CARDIMED

CLIMATE ADAPTATION AND RESILIENCE DEMONSTRATED IN THE MEDITERRANEAN REGION

CARDIMED modelling framework for the WEFE Nexus

Deliverable 5.1

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Contents

Executive summary 3

1 Introduction 4

1.1 Purpose of this document 4

1.2 Intended Readership 4

1.3 Document Structure 4

2 Background 6

2.1 CARDIMED project 6

2.2 Context of the WEFE Nexus Framework 6

2.3 Objectives of CARDIMED WEFE Nexus Framework 7

3 Grouping and Analysis of DEMOs by Area Type 9

3.1 Climate Resilience Solutions for Urban Areas 9

3.1.1 DEMO 4.1 in Catania (Sicily, Italy) 9

3.1.2 DEMO 4.2 in Ferla (Sicily, Italy) 10

3.1.3 DEMO 5.1 in Saint-Jérôme (Marseille, France) 11

3.1.4 DEMO 5.2 in Saint Charles (Marseille, France) 12

3.1.5 DEMO 6.2 in Zaragosa (Aragon, Spain) 13

3.1.6 DEMO 9.1 in Nicosia (Cyprus) 14

3.1.7 DEMO 9.2 in Nicosia (Cyprus) 15

3.1.8 DEMO 9.3 in Nicosia (Cyprus) 15

3.1.9 Summary of Findings of CARDIMED DEMOs for Urban Areas 16

3.2 Climate Resilience Solutions for Peri-Urban Areas 17

3.2.1 DEMO 2 in Oinofyta (Beotia, Greece) 17

3.2.2 DEMO 3 in Alghero (Sardinia, Italy) 18

3.2.3 Summary of Findings of CARDIMED DEMOs for Peri-Urban Areas 19

3.3 Climate Resilience Solutions for Rural Areas 19

3.3.1 DEMO 1.1 in Antissa Village (Lesvos island, Greece) 19

3.3.2 DEMO 1.2 (A and B) in Ano Mera (Mykonos island, Greece) 21

3.3.3 DEMO 1.3 in Kamares basin (Sifnos island, Greece) 22

3.3.4 Summary of Findings of CARDIMED DEMOs for Rural Areas 23

3.4 Climate Resilience Solutions for Natural Areas 24

3.4.1 DEMO 6.1 near Alcañiz (Aragon, Spain) 24

3.4.2 DEMO 7 in Central Alentejo – streams (7.1) and montado (7.2) ecosystems (Portugal) 25

3.4.3 DEMO 8 in Gediz delta ecosystem (Izmir, Turkey) 26
3.4.4 Summary of Findings of CARDIMED DEMOs for Natural Areas 28
4 Methodology 29
4.1 Development of the WEFE Nexus Framework 29
4.2 Causal Loop Diagram (CLD) Development 31
4.3 Data Needs Specification 33
4.4 Identification of causality 34
4.5 System Behaviour Prediction 35
5 CARDIMED WEFE Nexus Framework Results 37
5.1 Urban Areas: Findings for all relevant DEMOs 62
5.1.1 DEMO 4.1 in Catania (Sicily, Italy) 62
Nexus Interlinkages and Causal Loop Diagram for DEMO 4.1 62
Scenario Development for DEMO 4.1 63
Data Needs Summary of DEMO 4.1 63
5.1.2 DEMO 4.2 in Ferla (Sicily, Italy) 64
Scenario Development for DEMO 4.2 65
Data Needs Summary of DEMO 4.2 65
5.1.3 DEMO 5.1 in Saint-Jérôme (Marseille, France) 66
Scenario Development for DEMO 5.1 67
Data Needs Summary of DEMO 5.1 68
5.1.4 DEMO 5.2 in Saint Charles (Marseille, France) 68
Scenario Development for DEMO 5.2 69
Data Needs Summary of DEMO 5.2 70
5.1.5 DEMO 6.2 in Zaragosa (Aragon, Spain) 70
Scenario Development for DEMO 6.2 71
Data Needs Summary of DEMO 6.2 72
5.1.6 DEMO 9.1 in Nicosia (Cyprus) 72
Scenario Development for DEMO 9.1 74
Data Needs Summary of DEMO 9.1 74
5.1.7 DEMO 9.2 in Nicosia (Cyprus) 75
Nexus Interlinkages and Causal Loop Diagram for DEMO 9.2 75
Scenario Development for DEMO 9.2 76
Data Needs Summary of DEMO 9.2 76
5.1.8 DEMO 9.3 in Nicosia (Cyprus) 77
Nexus Interlinkages and Causal Loop Diagram for DEMO 9.3 77
Scenario Development for DEMO 9.3 78
Data Needs Summary of DEMO 9.3 79

