, the TN yield has been estimated in different areas of the watershed, with some areas indicated as TN hotspots. All land uses contributed to TN yield, with corn and horticulture crops being particularly significant. In the future, the TN yield has shown an increase in most of the sub-basins, and some additional sub-basins have become TN hotspot areas, while some sub-basins have shown a decrease in TN levels. Concerning the TN yield within various land uses at the watershed level, except for winter wheat, which covers the largest portion of the watershed showed an increase in TN, while all other land use types demonstrated a decrease in TN. Regarding the TP yield under the baseline scenario, certain areas in the upper, middle and down parts of the watershed exhibited high TP yield. The simulated future TP yield at the watershed and sub-basin levels revealed a decrease compared to baseline conditions. Regarding different land uses at a watershed level, some showed a decrease in TP, while others showed an increase compared to the baseline conditions. The results of this study underscore the critical need for targeted agricultural practices in areas with high soil erosion and nutrient yield. By quantitatively assessing the impact of human activities on the hydrological responses of the river basin, we highlight the urgent necessity for sustainable agronomic strategies. These findings provide a robust framework for balancing agricultural productivity and environmental preservation. Future research should build upon this framework to refine and optimize approaches that achieve long-term sustainability and resilience in agroecosystems.

CHAPTER 3

CHAPTER 3 SYNERGIZING CONSERVATION PRACTICES AND POLICY: A MODEL FOR NEXUS IMPLEMENTATION THROUGH BEST MANAGEMENT PRACTICES FOR ENHANCING SOIL AND WATER QUALITY IN AN ITALIAN AGRICULTURAL BASIN.

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Summary

Soil erosion and nutrient pollution have emerged as critical global environmental challenges in recent years. Implementing soil and water conservation measures has proven to effectively mitigate soil loss and reduce nutrient contamination. For this purpose, this study aims to implement different Best Management Practices (BMPs) and identify effective BMPs for controlling both on- and off-site impacts resulting from soil erosion and nutrient pollution in the plain, Italy, a region vulnerable to these issues due to its Mediterranean climate and agricultural practices. Using the Soil and Water Assessment Tool (SWAT), the study quantified soil loss at a watershed, sub-basin and land use scales as well as sediment and nutrient loads at a river scale, analyzing the impact of individual BMPs, such as terracing, contour farming, no-tillage, and residue management as well as their combinations. Results showed that the combined implementation of BMPs was the most effective, reducing sediment load in the Marta River by up to 33.9%, with an annual value of 1,736.7 tons in the most affected sub-basins. Among the implemented individual BMPs, terracing significantly reduced soil loss, achieving a reduction of up to 77% in particular sub-basins and land uses and 37% across the watershed. It reduced sediment loading into the river, achieving a 22% reduction in the most severely impacted area with high sedimentation levels. In terms of nutrient reduction, combined BMPs reduced total nitrogen (TN) by up to 27% and total phosphorus (TP) by up to 27.5%, while terracing alone reduced TN and TP by up to 26.2% and 22.7% in critically impacted areas, respectively. Residue management, no-tillage, and contour farming contributed to the reduction of pollutants, with varying effectiveness depending on the pollutant type, site conditions, and specific mechanism of action. The findings underscore

the importance of integrated BMP strategies for sustainable soil and water management in agricultural watersheds.

3.1 Context and Background

Soil erosion and sediment transport are critical issues for local, national, and European policymakers (Gobin et al., 2004; Panagos & Katsoyiannis, 2019; van Leeuwen et al., 2019). This has led to an increasing demand for reliable models to delineate target zones where conservation measures will be most effective (Borrelli et al., 2021; Haregeweyn et al., 2017). Studies focused on soil and water conservation measures have been carried out worldwide (Afroz et al., 2021; Berihun et al., 2020; Briak et al., 2019; Didoné et al., 2017; Gashaw et al., 2021; Klik & Eitzinger, 2010; Mullan & Favis-Mortlock, 2011; Ricci et al., 2020; Silva et al., 2024; Strauch et al., 2013). Understanding the effects of soil and water conservation practices is crucial for effective land use management (Silva et al., 2024). Conservation practices are generally categorized into soil management, vegetative measures, and structural practices (Bertoni & Lombardi neto, 2008). Soil management enhances infiltration by improving soil structure, vegetative measures protect the surface by reducing raindrop impact, and structural techniques reduce runoff velocity and volume by altering topography (Bombino et al., 2019; Martínez-Mena et al., 2020; Silva et al., 2024). Studies on management practices have largely focused on on-site impacts. Uniyal et al. (2020) assessed the effectiveness of vegetative and structural measures in an Indian watershed using the SWAT model, finding structural BMPs more effective at reducing sediment yields and runoff. Conversely, Laufer et al. (2016) demonstrated that vegetative measures in Southern Germany significantly mitigated soil erosion, achieving a 98% reduction relative to intensive tillage practices. Himanshu et al. (2019) reported that conservation methods including conservation tillage, zero-tillage, and field cultivation, led to a 9% sediment yield decrease in an Indian watershed compared to conventional tillage via the SWAT simulation results. In Brazil, Rocha et al. (2012) analyzed various conservation techniques like resting periods for pastures, contour and no-till farming, crop rotation and intercropping, etc., showing enhancements in water infiltration and reductions in sediment and nutrient losses. Didoné et al. (2017) indicated that combining practices, including crop rotation, contour farming, terracing, and the establishment of a riparian forest, effectively diminished erosion in a Brazilian agricultural watershed. While no-tillage alone was insufficient, its combination with structural approaches, like terraces, proved valuable (Londero et al., 2018).

Conservation efforts also enhance hydrological balance by reducing runoff and boosting water percolation (Arabi et al., 2008; Boufala et al., 2022; Freitas et al., 2021; Silva et al., 2024). Off-site impacts are lesser-studied; however, Weaver et al. (2005) explored ecological disruptions from sediment and nutrients, advocating for management strategies such as minimizing tillage and optimizing fertilizer use to reduce nutrient loss in Western Australian catchments. Verstraeten et al. (2001) addressed off-site erosion in Belgium with measures like leaving erodible land fallow and using ponds to trap sediment, reducing erosion risk by up to 25% and sediment delivery to rivers by 50%. In South Korea, Ali & Reineking (2016) found that managing field margins, especially on steep slopes, significantly curbed sediment retention and that dense vegetation was essential for mitigating off-site erosion.

To address the on-site as well as off-site impacts of soil erosion and nutrient pollution, implementing conservation measures, either individually or combined, plays a crucial role in enhancing soil properties, strengthening topography, reducing surface runoff, and ultimately lowering sediment and nutrient loads in water bodies. It is essential to understand these conservation practices' effects within representative agricultural watersheds, as this knowledge aids farmers and policymakers in selecting effective BMPs to tackle challenges related to erosion and pollution. This study specifically fills a critical gap in assessing the off-site impacts of conservation measures by evaluating various strategies and their combined effects in the plain, Italy. By using the SWAT model, this research advances the current state of knowledge by systematically assessing sediment and nutrient loading in rivers, thereby providing comprehensive insights into the efficacy of individual and combined conservation practices. This approach not only advances our understanding of effective soil erosion and nutrient management strategies but also sets a benchmark for assessing BMPs in similar watersheds globally.

3.2 Best Management Practices (BMPs) Modeling

Various land management strategies using the SWAT model exist (Gashaw et al., 2021; Hussain et al., 2019; Mosbahi & Benabdallah, 2020; Nabi et al., 2020; Ricci et al., 2020; Silva et al., 2024; Wang et al., 2021). This study, after calibrating and validating monthly flow discharge, NO_3^-, and TN, simulated multiple BMPs individually and combined to evaluate their impact on soil erosion and nutrient pollution. Initially, sub-basins with high soil loss and nutrient yield were identified under the baseline scenario, fully described and analyzed in detail in Chapter Two, followed by applying BMPs. The measures were implemented in ideal scenarios for each Hydrologic Response Unit (HRU) within the most critical sub-basins (22, 23, 27, and 28) to assess their effectiveness on river sediment and nutrient loading (see Figure 47), and they were also implemented in additional sub-basins (1, 6, 7, 9, 14, 25) to assess their impact on soil loss at the watershed, sub-basin, HRU and land use levels (see Figure 19). BMP selection was based on principles like protecting the soil surface, enhancing infiltration, improving soil structure, increasing surface roughness, and nutrient retention (Bertoni & Lombardi neto, 2008). These practices are vital for managing erosion and reducing nutrient transport, which degrades water quality. This study designed and tested four individual BMPs: terracing, contour farming, residue management, and no-tillage. According to (Bertoni & Lombardi neto, 2008), terracing and contour farming belong to the category of structural practices, while residue management and no-tillage belong to the soil management category. Each management practice uses specific mechanisms to control soil erosion and nutrient pollution. Terraces can lower the volume of surface runoff by holding water in small depressions and reduce the peak flow rate by shortening the hillside length. Additionally, terraces lower the erosive power of runoff and allow sediments to settle. USLE support practice factor (TERR_P), SCS curve number (TERR_CN) and hillside slope length (TERR_SL) were adjusted to represent the terraces operation. Contour farming reduces overland flow by holding water in small depressions, lowers the erosive power of runoff, and promotes water absorption into the soil. To simulate the impacts of contour farming, SCS curve number (CONT_CN) and USLE practice factor (CONT_P) were modified. Residue management mitigates the peak and surface runoff by increasing surface roughness and expanding land cover, allowing more time for water to infiltrate the soil. It also lowers the rate and volume of overland flow, as well as reduces raindrop impacts on soil. Manning's roughness coefficient for overland flow (OV_N) and SCS curve number (CN) were adjusted to represent the operation. The undisturbed soil during no-tillage practices reduces surface runoff, improves water infiltration, and preserves soil structure. No-tillage operation is typically activated by removing the existing tillage operation in targeted HRUs and adjusting each of Manning's roughness coefficient for overland flow (OV_N), SCS curve number (CN) and biological mixing efficiency (BIOMIX). Previous research has shown that combining conservation practices is generally more effective in controlling erosion and nutrient runoff than implementing an individual practice (Puertes et al., 2021; Ricci et al., 2022). For this reason, these four BMPs were also tested together to assess their combined effectiveness in reducing erosion and nutrient runoff. A detailed overview of the BMPs utilized in this study, and the SWAT parameter adjustments can be found in Table 16. Finally, different BMP scenarios were simulated and compared to the baseline scenario, focusing on the average annual soil loss at the watershed, subbasin, HRU and land use levels, as well as the average annual sediment and nutrient load at the reach (river) level.

Table 16. Marta River watershed management: Best Management Practices (BMPs) and changes in SWAT parameters.

Type of BMP	BMP's	SWAT input parameters	Parameter value	Selected areas	
				Sub-basins	**Land uses**
Structural practices	**Terracing**	TERR_P (.ops)	0.1 for slope 1-8% 0.14 for slope 8-15% 0.18 for slope >15%	1, 6, 7, 9, 14, 22, 23, 25, 27 and 28	winter wheat cereals corn short rotation forage horticulture olive complex cultivation pattern land principally occupied by agriculture with areas of natural vegetations broad-leaved forest
		TERR_CN (.ops)	-6 Curve number (CN) value decreases by 6 units from its calibrated value		
		TERR_SL (.ops)	$(0.13 \times SLOPE + 0.6) \times \frac{100}{SLOPE}$		
	Contour farming	CONT_CN (.ops)	-3 Curve number (CN) value decreases by 3 units from its calibrated value		
		CONT_P (.ops)	0.5 for slope 1-8% 0.7 for slope 8-16% 0.8 for slope 16-20% 0.9 for slope >20%		
Soil management	**Residue management**	CN2 (.mgt)	-2 Curve number (CN) value decreases by 2 units from its calibrated value		
		OV_N (.hru)	0.2 (0.5-1 t ha^{-1} of residue)		
	No-tillage	Removing tillage operation in selected HRUs			
		CN2 (.mgt)	-5 Curve number (CN) value decreases by 5 units from its calibrated value		

	OV_N (.hru)	0.31
	BIOMIX (.mgt)	0.1
Combined BMPs	Applying all management practices in combination	

3.3 Results and Discussion

3.3.1 Assessment of the watershed soil loss and river sediment load

The simulation outputs of different BMPs after applying on sub-basins 22, 23, 27, and 28, showed a reduction in the average annual sediment load inside Marta River, further detail demonstrated in Figure 32. Each BMP exhibited a reduction in the sediment load at varying rates, with the most significant reduction observed during the operation of combined BMPs, where the average yearly sediment load reached 943.4 t y^{-1}, 1525.3 t y^{-1}, 1651 t y^{-1}, and 1736.7 t y^{-1} with a reduction rate of 28.8 %, 30.3 %, 21.6 %, 33.9 % compared with the baseline sediment load with 1324.2 t y^{-1}, 2188.4 t y^{-1}, 2105.9 t y^{-1}, and 2627 t y^{-1} in reaches 22, 23, 27 and 28, respectively. This was followed by the second BMP, which was terracing, resulting in a sediment load decrease to 1096.1 t y^{-1}, 1810.2 t y^{-1}, 1744.76 t y^{-1} and 2049.2 t y^{-1}, with a reduction rate of 17.2 %, 17.3 %, 17.2 %, 22 % in reaches 22, 23, 27 and 28, respectively. Terracing and contour farming are common effective practices for reducing soil erosion, in this study contour farming is less effective in sediment reduction compared with terracing. This is because terracing physically alters steep slopes, lowering the volume of surface runoff and increasing water retention, which reduces soil displacement, while contour farming slows overland flow, but doesn't modify slope length or structure as considerably (Arabi et al., 2008). Residue management was the least effective method for reducing sediment in the river, resulting in a sediment load of 1216.3 t y^{-1}, 1990.5 t y^{-1}, 1869.6 t y^{-1} and 2384.8 t y^{-1}. Applying multiple conservation practices in combination addresses several erosion processes at once and initiates synergistic effects (Arnillas et al., 2021). The combined implementation of BMPs raises soil protection by reducing surface runoff, preserving soil structure and enhancing water infiltration because each practice targets different factors (Li, 2021; Ricci et al., 2022), for example, terracing and contour farming reduces surface runoff and trap sediments on slopes, while residue management protects the soil from rainfall impact, and no-tillage decreases soil disturbance (Arabi et al., 2008). The study outcomes align with the findings of Puertes et al. (2021) and Silva et al. (2024) which demonstrated that the combination of BMPs is the most effective in decreasing sediment load. These results are also parallel with the findings of Arabi et al. (2008) and Luna Juncal et al. (2023), which proved that terracing is the most effective method among all tested individual BMPs for reducing erosion and sediment load. The implemented BMPs are more effective in (sub-basin-28) in reducing sediment load. This is because the outlet subbasin collects runoff and sediments from upstream areas and decreases in sediment load from BMPs applied on upstream areas combined, leading to a more noticeable decrease at the outlet. Table 17 demonstrates the Reduction rate of sediment load in different reaches under various individual and combined BMPs.

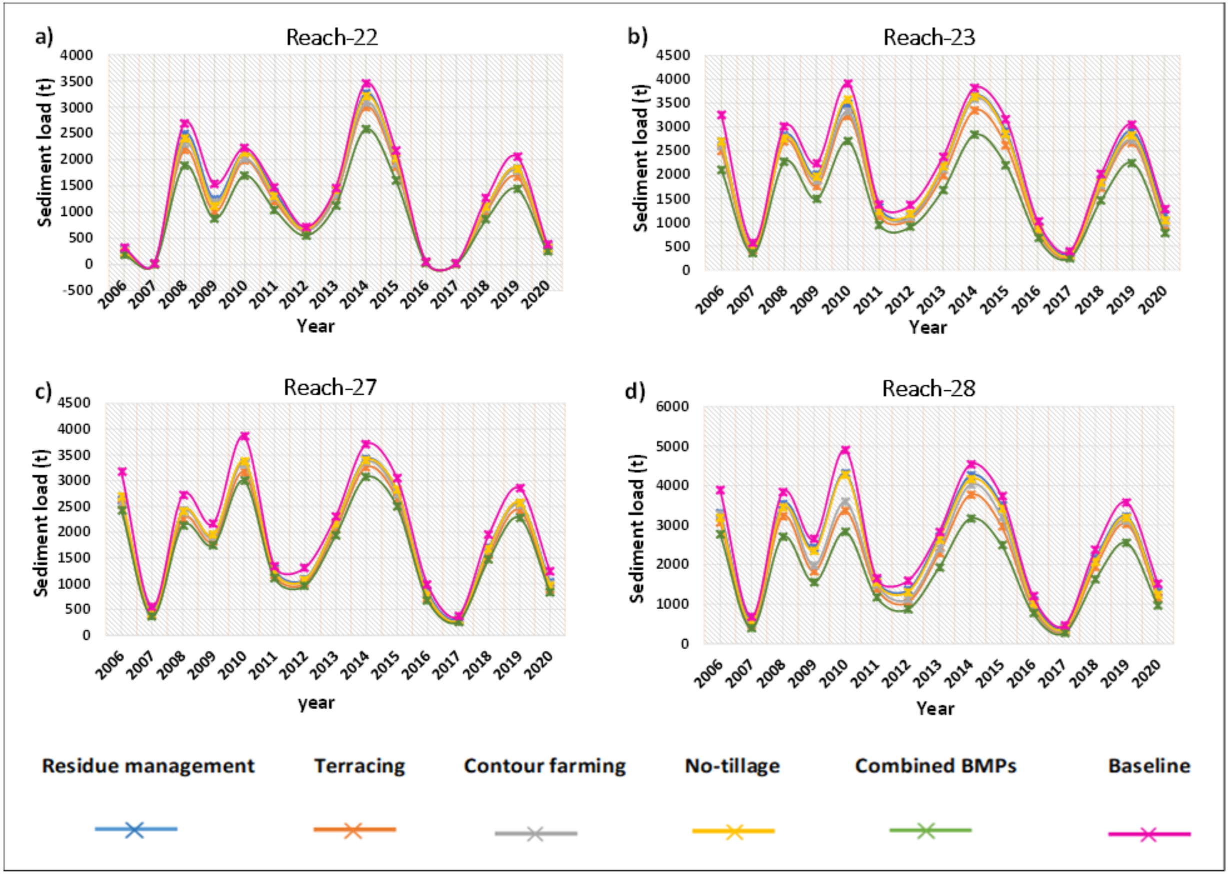

Figure 32. Annual sediment load distribution in the reach of managed sub-basins under different BMPs: a) Reach-22, b) Reach-23, c) Reach-27, d) Reach-28.

Table 17. Reduction rate of sediment load in different reaches under various individual and combined BMPs.

Sub-basins	Residue management	Terracing	Contour farming	No-tillage	Combined BMPs
	Reduction rate (%)				
Sub-basin-22	8.1	17.2	13	10.2	28.8
Sub-basin-23	9	17.3	13	10.4	30.3
Sub-basin-27	11.2	17.2	13	12	21.6
Sub-basin-28	9.2	22	16.7	11.9	33.9

After determining the effectiveness of terracing practice at a reach scale, a more detailed analysis was conducted to clarify how terracing also reduces soil loss in different hotspot areas and their related land uses. The results are shown in Figure 33 and fully detailed in Table 18. Study outcomes have revealed that terracing implementation in hotspot areas substantially influences soil loss by improving and decreasing it at sub-basin and land use levels. The soil loss for sub-basins 1, 6, 7, 9, 14, 23, 25, and 28 were 6.94 t ha^{-1} y^{-1}, 6.67 t ha^{-1} y^{-1}, 4.82 t ha^{-1} y^{-1}, 5.33 t ha^{-1} y^{-1}, 6.17 t ha^{-1} y^{-1}, 11.32 t ha^{-1} y^{-1}, 6.03 t ha^{-1} y^{-1} and 13.61 t ha^{-1} y^{-1}, respectively under terracing practices. However, soil loss was 18.01 t ha^{-1} y^{-1}, 18.22 t ha^{-1} y^{-1}, 21.05 t ha^{-1} y^{-1}, 14.86 t ha^{-1} y^{-1}, 16.01 t ha^{-1} y^{-1}, 18.55 t ha^{-1} y^{-1}, 16.22 t ha^{-1} y^{-1} and 20.68 t ha^{-1} y^{-1}, in sub-basins 1, 6, 7, 9, 14, 23, 25, and 28, respectively for the case of non-implementing terrace (see Figure 34). The percentage sediment reduction was calculated to be 61%, 63%, 77%, 64%, 61%, 38%, 62% and 34% for sub-basins 1, 6, 7, 9, 14, 23, 25 and 28, respectively (see Table 18). Regarding the land uses associated with these sub-basins, the soil loss rates for winter wheat cereals, corn, horticulture, olive, complex cultivation pattern, land principally occupied by agriculture with areas of natural vegetation and broad-leaved forest under the application of terraces were 2.29 t ha^{-1} y^{-1}, 54.11 t ha^{-1} y^{-1}, 0.05 t ha^{-1} y^{-1}, 0.02 t ha^{-1} y^{-1}, 5.5 t ha^{-1} y^{-1}, 30.98 t ha^{-1} y^{-1}, and 0.01 t ha^{-1} y^{-1}, respectively, whereas the soil loss was 6.89 t ha^{-1} y^{-1}, 81.9 t ha^{-1} y^{-1}, 0.18 t ha^{-1} y^{-1}, 0.09 t ha^{-1} y^{-1}, 15.18 t ha^{-1} y^{-1}, 73.95 t ha^{-1} y^{-1} and 0.04 t ha^{-1} y^{-1}, respectively for the non-terraced case, as demonstrated in Figure 35. The soil loss decreased by 66% for winter wheat cereals, 33% for corn, 72% for horticulture, 77% for olive groves, 63% for complex cultivation patterns, 58% for land principally occupied by agriculture with areas of natural vegetation and 75% for the broad-leaved forest. At a watershed level, the average soil loss was 5.81 t ha^{-1} y^{-1} under terrace application while soil loss was 9.24 t ha^{-1} y^{-1} for non-implementing terrace. This indicates that the soil loss decreased by 37% (see Table 18). The study findings are in agreement with the results of Arabi et al. (2008), Hussain et al. (2019), and Mosbahi & Benabdallah (2020) demonstrating the effectiveness of terrace implementation in high erosion areas.