5.2 Peri-Urban Areas: Findings for all relevant DEMOs 79
5.2.1 DEMO 2 in Oinofyta (Beotia, Greece) 79
Nexus Interlinkages and Causal Loop Diagram for DEMO 2 79
Scenario Development for DEMO 2 81
Data Needs Summary of DEMO 2 81
5.2.2 DEMO 3 in Alghero (Sardinia, Italy) 82
Nexus Interlinkages and Causal Loop Diagram for DEMO 3 82
Scenario Development for DEMO 3 83
Data Needs Summary of DEMO 3 84
5.3 Rural Areas: Findings for all relevant DEMOs 84
5.3.1 DEMO 1.1 in Antissa (Lesvos, Greece) 84
Nexus Interlinkages and Causal Loop Diagram for DEMO 1.1 84
Scenario Development for DEMO 1.1 86
Data Needs Summary of DEMO 1.1 86
5.3.2 DEMO 1.2A in Ano Mera (Mykonos, Greece) 87
Nexus Interlinkages and Causal Loop Diagram for DEMO 1.2A 87
Scenario Development for DEMO 1.2A 88
Data Needs Summary of DEMO 1.2A 88
5.3.3 DEMO 1.2B in Ano Mera (Mykonos, Greece) 89
Nexus Interlinkages and Causal Loop Diagram for DEMO 1.2B 89
Scenario Development for DEMO 1.2B 90
Data Needs Summary of DEMO 1.2B 91
5.3.4 DEMO 1.3 in Kamares basin (Sifnos, Greece) 91
Nexus Interlinkages and Causal Loop Diagram for DEMO 1.3 91
Scenario Development for DEMO 1.3 92
Data Needs Summary of DEMO 1.3 93
5.4 Natural Areas: Findings for all relevant DEMOs 93
5.4.1 DEMO 6.1 near Alcañiz (Aragon, Spain) 93
Nexus Interlinkages and Causal Loop Diagram for DEMO 6.1 93
Scenario Development for DEMO 6.1 94
Data Needs Summary of DEMO 6.1 95
5.4.2 DEMO 7 in Central Alentejo – streams (7.1) and montado (7.2) ecosystems (Portugal) 95
Nexus Interlinkages and Causal Loop Diagram for DEMOs 7.1 and 7.2 95
Scenario Development for DEMOs 7.1 and 7.2 97
Data Needs Summary of DEMOs 7.1 and 7.2 97
5.4.3 Demo 8 in Izmir delta ecosystem (Turkey) 98
Nexus Interlinkages and Causal Loop Diagram for DEMO 8 98

Scenario Development for DEMO 8 99
Data Needs Summary of DEMO 8..... 100
6 Integration of Nexus Quantification, Circularity and Sustainability Assessment, and Decision Support in CARDIMED.....101
7 Challenges and Limitations 103
8 Conclusion 105
References.....106

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List of Figures

Figure 1. Stepwise methodology of the CARDIMED WEFE nexus 30

Figure 2. Causal loop diagram application into CARDIMED DEMOs for WEFE Nexus assessment, using DEMO 1.2A as an example. 33

Figure 3. Process of Identifying Causal Relationships Using Convergent Cross Mapping (CCM) 35

Figure 4. CLD of DEMO 4.1 62

Figure 5. CLD of DEMO 4.2 64

Figure 6. CLD of DEMO 5.1 66

Figure 7. CLD of DEMO 5.2 69

Figure 8. CLD of DEMO 6.2 71

Figure 9. CLD of DEMO 9.1 73

Figure 10. CLD of DEMO 9.2 75

Figure 11. CLD of DEMO 9.3 77

Figure 12. CLD of DEMO 2 80

Figure 13. CLD of DEMO 3 82

Figure 14. CLD of DEMO 1.1 85

Figure 15. CLD of DEMO 1.2A 88

Figure 16. CLD of DEMO 1.2B 90

Figure 17. CLD of DEMO 1.3 92

Figure 18. CLD of DEMO 6.1 94

Figure 19. CLD of DEMO 7.1 96

Figure 20. CLD of DEMO 7.2 97

Figure 21. CLD of Demo 8 99

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List of Tables

Table 1. Summary information of CARDIMED DEMO 4.1 10
Table 2. Summary information of CARDIMED DEMO 4.2 11
Table 3. Summary information of CARDIMED DEMO 5.1 11
Table 4. Summary information of CARDIMED DEMO 5.2 12
Table 5. Summary information of CARDIMED DEMO 6.2 13
Table 6. Summary information of CARDIMED DEMO 9.1 14
Table 7. Summary information of CARDIMED DEMO 9.2 15
Table 8. Summary information of CARDIMED DEMO 9.3 16
Table 9. Summary information of CARDIMED DEMO 2 17
Table 10. Summary information of CARDIMED DEMO 3 18
Table 11. Summary information of CARDIMED DEMO 1.1 20
Table 12. Summary information of CARDIMED DEMO 1.2A 21
Table 13. Summary information of CARDIMED DEMO 1.2B 22
Table 14. Summary information of CARDIMED DEMO 1.3 23
Table 15. Summary information of CARDIMED DEMO 6.1 25
Table 16. Summary information of CARDIMED DEMO 7.1 and DEMO 7.2 26
Table 17. Summary information of CARDIMED DEMO 8 27
Table 18. Exogenous factors and their applicability to CARDIMED's DEMOs 41
Table 19. Endogenous water-related factors and their applicability to CARDIMED's DEMOs 48
Table 20. Endogenous energy-related factors and their applicability to CARDIMED's DEMOs 53
Table 21. Endogenous farming-related factors and their applicability to CARDIMED's DEMOs 56
Table 22. Endogenous factors related to ecosystem (dis)services and their applicability to CARDIMED's DEMOs 59

List of Abbreviations

Acronym	Full Name
CLD	Causal Loop Diagram
DSS	Decision Support System
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
NBS	Nature-based Solution
DEMO	Demonstration site
WEFE	Water-Energy-Food/Farming-Ecosystem

Executive summary

This deliverable presents the development of a structured WEFE Nexus framework within the CARDIMED project to systematically evaluate the role of Nature-based Solutions (NBS) across demonstration sites (DEMOs). The framework follows a stepwise methodology that captures interdependencies between water, energy, food/farming, and ecosystems, ensuring that synergies, trade-offs, and feedback loops are effectively analysed. The methodology integrates a participatory approach to constructing causal loop diagrams (CLDs), which serve as prior beliefs about DEMOs behaviour and provide a qualitative representation of system dynamics. This participatory process ensures that stakeholder knowledge, local constraints, and contextual factors are incorporated into the analysis, forming the foundation for quantitative nexus assessments.

The framework begins with the classification of DEMOs into urban, peri-urban, rural, and remote/wilderness categories to account for the different environmental and socio-economic conditions that shape WEFE interactions. Since not all DEMOs address all four nexus components, tailored approaches are developed to assess their specific resource flows and interlinkages. The CLDs act as a crucial tool in identifying reinforcing and balancing feedback loops, supporting both qualitative insights and the subsequent quantification of nexus interactions. This stepwise transition from qualitative system mapping to data-driven assessment represents an innovation in nexus research, as it moves away from rigid equation-based modelling toward a more flexible and adaptive representation of resource dynamics.

The framework's quantification phase is designed to measure key nexus interactions such as water and energy consumption, alternative water production, nutrient cycles, and ecosystem service provisioning. These quantified outputs directly inform sustainability and circularity assessments by contributing to environmental, economic, and social impact evaluations. The structured approach ensures that NBS interventions can be assessed not only for their direct benefits but also for their system-wide implications on resource efficiency, resilience, and climate adaptation.

A core innovation of this deliverable is the integration of the WEFE Nexus framework into the CARDIMED Decision Support System (DSS). The nexus quantification process feeds into an equation-free modelling approach that enables dynamic scenario testing. Unlike traditional models that rely on predefined equations, this flexible approach allows stakeholders to assess how changes in external drivers – such as climate variability, precipitation patterns, or policy shifts – affect WEFE interactions over time. The DSS provides a user-friendly platform for policymakers, planners, and local actors to explore trade-offs and optimize resource allocation under different future scenarios.

By linking participatory nexus modelling, data-driven quantification, and digital decision support, this deliverable strengthens the analytical capacity of CARDIMED to evaluate the effectiveness of NBS. The results provide a comprehensive framework for understanding how NBS interventions interact with interconnected resource systems, enabling informed decision-making and adaptive management strategies that maximize sustainability, resilience, and long-term benefits for Mediterranean communities.