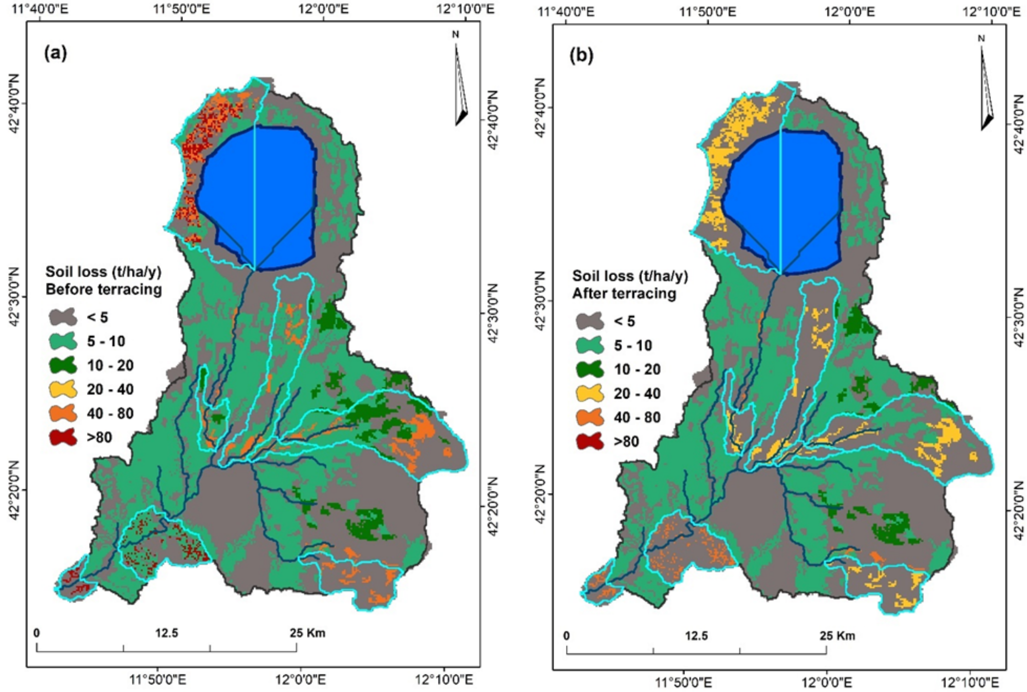

Figure 33. Soil erosion of hotspot areas within the Marta River (Tarquinia) watershed: a) before terrace implementation; b) after terrace implementation.

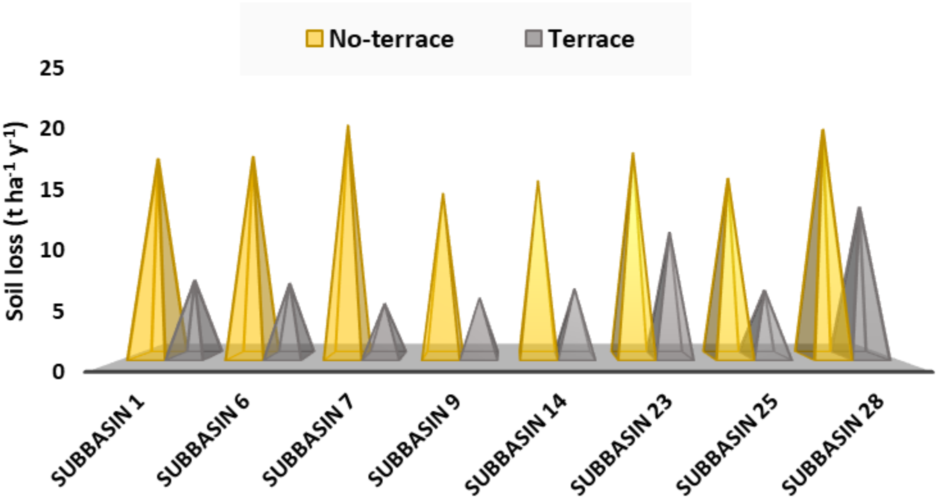

Figure 34. Soil erosion in highly eroded sub-basins before and after terrace implementation.

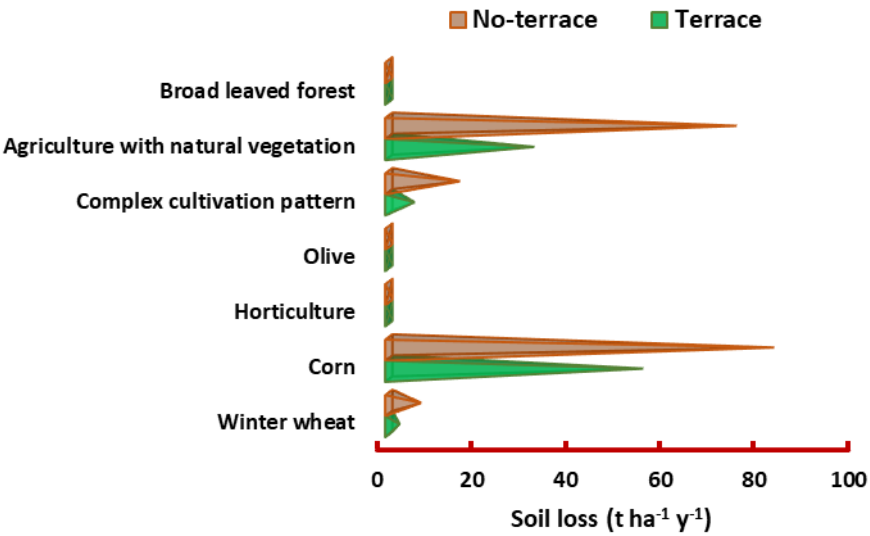

Figure 35. Soil loss in land uses associated with highly eroded areas before and after terrace implementation.

Table 18. Soil loss (t ha^{-1} y^{-1}) of hotspot areas and the related land uses before and after terrace implementation.

	Soil loss (t ha^{-1} y^{-1})			
Spatial scale	**No-terrace**	**Terrace**	**% change**	**Area (ha)**
Watershed	9.24	5.81	37	104762.5
Sub-basin				
Sub-basin-1	18.01	6.94	61	11342
Sub-basin-6	18.22	6.67	63	7884.5
Sub-basin-7	21.05	4.82	77	1292
Sub-basin-9	14.86	5.33	64	686.2
Sub-basin-14	16.01	6.17	61	5382.4
Sub-basin-23	18.55	11.32	38	3658.9
Sub-basin-25	16.22	6.03	62	2892.6
Sub-basin-28	20.68	13.61	34	614.2
Land use				
Winter wheat	6.89	2.29	66	11167.1
Corn	81.9	54.11	33	9.2
Horticulture	0.18	0.05	72	605.2
Olive	0.09	0.02	77	2451
Complex cultivation pattern	15.18	5.5	63	2079.3
Land occupied by agriculture with areas of natural vegetation	73.95	30.98	58	6455.2
Broad-leaved forest	0.04	0.01	75	5526.1

3.3.2 Assessment of total nitrogen (TN) load in a river system

The simulation results for different BMPs applied to sub-basins 22, 23, 27 and 28 indicated a decrease in TN levels within Marta River, as detailed in Figure 36. Each BMP contributed to a reduction in TN. However, the rates varied, with combined BMPs showing the most substantial decrease, where the average yearly TN load reached 10236.6 kg y^{-1}, 257740.5 kg y^{-1}, 303281.6 kg y^{-1}, and 303375.4 kg y^{-1} with a reduction rate of 27 %, 21.8 %, 14.1 %, and 14.8 % compared with the baseline TN load with 14018 kg y^{-1}, 329653.5 kg y^{-1}, 353193.5 kg y^{-1} and 356043.6 kg y^{-1} in reaches 22, 23, 27 and 28, respectively. The findings are consistent with those of Ricci et al. (2022) and Puertes et al. (2021), which showed that implementing a comprehensive set of BMPs is essential to address all agricultural pollution, as each practice targets separate factors. After demonstrating the effectiveness of the combined BMPs, the study also confirmed that the next most effective practice was terracing, which was able to lower TN load in the river to 10342.4 kg y^{-1}, 267358.6 kg y^{-1}, 310819.9 kg y^{-1} and 305962.7 kg y^{-1} with reduction rate of 26.2 %, 18.9 %, 12 %, 14.1 % in reaches 22, 23, 27 and 28, respectively. These results are consistent with those of Arabi et al. (2008), which demonstrated that terracing is the most effective practice in reducing nutrient load through lowering surface runoff volume, reducing the peak flow rate and reducing the erosive power of runoff. On the other hand, residue management, no-tillage and contour farming also reduced TN load at specific rates but are less effective compared to combined BMPs and terracing. Table 19 demonstrates the reduction rates of TN load in different reaches under various individual and combined BMPs.

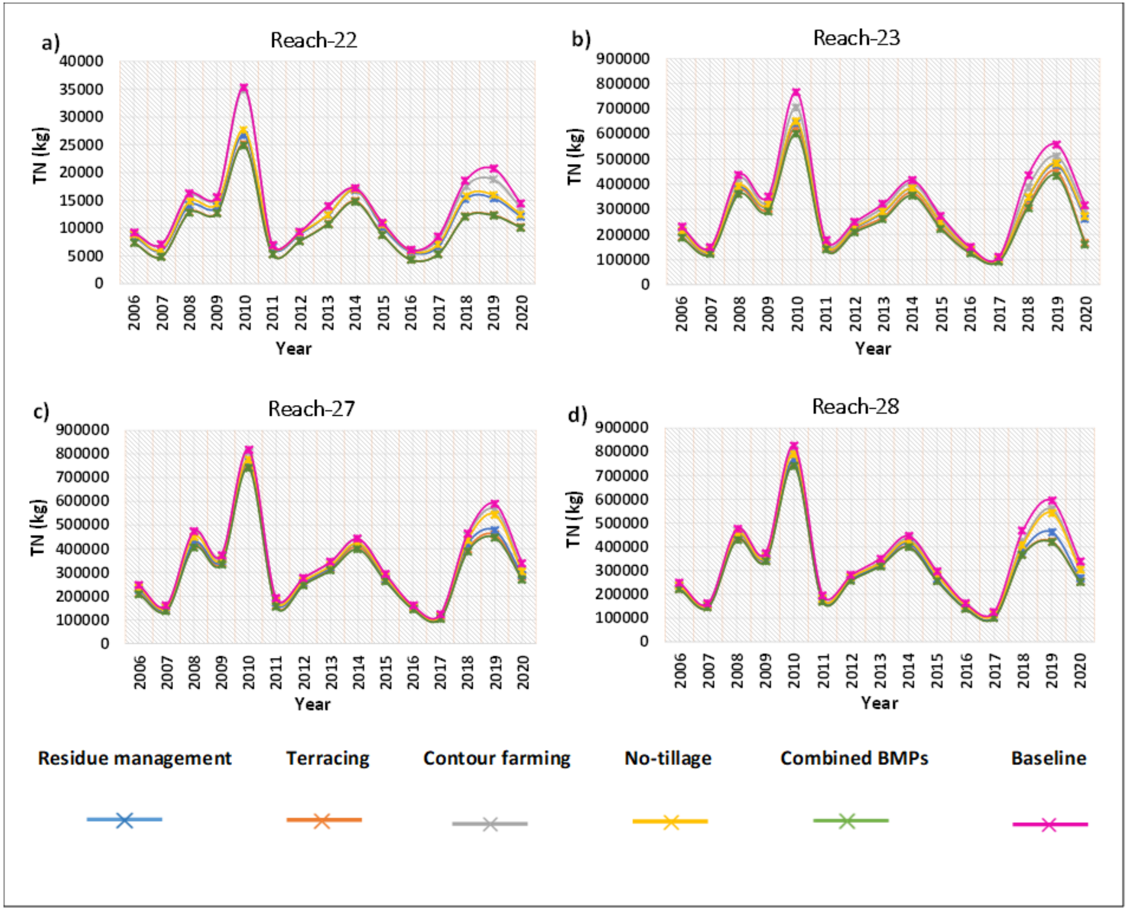

Figure 36. Annual total nitrogen (TN) load distribution in the reach of managed sub-basins under different BMPs: a) Reach-22, b) Reach-23, c) Reach-27, d) Reach-28.

Table 19. Reduction rates of total nitrogen (TN) load in different reaches under various individual and combined BMPs.

Sub-basins	Residue management	Terracing	Contour farming	No-tillage	Combined BMPs
	Reduction rate (%)				
Sub-basin-22	14.7	26.2	2.9	12	27
Sub-basin-23	13	18.9	5.9	11.7	21.8
Sub-basin-27	9.1	12	2	5.6	14.1
Sub-basin-28	10.9	14.1	4	6.3	14.8

3.3.3 Assessment of total phosphorus (TP) load in a river system

Similar to sediment and TN loads at the Marta River, TP load also showed a reduction in reaches of managed sub-basins 22, 23, 27, and 28 following the implementation of different BMPs, more details are shown in Figure 37. The most effective BMP for reducing TP load at the river was observed in the combined BMPs implementation, which brought down the TP to 4458.8 kg y^{-1}, 83561.3 kg y^{-1}, 78642.1 kg y^{-1}, and 80654.4 kg y^{-1}, achieving a reduction rate of 24.7 %, 24 %, 27.5 %, and 26.2 % compared with the baseline TP load with 5921.2 kg y^{-1}, 109996.1 kg y^{-1}, 108464.8 kg y^{-1} and 109293.9 kg y^{-1} in reaches 22, 23, 27, and 28, respectively. Among all the implemented individual BMPs, the terracing practice proved to be the most effective, reducing TP load to 4745 kg y^{-1}, 85125.4 kg y^{-1}, 83847.8 kg y^{-1}, and 85421.4 kg y^{-1} with a reduction rate of 19.9 %, 22.6 %, 22.7 %, and 21.8 % in reaches 22, 23, 27, and 28, respectively. Nutrients, like phosphorus and nitrogen, are often closely associated with soil particles, making them susceptible to transport during erosion events (Coffey et al., 2018; Ikeda et al., 2009). Through terracing implementation, the movement of these sediments and their attached nutrients was significantly minimized, thereby reducing the overall pollution load entering the river. The combination of terracing with other BMPs, such as contour farming, no-tillage and residue management, further enhanced this effect by stabilizing the soil and limiting nutrient runoff, leading to improved water quality and soil conservation outcomes. These results align with those of

Silva et al. (2024), Arabi et al. (2008), and Ricci et al. (2022), who demonstrated that these two practices (combined BMPs and terracing) are the most effective for reducing nutrient loads. Residue management, no-tillage and contour farming also demonstrated a specific rate of reduction in TP load that was lower than that of combined BMPs and terracing. Table 20 demonstrates the reduction rate of TP load in different reaches under various individual and combined BMPs.

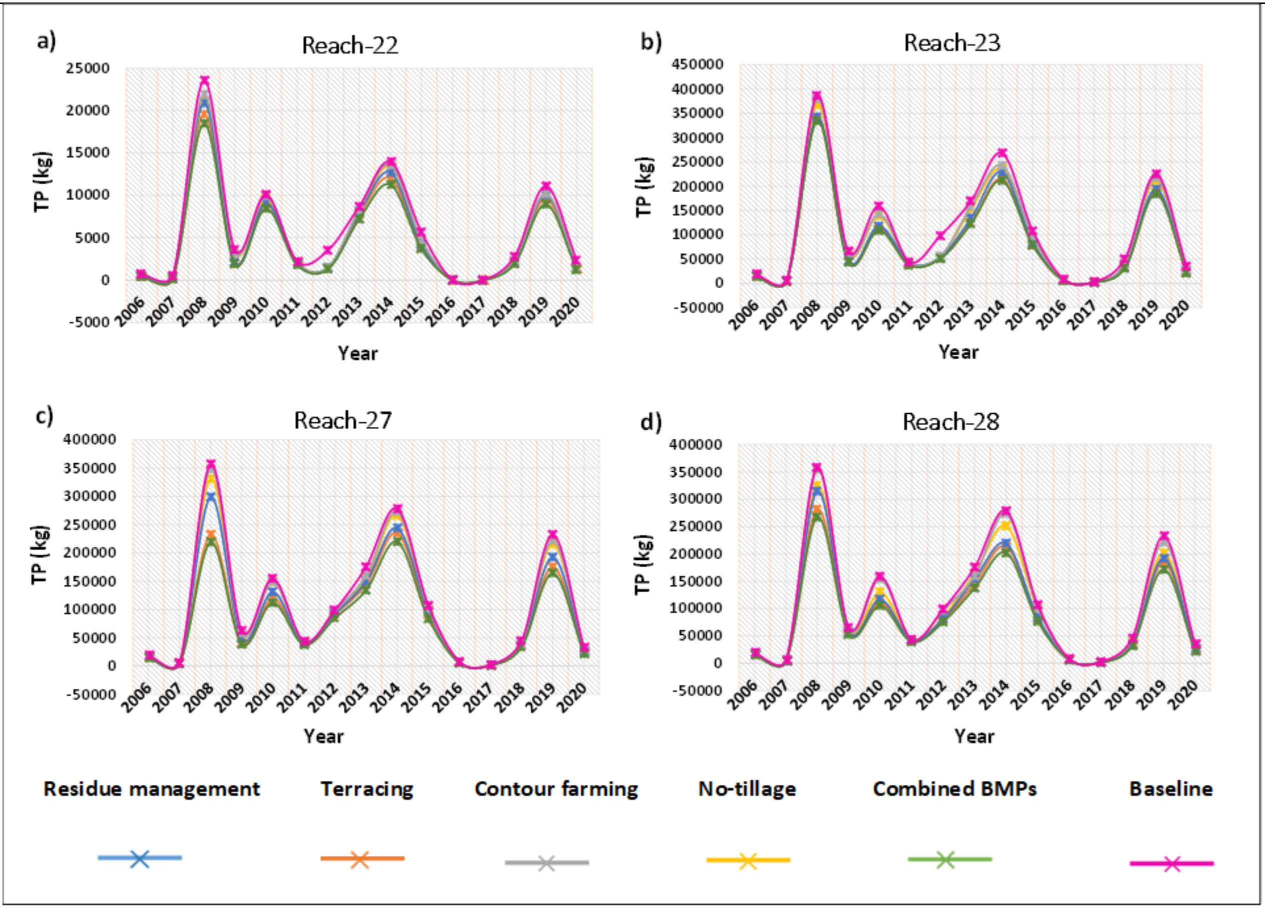

Figure 37. Annual total phosphorus (TP) load distribution in the reach of managed sub-basins under different BMPs: a) Reach-22, b) Reach-23, c) Reach-27, d) Reach-28.

Table 20. Reduction rates of total phosphorus (TP) load in different reaches under various individual and combined BMPs.

Sub-basins	Residue management	Terracing	Contour farming	No-tillage	Combined BMPs
	Reduction rate (%)				
Sub-basin-22	15.5	19.9	9.4	11.6	24.7
Sub-basin-23	19.1	22.6	8.8	11.3	24
Sub-basin-27	14.6	22.7	4.4	7.2	27.5
Sub-basin-28	17.3	21.8	3.8	10.9	26.2

3.4 Key Findings and Implications

This study provides a scientific assessment of how individual and combined BMPs can significantly reduce pollutants in agricultural landscapes (on-site) and their associated water sources (off-site). The innovative aspect of this research lies in its systematic evaluation of BMP combinations, revealing that these approaches effectively target specific pollution factors. In sub-basins 22, 23, 27, and 28, combined BMPs resulted in sediment load reductions of 28.8%, 30.3%, 21.6%, and 33.9%, respectively; TN reductions of 27%, 21.8%, 14.1%, and 14.8%; and TP reductions of 24.7%, 24%, 27.5%, and 26.2%.

The analysis further identifies terracing as particularly effective among individual BMPs for minimizing sediment and nutrient loading into water sources, emphasizing the interaction between nutrients like phosphorus and nitrogen with sediment particles during transport. Under terracing practices, sediment load reductions were observed at 17.2 %, 17.3 %, 17.2 %, and 22 %, TN reductions at 26.2 %, 18.9 %, 12 %, and 14.1 %, and TP reductions at 19.9 %, 22.6 %, 22.7 %, and 21.8 % in reaches 22, 23, 27 and 28, respectively.

Other BMPs, such as residue management, no-tillage, and contour farming, also play critical roles in reducing pollutants, with their effectiveness varying depending on the pollutant type, site conditions, and specific mechanisms involved. Some BMPs are more efficient in reducing sediment loads, while others are better at mitigating nutrient loads. This variability underscores the necessity of employing a multi-strategy approach to achieve optimal water quality outcomes.

This study's insights are invaluable for policymakers, stressing the importance of tailored BMP implementation in agricultural areas to effectively reduce off-site impacts from soil erosion and nutrient pollution. The findings offer a model that can be replicated in other studies to devise robust strategies for enhancing water quality in diverse real-world contexts. The approach used in this research can guide further studies in replicating these BMP applications across different geographical and environmental settings, contributing to broader implementation and scalability of effective water management practices.

CHAPTER 4

CHAPTER 4 INTEGRATED MODELING APPROACH FOR SUSTAINABLE WATER, ENERGY, FOOD, AND ECOSYSTEM SECURITY

CHAPTER 4 INTEGRATED MODELING APPROACH FOR SUSTAINABLE WATER, ENERGY, FOOD, AND ECOSYSTEM SECURITY

Summary

Participatory System Dynamics Modeling (PSDM) has emerged in recent literature as a powerful tool for integrated modeling and scenario analysis. It enhances the understanding of current system behaviors but also helps projecting future trajectories under various conditions, thereby supporting the identification of measures to improve system resilience. A comprehensive stock and flow model, coupled with the soil and water assessment tool (SWAT) hydrological model, has been developed to show the impacts of agricultural practices on water resources and ecosystem sustainability under different climate change scenarios. The stock and flow model, developed in collaboration with stakeholders within the Learning and Action Alliances (LAAs), utilized the conceptual information included in the Causal Loop Diagrams and scientific knowledge (e.g. from SWAT) to build a quantitative (stock and flow) model to show current system state and its potential evolution. Specific attention is given to the selected Nature-Based Solution (NBS) and its role in promoting sustainable pathways for system evolution.

4.1 Context and Background

System dynamics modeling (SDM) is increasingly used in Nexus studies (Laspidou et al., 2020; Nazari-Sharabian et al., 2019; Phan et al., 2021; Sušnik et al., 2021) for its ability to uncover interdependencies and assess potential trade-offs within the complex interactions of the WEF system (Altamirano et al., 2018; Kellner, 2023), as well as allowing the simulation and evaluation of the dynamic behavior of these interconnected systems, offering valuable insights into sustainable resource management (Mirchi et al., 2012; Rebs et al., 2019; Turner et al., 2016). Additionally, it enhances collaboration and supports decision-making by integrating detailed local data and insights into the quantitative analysis.

Quantitative SDM (i.e. stock and flow models) can support the formulation of effective strategies but also assist in designing and implementing solutions by providing a clear understanding of the dynamics and interdependencies within the system (Coletta et al., 2021; Scrieciu et al., 2021). Stock and flow models build on the qualitative insights that are provided by CLDs (Pagano et al., 2019; Tiller et al., 2021; Zare et al., 2019), incorporating a set of simulation equations to quantify the linkages between different types of variables. Quantitative SD models enable the simulation of complex system behavior over time, providing a dynamic view of how systems evolve (Phan et al., 2021; Sušnik et al., 2012). It quantifies relationships between variables through mathematical modeling (Luna-Reyes & Andersen, 2003), predict future scenarios based on different policy options or changes in system parameters (Mirchi, 2013; Wen et al., 2022), performs sensitivity analysis to identify critical variables that influence system outcomes, and evaluates the impact of potential interventions (Pluchinotta et al., 2018). The end goal of quantitative modeling is to develop a model that simulates the dynamic interactions among the key variables identified in the CLD, thus enabling a deeper understanding and analysis of the entire system (Phan et al., 2021).

In this context, it is worth emphasizing that quantitative SDM is powerful for scenario analysis, offering comprehensive insights into complex systems as it aids in uncovering assumptions, creating internally consistent scenarios, exploring uncertainties, and designing policies that can withstand deep uncertainty (Pruyt, 2013). It is particularly useful for evaluating policies across various scenarios, thus enhancing clarity in decision-making and adaptation strategies (Engelbertink, 2019; Sterman, 2000). Unlike traditional predictive tools, SDM emphasizes exploring current system structures and their potential impacts under different scenarios, rather than providing precise future forecasts (Featherston & Doolan, 2013; Forrester, 1998). By generating and examining multiple possible futures, SDM helps decision-makers test assumptions, assess potential impacts, and develop strategies, providing a rich, plausible view of future scenarios (Forrester, 1998; Pluchinotta et al., 2018).