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1 Introduction

1.1 Purpose of this document

This deliverable is created within the scope of Subtask 5.1.1 - CARDIMED framework of the WEFE Nexus, outlining the development of a theoretical Water, Energy, Food, and Ecosystem (WEFE) Nexus framework for evaluating the nature-based solutions (NBS) implemented in each CARDIMED DEMO. Developed in collaboration with WP5 partners and DEMO leaders, the framework facilitates the identification of data needs, interlinkages, and trade-offs among the relevant WEFE components in each DEMO.

The WEFE Nexus framework is a foundational tool that provides a systemic understanding of the interactions and comprehensive benefits of NBS. It enables a qualitative representation of interlinkages using causal loop diagrams (CLD) and serves as the basis for developing individual models of nexus components in Subtasks 5.1.2–5.1.4 and for quantifying nexus dynamics in Task 5.2. By combining qualitative and quantitative approaches, the framework establishes a stepwise methodology that supports both the theoretical foundation (Task 5.1) and the quantification efforts (Task 5.2).

The 17 CARDIMED DEMOs, implemented in diverse settings with varying objectives and challenges, necessitate a robust and adaptable framework. Not all DEMOs target the same WEFE components, and the framework has been designed to address these differences while maintaining consistency across the CARDIMED project. Its flexibility ensures it can accommodate the unique characteristics of each DEMO and evaluate the synergies, trade-offs, and systemic dynamics associated with the implemented NBS.

The outcomes of this deliverable will contribute to subsequent WP5 tasks and deliverables, including shaping data collection strategies in Task 4.2, guiding sub-model development in Subtasks 5.1.2–5.1.4, and informing the quantification and prioritization of nexus linkages in Task 5.2. Beyond these technical contributions, the framework ensures a holistic evaluation of NBS impacts, moving beyond isolated assessments of individual WEFE components.

In summary, this deliverable establishes a robust theoretical foundation for analysing the systemic dynamics of NBS within the CARDIMED project. The WEFE Nexus framework is a versatile tool that balances consistency across DEMOs with adaptability to their specific contexts, supporting detailed modelling and analysis in subsequent project phases.

1.2 Intended Readership

This deliverable is intended for public use and aims to serve multiple audiences. It is designed to inform stakeholders, including policymakers, researchers, and practitioners, about the methodology and outcomes of Subtask T5.1.1. By providing a clear and comprehensive overview of the WEFE Nexus framework, this document supports its application in evaluating NBS and addressing interlinkages within the WEFE nexus.

Additionally, this deliverable serves as a guide for project partners and DEMO leaders, offering insights into the practical implementation of the WEFE Nexus framework. It outlines its role as a foundational tool for subsequent tasks, including model development in Subtasks 5.1.2–5.1.4, nexus quantification in Task 5.2, and sustainability and circularity assessments in Task 5.3. By doing so, it ensures alignment and consistency across project activities, while enabling effective utilization of the framework for achieving CARDIMED's objectives.

1.3 Document Structure

This deliverable is structured to provide a comprehensive analysis of the WEFE Nexus framework and its application within the CARDIMED project. It follows a logical progression, beginning with an overview of the project's objectives and the significance of the WEFE Nexus approach, before presenting the methodology used to develop the framework. The results section provides a detailed analysis of DEMO interlinkages and nexus quantification, followed by scenario development and integration with sustainability and decision-

support assessments. The document concludes by summarizing key findings, identifying challenges, and outlining potential areas for refinement and future work. This document is structured as follows:

Chapter 1 – Introduction: Outlines the purpose, scope, and objectives of this deliverable, setting the foundation for the WEFE Nexus framework.

Chapter 2 – Background: Offers context for the WEFE Nexus framework and its role in the CARDIMED project. This section also outlines the objectives of Subtask T5.1.1 and its integration with related tasks and work packages.

Chapter 3 – Grouping of Demonstration Sites by Area Type: Classifies DEMOs into urban, peri-urban, rural, and remote/wilderness categories to structure the nexus assessment.

Chapter 4 – Methodology for the Development of the WEFE Nexus Framework: Describes the stepwise approach used to construct the framework, including participatory CLD development, qualitative system mapping, and the transition to quantitative nexus assessment.