Numerous studies have investigated Nexus systems using quantitative System Dynamics Modeling (SDM). For example, Wen et al. (2022) conducted a study in Daqing, China, aiming to promote sustainable development in a resource-based region (RBR). The research involved developing a feedback model using SDM to capture WEF dynamics from both supply and demand perspectives and categorize WEF resources. Future scenarios were designed to evaluate the impacts of real policies designed by various government departments on the WEF Nexus system. Another study was conducted by Purwanto et al. (2021) in Karawang Regency, Indonesia, where a stock-flow diagram was developed to simulate the impacts of planned policy interventions on WEF security. This quantitative model, built on a previously established CLD, enabled a detailed analysis of the WEF system. The study explored scenarios, such as changes in population growth, agricultural land conversion rates, the development of artificial ponds and solar energy, and per-capita resource consumption changes. The study carried out by Zeng et al. (2022) addressed the critical challenge of managing the WEF Nexus by integrating human sensitivity and reservoir operations within a system dynamics framework. Focusing on the mid-lower reaches of the Hanjiang River basin in China, the research utilized a system dynamics model to simulate the co-evolution of water, energy, food, and societal interactions (WEFS), coupling with the Interactive River-Aquifer Simulation model (IRAS) to assess the impact of reservoir operations on water supply for energy and food systems. By incorporating environmental awareness as a quantitative measure of human sensitivity, the model allowed for the adjustment of WEFS interactions through feedback mechanisms. In their study, Naderi et al. (2021) examined the complex feedback between food, energy, and water (FEW) systems to inform sustainable development decisions. The research presents both a qualitative representation and a quantitative system dynamics simulation of the water resources system in the Qazvin plain, Iran, considering the energy intensity of water supply and its use across different sectors, such as urban, industrial, and agricultural. By utilizing historical data, a system dynamics model was developed to project the effects of integrated water and energy sector dynamics over the next two decades.

Recent research by Sušnik et al. (2021) a national-scale system dynamics model for the water-energy-food-land-climate (WEFLC) nexus in Latvia is developed. The model incorporates both qualitative and quantitative assessments with local stakeholders to validate its structure and integrate Latvian policy objectives into future scenarios. A study by Wang et al. (2023) developed a system dynamics model that integrates society, economy, and environment systems (SEE) into the water-energy-food (WEF) nexus, creating a comprehensive environmental system simulation for Hunan Province, China. The approach offers practical insights into the trade-offs and synergies of different policies, aiming to enhance the effectiveness of environmental policy formulation. Another study conducted by Dang et al. (2024) aimed to tackle the complex challenges associated with groundwater irrigation districts, which are critical components of the water-food-environment-ecosystem (WFEE) nexus. These challenges include water scarcity, pollution, and ecological degradation. The study developed a quantitative system dynamics model to systematically characterize and evaluate the WFEE nexus, focusing on the interactions between groundwater resources and agricultural practices. By simulating various improvement strategies, such as adjustments in planting areas, optimization of planting patterns, and enhancements in irrigation methods, the model provides actionable decision support.

The literature above highlights that integrating data and knowledge from diverse disciplines such as hydrology, social sciences, and economics is a core aspect of Nexus approaches. In recent years, some researchers have investigated the benefits of quantitatively integrating SDM with sector-specific models, particularly in hydrology. For example, Nazari-Sharabian et al. (2019) utilized the combination of SWAT and SDM to study the impact of pollutants on some hydrological balance components, exploring also the consequences of climate change under various scenarios which included variations in population dynamics, industrial and agricultural activities, water preservation policies, and planning pollution control. Deng et al. (2023) introduced an innovative approach for integrating SDM with the hydrological model (SWAT-MODFLOW). Relying on the complicated dynamics of socio-economic factors and water systems within the framework of seasonal scarcity of water, the work aimed to assess the water supply-demand stability while investigating the groundwater state across various scenarios. Although SDM can help in this regard, it still has some limitations, such as the challenges in fully capturing the complexities of hydrological dynamics, in integrating different sources of data/information and in incorporating spatial information (Nikolic & Simonovic, 2015; Sušnik et al., 2012; Vamvakeridou-Lyroudia et al., 2008).

In the present study, a comprehensive stock and flow model has been developed for the area, based on the information included in the CLD and proposing a preliminary coupling with the SWAT model. It should support policymakers in the identification of potential sustainability pathways for the study area, based on the investigation of the relationship between agricultural practices and the state of the environment (in particular, the state of water resources and ecosystem sustainability under various climate change scenarios). This work is conducted as part of the PhD research activities in collaboration with Dr. Nikos Mellios and Prof. Chrysi Laspidou from the University of Thessaly and the Athena Research and Innovation Centre, Greece.

4.2 Method

4.2.1 Preliminary activities: Preparation and conceptualization

Preliminary activities include dialogue with stakeholders and, specifically, a clear identification of the main challenges and strategic objectives for the area, which should help focus on the scenario analysis. The definition mainly refers to the creation of a shared understanding of the problem, including the identification of a relevant timeframe and relevant variables, as well as boundaries of the analysis. The series of interviews, focus groups and workshops organized in the study area throughout project duration helped in this direction.

4.2.2 Scenario definition

In the previous steps, the system is conceptualized identifying model boundaries and key variables and building causal loop diagrams and stocks and flows. Based on these results, the first objective is to provide a ‘’surprise-free” scenario to understand the dynamics of the current system, without accounting for uncertainty. This condition has been identified in the following as BAU (‘Business-As-Usual”).

The definition of scenarios requires that the variables and related trends/events that significantly affect the issues are considered. The identification of trends, events, and uncertainties are the main ingredients to develop scenarios. The literature review of Amer et al. (2013) suggests that considering 3 – 8 uncertain factors usually generate a variable number of scenarios, typically between 3 and 6. In general, finding a balance is not easy as a great number of scenarios tend to be confusing while one scenario is a point estimate forecast. It is often useful to identify scenarios using ‘themes’, such as best-case, worst-case, economic crisis, environmental concern, technologic transition, etc., on a case-specific basis.

4.2.3 Scenario development and validation

Actual scenarios are constructed in this phase based on the simulated models, and key variables (i.e. variables that are influential in the scenario) are identified, along with realistic/expected values. In scenario planning based on SDM, it is particularly important to identify elements that show non-linear behavior. When scenarios are prepared, it is important that the team collectively presents and evaluates them. The identified scenarios should be tested for plausibility, consistency, utility/ relevance, novelty, and differentiation. Scenarios respectively must be capable of happening (plausible), must ensure that no built-in inconsistency and contradiction exists (consistency), must provide insights into to future which help to make decisions (utility/ relevance), must challenge the organization’s wisdom about the future (challenge), and must be structurally different (Amer et al., 2013).

Ideally, this step of analysis should be followed by an additional step of Evaluation and Strategic Decision making, in which the realized outcomes are evaluated, and further research needs are identified to support strategic decision-making.

4.3 Results and Discussion

The stock and flow model developed for the study area has been connected with the hydrological model (SWAT) built for the study area, with the aim of investigating the interplay between agricultural practices and the state of the environment in the case study. The stock and flow model has been built using Stella® Software.

The stock and flow model has been designed to simulate more than 80 years with a monthly time step. The duration of the simulation depends on the identification of a relevant time step to account for the main changes that may occur in the system (mainly in terms of CC) but can be adapted. As already mentioned, the time step has been selected considering its relevance to describe with enough detail some key phenomena (e.g. monthly variation of water demand) and coherence with the time step used in other models (e.g. water allocation). Increasing the time step (e.g. seasonal or annual) would result in a potentially relevant loss of information at least for some dynamics, while reducing it (e.g. daily) would add limited information in terms of the quality of the outputs while potentially increasing the computational burden.

This model has been organized in the form of sub-models as well, both to simplify the visual structure of the whole model, without compromising the description of interconnections and to facilitate users interested in getting insights into a specific sector or dynamic. The main model is represented in the following Figure 38.

Spatial information has been included in a semi-distributed way, considering the 28 sub-basins that have been identified using the SWAT model over the study area. Additionally, from the conceptual point of view, we also identified three main areas, namely the ‘upstream’, ‘middle’, and ‘downstream’ parts of the catchment, considering the dominant land use, activities, and challenges. As the main irrigation district extends outside the physical boundaries of the watershed (yet using resources taken from the river Marta), we also introduced specific sub-models (see e.g. ‘Land use outside LW’ and ‘Food outside LW) to account for this additional area – and related impacts. Figure 38 provides an overview of the main model, with details in this regard. Based also on the evidence of participatory exercises, the focus of the water sub-model is on water use for different purposes (with a focus on agriculture) and the impacts of human activities (mainly agriculture) on water quality; the agriculture (or food) sub-model is mainly built around the productivity and sustainability of the main crops for the area, with also a focus on the impacts of the adopted practices on water resources and the environment; the ecosystems sector is focused on the main impacts of human activities and resources use on the state of the environment.

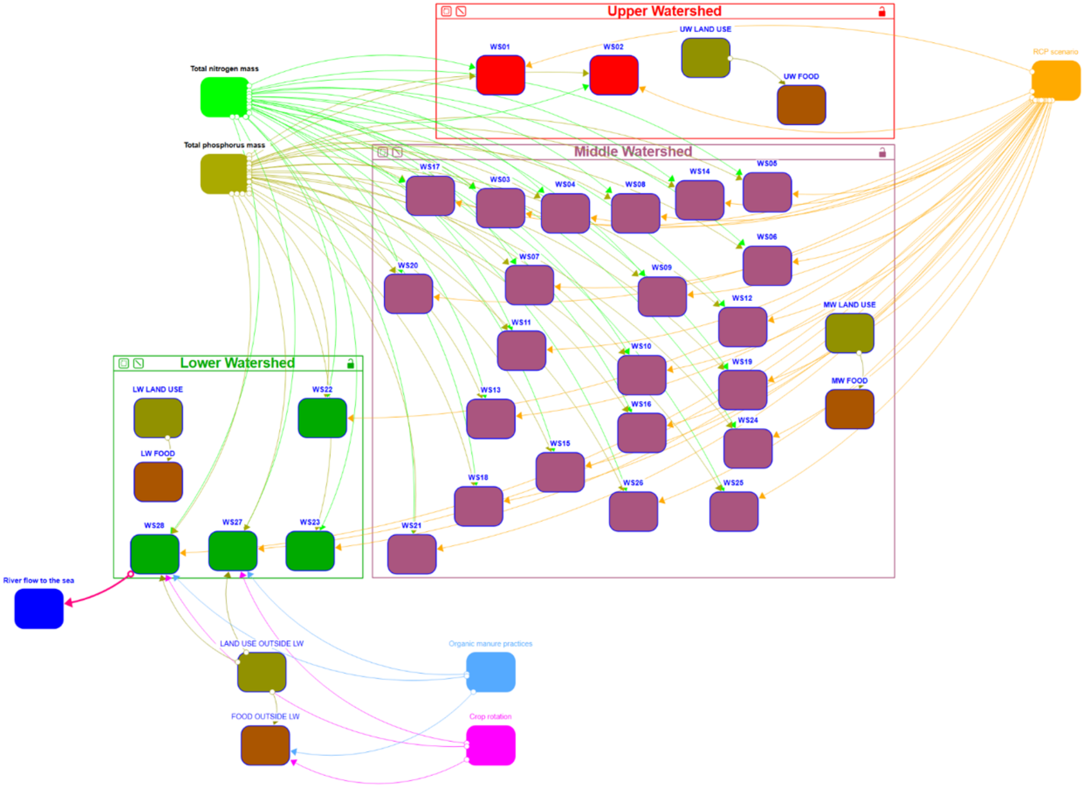

Figure 38. Overview of the stock and flow model for the Tarquinia plain area. The figure shows the organization of the model into 28 sub-basins and 3 main areas (upper, middle and lower). Additional boxes represent sub-models that describe specific dynamics (climate change, land use, food production, etc.).

The following Figure 39 provides a detailed overview of the last sub-basin of the watershed (WS28). The complexity of the sub-model is mainly related to the need to carefully account for all the impacts associated with the activities that take place upstream, but still influence the Marta River (e.g. in terms of water withdrawals, nitrogen, and phosphorous) in different climatic scenarios (e.g. RCP4.5 and RCP8.5). The expected impact of the NBS selected for the area is also included in the model.

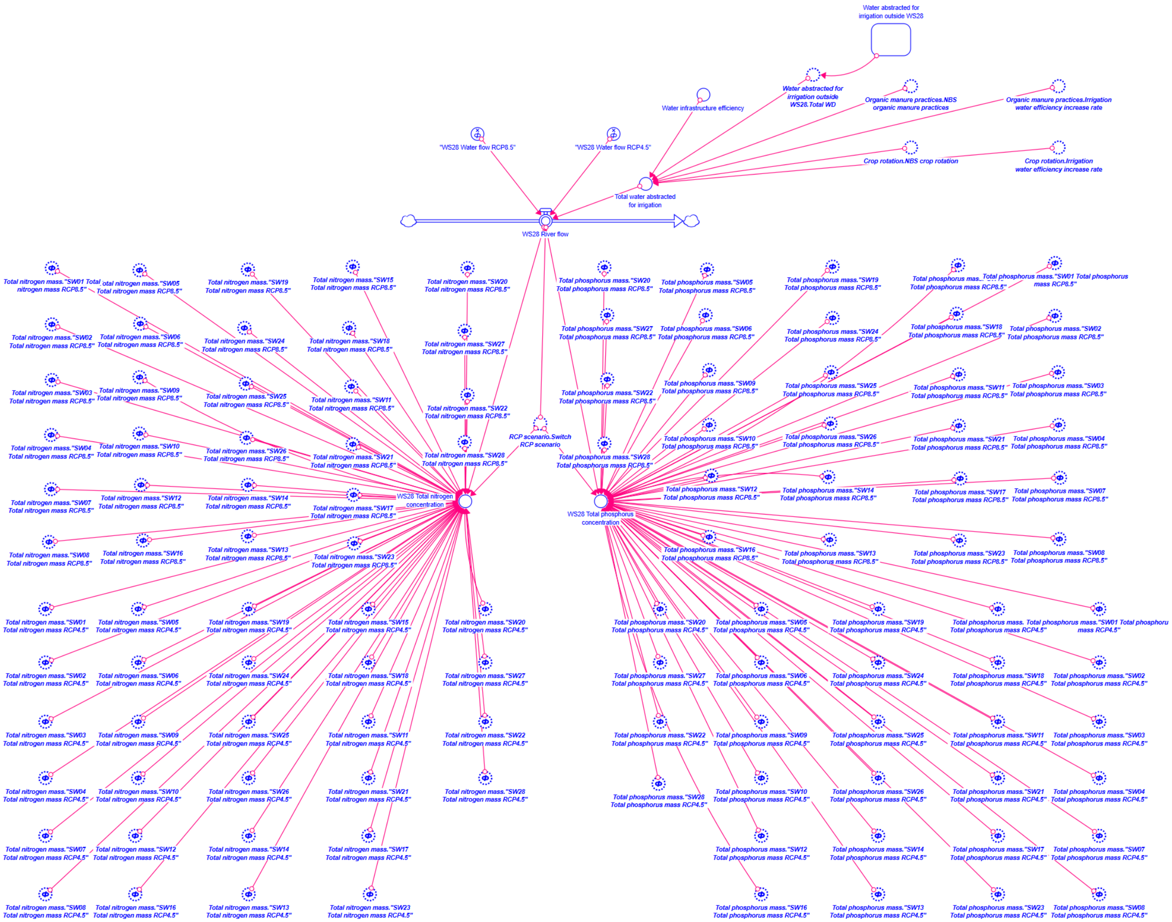

Figure 39. Overview of the sub-model for the WS28 in the Tarquinia plain area.

Scenarios were prepared before the last regional meeting (which was organized on the 16th of April 2024), based on the evidence from the previous stages of stakeholder involvement and following the advice of pilot leaders. In the following, the results of the scenario analysis are presented and discussed (see Figure 40, Figure 41, Figure 42, Figure 43, Figure 44, and Figure 45), specifically: i) the monthly flow in the Marta River under the RCP 4.5 and RCP 8.5 scenarios in the WS28; ii) the monthly nitrogen load in the Marta River under the RCP 4.5 and RCP 8.5 scenarios in the WS28; iii) the monthly phosphorus load in the Marta River under the RCP 4.5 and RCP 8.5 scenarios in the WS28; iv) the monthly water abstraction for irrigation in current conditions and modeling the effect of the introduction of the selected NBS; v) the food production associated to corn crops, including the effects of specific NBS; vi) the food production associated to horticultural crops, including the effects of specific NBS.

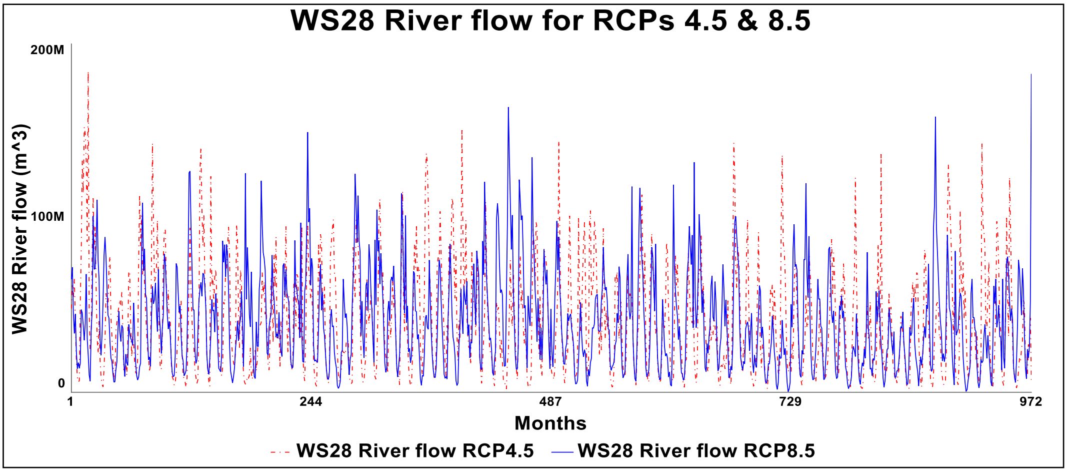

Figure 40. River flow in the WS28 in the Tarquinia plain area, for RCP4.5 and 8.5.

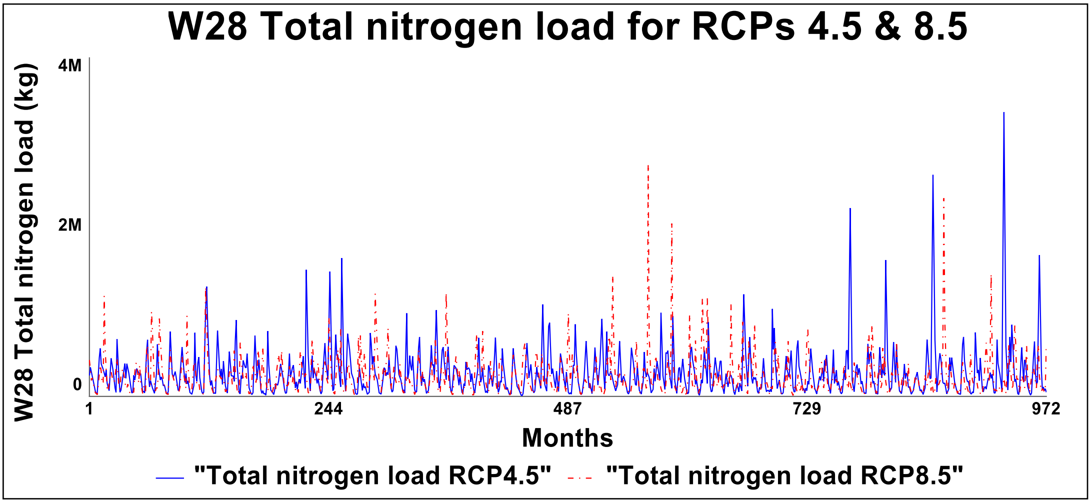

Figure 41. Total nitrogen load in the WS28 in the Tarquinia plain area, for RCP4.5 and 8.5.

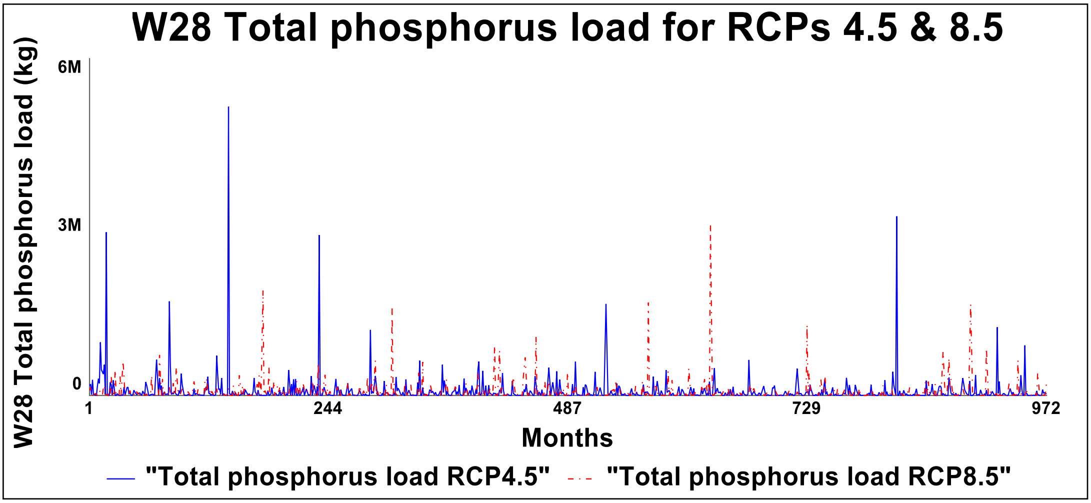

Figure 42. Total phosphorus load in the WS28 in the Tarquinia plain area, for RCP4.5 and 8.5.

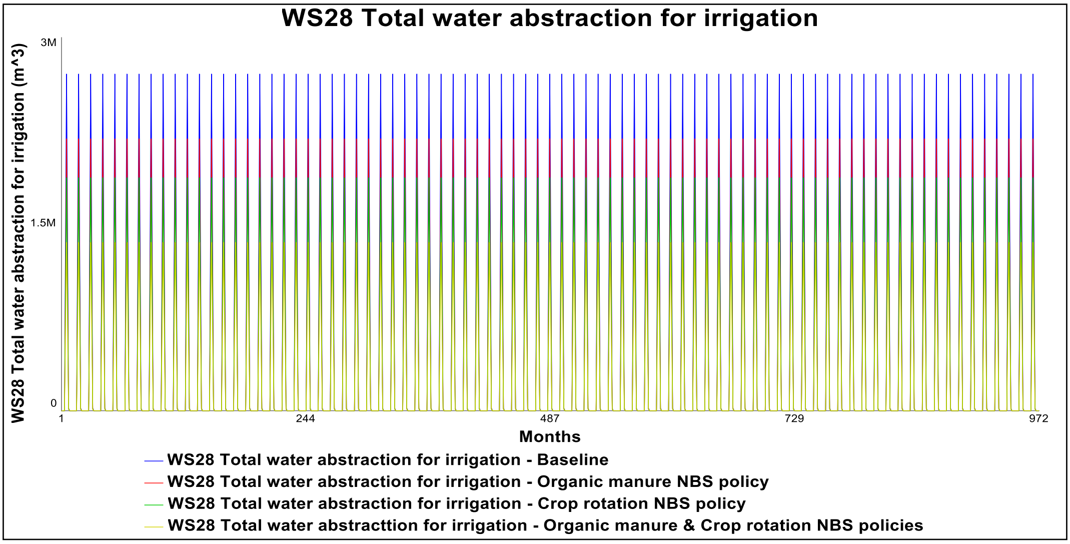

Figure 43. Water abstraction for irrigation in the WS28 in the Tarquinia plain area, under different NBS (Crop rotation, Organic manure, and their combination).