Chapter 5 – Results of the WEFE Nexus Analysis: Presents the identified nexus interlinkages, causal relationships, and quantified interactions for each DEMO, structured according to their area classification. For each DEMO, potential scenarios to be investigated in the quantification part are also presented, as well as the data needs.

Chapter 6 – Integration with Circularity, Sustainability Assessments, and the DSS: Discusses how nexus quantification informs circularity and sustainability evaluations and how the framework connects to the CARDIMED DSS for interactive scenario exploration.

Chapter 7 – Challenges and Limitations: Identifies methodological challenges, data constraints, and areas requiring further refinement.

Chapter 8 – Conclusions: Summarizes key contributions of the deliverable, emphasizing its role in supporting CARDIMED's objectives and outlining next steps for framework implementation.

2 Background

2.1 CARDIMED project

The Mediterranean region faces significant challenges due to climate change, including increased temperatures, water scarcity, and biodiversity loss. Addressing these issues requires a comprehensive and collaborative approach that leverages innovative solutions tailored to the region's unique environmental and socio-economic contexts.

The CARDIMED project aims to enhance climate resilience in the Mediterranean by uniting efforts across various regions and communities. It focuses on deploying digital infrastructure to harmonize data collection and evaluation processes, providing open data to all actors involved in the NBS value chain, and integrating crucial functions for climate resilience. These actions are implemented across nine demonstration sites, comprising 34 different types of NBS that tackle climate change and promote circularity. A key component of CARDIMED is the integration of holistic modelling tools that adopt the WEFE Nexus approach. This approach provides comprehensive knowledge on the complex interfaces of NBS, decisively contributing to addressing socio-ecological challenges and issues related to valuation and low investment rates in NBS (Carvalho et al., 2022).

NBS are strategies that utilize or are inspired by natural processes and ecosystems to address societal challenges, offering sustainable and cost-effective alternatives to traditional infrastructure (Seddon et al., 2020). NBS are inherently interconnected, as their implementation often impacts multiple sectors simultaneously. For example, an intervention designed to enhance water availability might influence agricultural productivity, energy demand, and ecosystem health. Without a comprehensive framework to understand and manage these interdependencies, NBS applications risk creating unintended trade-offs or missing opportunities for synergies.

The nexus approach is therefore essential for the effective deployment of NBS, as it provides a holistic perspective that captures the complex interlinkages among water, energy, food, and ecosystems (Nair et al., 2014; Vanino et al., 2024). By embedding NBS within the WEFE framework, CARDIMED aims to systematically evaluate these interactions, ensuring that the benefits of NBS are maximized while potential conflicts or trade-offs are minimized. This integrated perspective is crucial for addressing the multifaceted socio-ecological challenges of the Mediterranean region, enabling truly sustainable and climate-resilient solutions.

2.2 Context of the WEFE Nexus Framework

The WEFE Nexus approach has gained significant attention in recent years for addressing the interconnected challenges of resource management, sustainability, and climate resilience (Simpson & Jewitt, 2019; Schlemm et al., 2024). This multidisciplinary approach promotes an integrated understanding of systems, supporting the evaluation of the comprehensive benefits provided by NBS. Rather than focusing on single, independent impacts within water, energy, food, or ecosystem components, the WEFE Nexus framework captures cross-sectoral interactions, synergies, and trade-offs to enhance decision-making and planning for sustainability interventions (Laspidou et al., 2020).

Traditional WEFE Nexus approaches often operate at a regional or national scale, focusing on large-scale resource systems and policy-level decision-making (Biggs et al., 2015). While these frameworks provide valuable insights into strategic regional planning and climate change management, they are less suited to smaller-scale, site-specific applications, such as those in CARDIMED's DEMOs. One key limitation is their inability to effectively address local or demo-scale systems, where interactions among WEFE components are highly context-specific and influenced by local variables, such as community needs, infrastructure, and ecosystem characteristics (Albrecht et al., 2018).

Moreover, many existing frameworks emphasize broad sectoral interdependencies, often generalizing interactions and overlooking the localized dynamics of NBS. For example, interventions like wastewater reuse

or rainwater harvesting can have unique impacts depending on the socio-economic and ecological context in which they are implemented. While studies such as Gondhalekar and Ramsauer (2017) demonstrated the potential for urban NBS to meet water and food demands in specific settings, broader frameworks often fail to capture these nuances. Similarly, the Multi-Sectoral Water Circularity Assessment (MSWCA) framework (Nika et al., 2020) integrates socio-economic indicators and circularity aspects but focuses on general applications rather than site-specific NBS configurations.