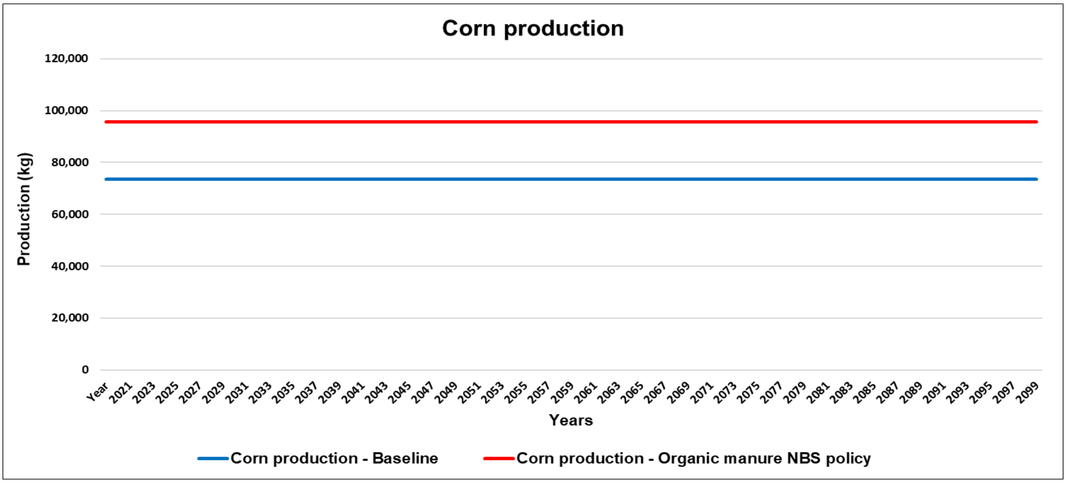

Figure 44. Corn production in the WS28 in the Tarquinia plain area, including the Impact of one NBS (Organic manure).

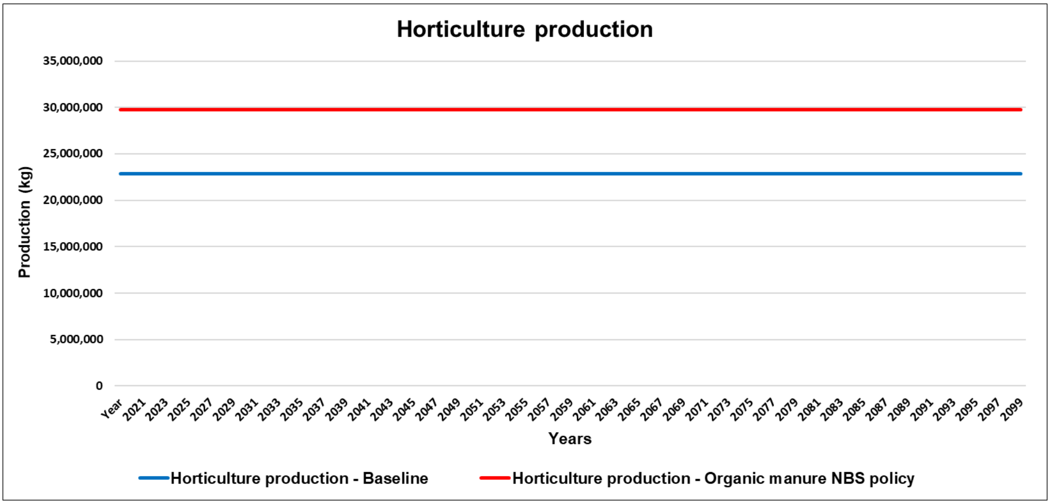

Figure 45. Horticulture production in the WS28 in the Tarquinia plain area, including the impact of one NBS (Organic manure).

In the present work, a preliminary integration between SDM and hydrological modeling (based on SWAT) has been proposed. Future research will be oriented in this direction, starting also from the key aspects and limitations identified and discussed in the following.

First, it is crucial to highlight and clarify (particularly when dealing with the stakeholders) that SDM cannot be considered a predictive tool. It is rather a way to understand and explore the current structure of a system and the reasons for its behavior, as well as its potential response to external drivers and stresses, based on a (comprehensive) understanding of how the system has evolved over time (Featherston & Doolan, 2013; Forrester, 1998). It can be therefore used to inform decision-making, supporting scenario planning, mainly exploring the potential evolution of the system under different conditions (Forrester, 1998; Yi et al., 2023). The scenario analysis is thus mainly to be used as a ‘what-if’ analysis to explore potential system evolution.

Second, stock and flow models can be used to integrate different variables and various sources of knowledge (Luna-Reyes & Andersen, 2003; Uriona & Grobbelaar, 2017; Zlatanovic, 2012). The models are therefore based both on fully quantitative variables (e.g. those describing water quantity, agricultural production, etc.) and on semi-quantitative variables (e.g. water quality, or agricultural sustainability, which are expressed in dimensionless form ranging between 0 and 1). Typically, the quantitative variables are based on the availability either of observed data or of results of sectoral models (e.g., hydrological models). This implies that the quality of information conveyed through the scenario analysis varies significantly depending on the specific variables that are considered. However, the key value added to the proposed approach lies in the integration (in the same view or analysis) of multiple variables that can be therefore evaluated and compared simultaneously. In other words, the main advantage is the potential for building a rich picture of the system under investigation, thus overcoming the development of a specific focus on one issue/sector. Decision- and policy-makers can therefore benefit from a deeper (and broader) understanding of the impacts of external drivers on the systems as well as of policies (considered in isolation or combined), exploring a multiplicity of conditions that would be hard to detail simultaneously using sectoral models (Meadows, 2008).

Third, the experience in this case study contributed to highlighting that the ‘dialogue’ itself is at least as important as the outcome of the scenario analysis (Schmitt Olabisi et al., 2010). The activities performed in the LAAs were oriented to facilitate collaboration among stakeholders, in particular for co-defining a vision for the study area and for identifying pathways for the system under investigation. The activities oriented to ‘scenario discovery’ (i.e. those aimed at selecting relevant, reasonable, and plausible scenarios) were associated with the definition of a vision for the study area and therefore helped stakeholders trying to find out consensus on how to drive the system towards sustainability. Nature-based Solutions were described and promoted as a potential response in this direction.

4.4 Key Findings and Implications

The present study proposed a preliminary attempt to integrate hydrological modeling (using SWAT) and a stock and flow model. Based on the activities performed in this study, it is worth reflecting on additional needs and potential opportunities for further innovation. Additional research could be indeed useful for further improving the model and, consequently, the quality of the scenario analysis. This would particularly require: i) an improved capacity to account for adaptation in the stock and flow model, activating specific behaviors or responses under specific conditions (e.g. when a critical threshold or a tipping point is reached); ii) a stronger mathematical formulation for selecting effective solutions based on scenario analysis using e.g. the multi-objective optimization; iii) an almost automatic integration and dialogue of the stock and flow model with the sectoral model (e.g. hydrological tools), to facilitate the creation and update of scenarios. Considering that uncertainty is an essential part of reality, an SD simulation model should account for it to more accurately reflect this reality. The most effective approach is to incorporate randomness into the model, i.e. include the points that would give random results each time you pass them during the model execution. Therefore, future activities will also focus on explicitly integrating stochastic elements into SD models.

CONCLUSIONS

Climate change can alter all hydrological processes, within a complex interplay with socio-economic dynamics, which makes the possibility to predict the state environmental systems difficult and uncertain. There is a need to develop tools capable of approaching such problems using integrated approaches and to develop scenario analyses on the state of natural resources and their likely future evolution under multiple conditions. Stakeholders need to be specifically supported in the identification of suitable mitigation/adaptation measures and in their implementation, to limit natural resource degradation.

This study focuses on the Tarquinia watershed (an agricultural basin in central Italy), which serves as a representative example of Mediterranean regions vulnerable to climate change. These vulnerabilities are linked to extreme events (floods and droughts), which increasingly affect water management and the state of natural resources, exacerbating the existing conflicts between agriculture and the state of the environment. Climate models suggest that climatic conditions in this region will change even more, with cascading impacts on hydrological components and environmental dynamics. Human activities, such as agriculture, which rely on the state of natural resources (e.g., water quantity and quality, soil quality, etc.) contribute to assessing system conditions more critical, but even more challenging.

In this context, the present work proposes an integration of methods and tools to support WEFE Nexus analysis. First, Qualitative PSDM (a CLD) allows for mapping the Nexus in a participatory way, helping stakeholders achieve consensus on the main challenges of the study area. Second, the impacts of climate change over the area are explored more in detail, as ensuring the availability and quality of freshwater resources in the Mediterranean is a critical concern, with agricultural practices exerting profound impacts on water availability and quality. The hydrological balance and diffuse pollutant load in the Marta River are analyzed utilizing the soil and water assessment tool (SWAT). Monthly streamflow monitoring data of discharge, NO_3^-, and TN from gauge stations were utilized to calibrate and validate the hydrological model using the SUFI-2 approach in the SWAT-CUP program. Additionally, the SWAT model has been forced by the most reliable climate models combinations (GCMs-RCMs) from the EURO-CORDEX after a rigorous evaluation of several EURO-CORDEX models combinations over the Marta River watershed. The simulation outputs demonstrated extensive soil loss in land uses where agricultural practices are intensively applied under both the baseline and future scenarios.

Third, the model is used to evaluate the long-term effects of various management strategies on pollutant loads in the watershed and water quality. Different BMPs suitable for controlling soil erosion and nutrient pollution in an area are identified and tested. Terracing, contour farming, no-tillage, and residue management (as well as all their combinations) are tested to understand potential on- and off-site effects. The study outcomes confirm that implementing multiple BMPs in combination is the most efficient method for preserving the quality of the river water from degradation due to sedimentation and nutrient pollution (N and P). Terracing as an individual BMP is the most effective among other BMPs in reducing soil loss in high erosion areas and reducing different pollutant loadings into the river. The findings underscore the importance of integrated sustainable soil and water management strategies in agricultural areas.

Lastly, the present study proposes a preliminary integrated modeling approach based on a comprehensive stock and flow model coupled with the SWAT hydrological model to help assess the multidimensional impacts of agricultural practices on water resources and ecosystem sustainability under different climate change (and policy) scenarios. Scenario analysis, conducted in collaboration with stakeholders helped enhancing system understanding and projecting future trajectories under various conditions, ultimately helping to find sustainable pathways for system evolution.

The Tarquinia watershed serves as a model for addressing similar challenges in the Mediterranean, demonstrating the importance of integrating multiple variables and approaches, fostering stakeholder dialogue to co-define visions and explore potential policy impacts. In this regard, the use of qualitative PSDM (CLDs) is highly relevant, as it supports an improved system understanding and an explicit analysis of Nexus interconnections and interdependencies. Although PSDM proves effective for exploring system dynamics and supporting decision-making, further innovation is needed to improve model reliability and usability for the purposes of decision-making, particularly when quantitative PSDM (stock and flow models) is used. This also requires a deeper integration with sectoral models, which is particularly helpful in accounting for adaptation actions, and can also incorporate stochastic elements to better reflect uncertainty. Current and future activities will be oriented to strengthen the integration of stock and flow models with sectoral models like hydrological tools.

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APPENDIX

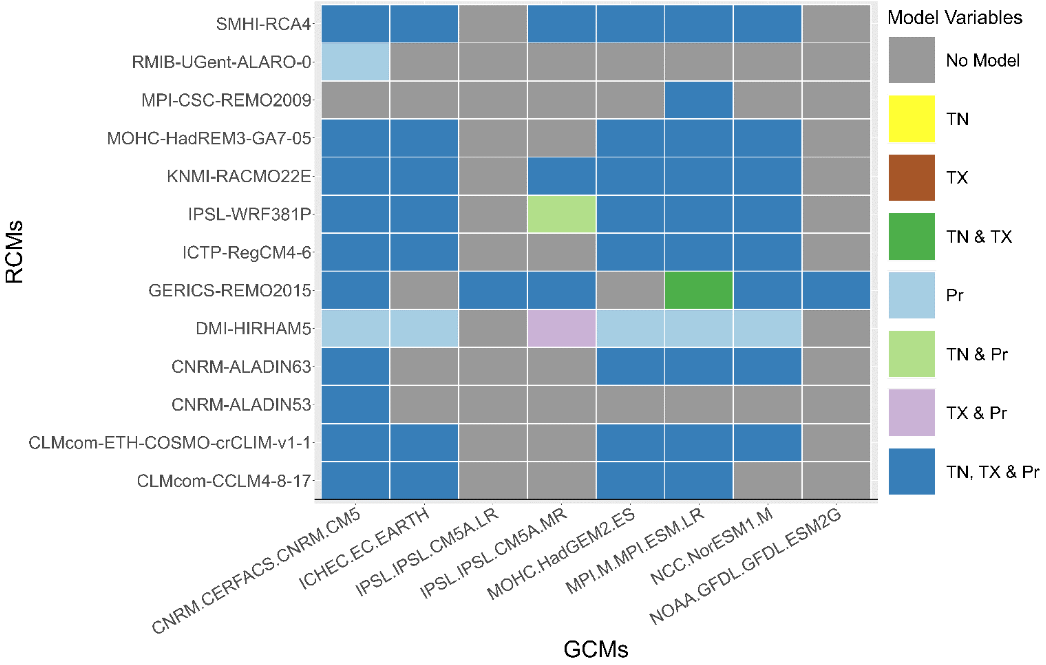


Figure 46 EURO-CORDEX GCM-RCM combinations used over the Tarquinia watershed. TN corresponds to the daily minimum surface temperature, TX to the daily surface maximum temperature and Pr to the daily total precipitation.

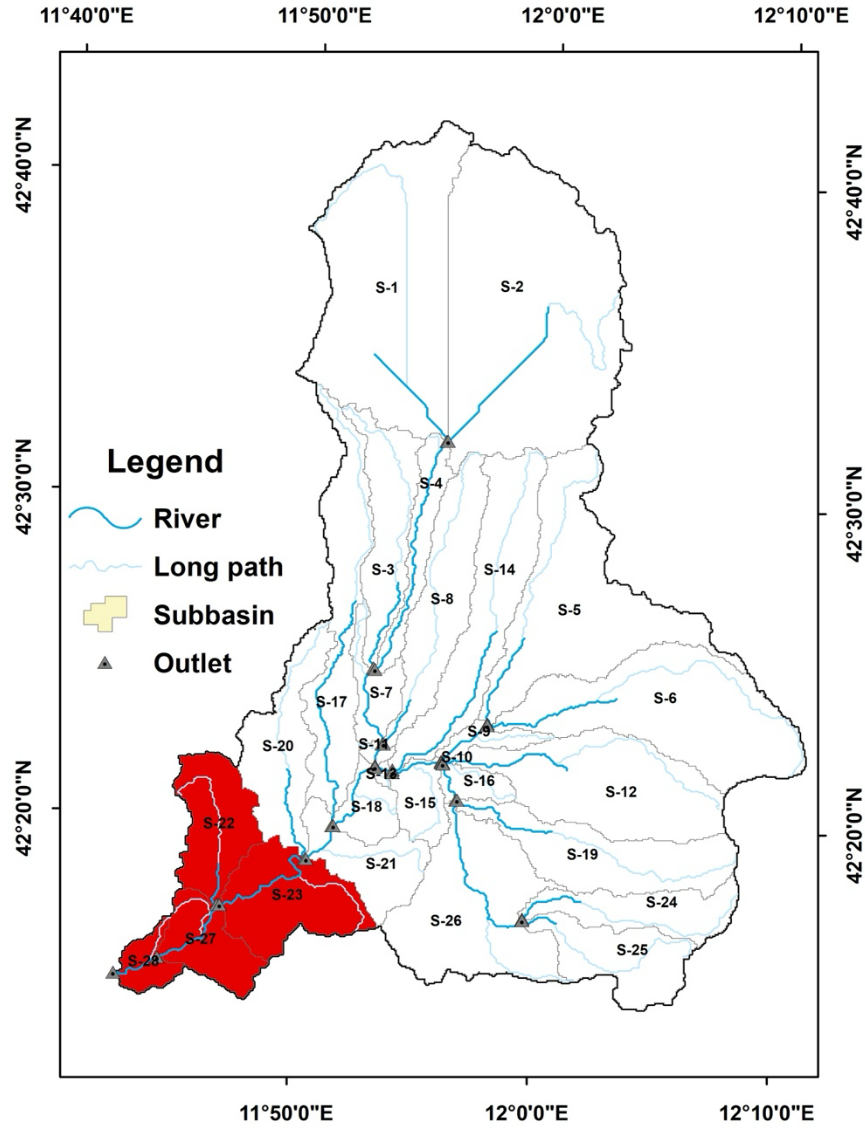
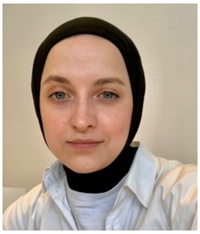


Figure 47. Selected subbasins for implementation of different management practices (highlighted in red).

CURRICULUM



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PERSONAL DETAILS

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RESEARCH EXPERIENCE

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- Development of an innovative methodology for integrating modeling systems to enhance the resilience of agricultural areas and associated water resources through climate change adaptation strategies.
- Analysis of the Water-Energy-Food-Ecosystem Nexus through integrated modeling, aimed at the identification of measures to reduce sectoral conflicts.

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University of Thessaly, research period abroad to carry out part of the doctoral research activities.

[November 2021] ongoing

Politecnico di Bari, the Risk and Environmental, Territorial and Building Development Ph.D. course, in collaboration with the Water Research Institute, National Research Council (IRSA-CNR, Bari)

[2020-2021]

Salahaddin University -Pedagogy Center, Pedagogical course for teaching.

[2017-2019]

Salahaddin University - College of Science -Environmental Department.

Master of science degree in water resources pollution under the title of "Accumulation and effects of Chromium and Cadmium on water quality and tissues of common Carp (*Cyprinus carpio L.*) fingerlings rearing in a closed system", Pof. S. Goran.

[2009-2013]

Salahaddin University - College of Science -Environmental Department.

Bachelor's degree in environmental science- Rank second among 56 students.

FURTHER INFORMATION

International English Language Testing System (IELTS) Academic Version – C1.

MAIN SCIENTIFIC PUBLICATIONS

Paper for journal

- * Yaseen, M. A., & Goran, S. M. (2019). Effect of different cadmium levels on growth and biochemical parameters of Cyprinus carpio fingerlings reared in a close system. Zanco Journal of Pure and Applied Sciences, 31(4), 139-152. https://www.iasj.net/iasj/download/23784751e37c6740.
- * Izzaddin, A., Langousis, A., Totaro, V., Yaseen, M., & Iacobellis, V. (2024). A new diagram for performance evaluation of complex models. Stochastic Environmental Research and Risk Assessment, 0123456789. https://doi.org/10.1007/s00477-024-02678-3.
- * Yaseen, M., Pagano, A., Giordano, R., Vanino, S., Fabiani, S., Baratella, V., Iacobellis, V., Izzaddin, A., & Portoghese, I. (2024). WEFE Nexus analysis using Participatory System Dynamics Modelling and Hydrological Modelling in an agricultural basin in Central Italy. Submitted
- * Yaseen, M., Mellios, N., Pagano, A., Giordano, R., Portoghese, I., Vanino, S., Iacobellis, V., Izzaddin, A., Laspidou, C. (2024). Synergizing Conservation Practices and Policy: A Model for Nexus implementation through Best Management Practices for enhancing soil and water quality in an Italian agricultural basin. [Submitted].
- * Yaseen, M., Portoghese, I., Pagano, A., Izzaddin, A., & Iacobellis, V. (2024). Assessing climate change impacts on hydrological dynamics in Tarquinia basin, Italy: An integrated study. Submitted

Paper/Abstract for conference proceedings

- * Yaseen, M., Portoghese, I., Giordano, R., Pagano, A., Iacobellis, V., Vanino, S., Pirelli, T., Fabiani, S., & Baratella, V. (2023). Integrating SWAT and Participatory System Dynamics Modelling for analyzing the WEF Nexus: the Tarquinia plain case study, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-10490, https://doi.org/10.5194/egusphere-egu23-10490.
- * Yaseen, M., Portoghese, I., Iacobellıs, V., Vanıno, S., Baratella, V., Fabıanı, S., Günaçtı, M., Gül, A. L., Barbaros, F., Gıordano, R. & Pagano, A. (2024). Integrating hydrological modelling and System Dynamics tools for understanding Water-Ecosystems-Food Nexus: hints from the Tarquinia area (Italy). 8th Europe Congress of the International Association for Hydro-Environment Engineering and Research (IAHR) (pp.1-2). Lisbon, Portugal.

Abstract

Sustainable management of natural resources requires integrated approaches to address interconnected challenges. This study adopts a Nexus framework within the Tarquinia/Marta River region, combining System Dynamics Modeling (SDM) and hydrological modeling to advance resource management. The region serves as a case study for applying the Water-Energy-Food-Ecosystem Nexus (WEFE Nexus) in Mediterranean agricultural areas. Participatory System Dynamics Modeling (PSDM) is employed to engage stakeholders and analyze resource interdependencies. A Causal Loop Diagram (CLD) is developed to map challenges such as agricultural-environmental conflicts, climate change impacts, and water quality degradation. The analysis highlights the need for agro-hydrological models to better understand these dynamics. The study utilizes the Soil and Water Assessment Tool (SWAT) hydrological model, calibrated and integrated with climate projections from the EURO-CORDEX initiative after rigorous performance evaluation. This approach quantifies hydrological processes, soil erosion, and nutrient yields under current and future climate scenarios. Results reveal substantial soil erosion and increases in total nitrogen (TN) and total phosphorus (TP) yields, with agricultural practices and climate change as key contributors. To mitigate these impacts, various Best Management Practices (BMPs) are evaluated, including terracing, no-tillage, contour farming, residue management, and their combinations. Combined BMPs prove most effective, significantly reducing soil erosion and nutrient pollution, with terracing showing exceptional efficacy in minimizing sediment loss in critical hotspot areas. Finally, the study transitions from qualitative CLDs to quantitative stock-and-flow models to explore long-term system responses and potential management strategies. This integrated approach evaluates Nature-Based Solutions (NBS) and their impacts on water resources, ecosystem health, and agricultural productivity under climate scenarios. By actively engaging stakeholders, the study identifies sustainable pathways and addresses methodological challenges to enhance resource management in the region and similar agricultural landscapes.