The decision to develop a customized WEFE Nexus framework aligns with recent trends in nexus research advocating for context-specific methodologies (Zellner et al., 2023). Studies (e.g. Albrecht et al., 2018; Liu et al., 2017) emphasize the need to move beyond one-size-fits-all models and adopt adaptive frameworks capable of addressing the unique challenges of local systems. Additionally, the integration of participatory tools like CLDs and advanced causal inference methods like CCM reflects the latest advancements in systems thinking and data-driven analysis (Sun et al., 2024; Uleman et al., 2024). By adapting the WEFE Nexus framework to the CARDIMED DEMOs, this project demonstrates the importance of scale, context, and targeted interventions in nexus research. This tailored approach not only supports the evaluation of NBS within each DEMO but also ensures that the outcomes are directly relevant to the specific challenges and opportunities in the Mediterranean biogeographical region.

Furthermore, the practical application of the WEFE Nexus framework to NBS introduces challenges, such as the need for extensive data collection and harmonization (Maragkaki et al., 2024; Restrepo et al., 2024). Effective modelling of NBS interactions requires high-quality, site-specific in-situ and ex-situ data, covering input-output relationships for each nexus component (e.g. water use, energy demand, ecosystem benefits). These data must be harmonized across temporal and spatial resolutions to enable integration into sub-models that capture the dynamic interlinkages between WEFE components. Existing frameworks often remain theoretical and lack operational methodologies for such systemic applications (Pahl-Wostl, 2019).

By addressing these gaps, CARDIMED's tailored WEFE Nexus framework ensures a systemic and flexible approach for evaluating the impacts of NBS in diverse settings, spanning rural, peri-urban, and urban contexts. This integration not only supports climate change mitigation and adaptation but also enhances decision-making and planning for sustainable resource management.

2.3 Objectives of CARDIMED WEFE Nexus Framework

The CARDIMED WEFE Nexus framework is designed to address the unique challenges and opportunities associated with the project's DEMOs by achieving the following key objectives:

1. **Establish a robust and adaptable framework**: Develop a flexible approach capable of accommodating the diverse scales, contexts, and combinations of WEFE components targeted across the 17 DEMOs. This adaptability ensures that the framework supports a wide range of NBS implementations, from rural to urban settings.
2. **Enable systemic evaluation of NBS**: Facilitate the identification and analysis of interlinkages, synergies, and trade-offs among WEFE components, ensuring the multi-faceted impacts of NBS in each DEMO are effectively captured. The framework aims to provide a comprehensive understanding of how NBS interventions contribute to sustainability and resilience within each DEMO.
3. **Support data-driven modelling and decision-making**: Define the necessary data requirements for modelling the interactions between WEFE components, guiding the collection and harmonization of high-quality in-situ and ex-situ data. This ensures that data inputs are aligned with the overall goals of assessing NBS impacts and supporting evidence-based decisions.
4. **Promote integration across diverse systems**: Ensure that the framework can bridge the varying objectives of each DEMO, where some prioritize water management, others focus on food production or energy efficiency, and still others emphasize ecosystem restoration. The framework facilitates alignment across these diverse goals while maintaining a systemic perspective.

5. **Enhance climate resilience and sustainability planning**: Provide a foundation for planning, implementing, and scaling NBS interventions, supporting efforts to address climate change mitigation and adaptation while fostering sustainable resource management practices across the Mediterranean region.

By achieving these objectives, the CARDIMED WEFE Nexus framework positions itself as a critical tool for analysing the interactions between natural and human systems, ensuring that NBS interventions are both effective and contextually appropriate. This alignment strengthens the project's ability to deliver meaningful contributions to climate resilience, sustainability, and circularity.

3 Grouping and Analysis of DEMOs by Area Type

To better understand and effectively develop a versatile methodology that is applicable to all CARDIMED DEMOs an in-depth analysis of each DEMO is performed, providing insights into their objectives, targeted nexus components, and areas of application. The sections below group the CARDIMED DEMOs based on their area types, identifying four relevant categories – i.e. solutions for i) urban, ii) peri-urban, iii) rural, and iv) natural areas.

The nexus components investigated in the CARDIMED DEMOs are the following:

Water – targeting the technical water cycle from water supply and demand of different users to wastewater treatment and reuse or discharge. It should be noted that water aspects related to the natural water cycle are not included in this nexus component but in the ecosystem (dis)services component, as they represent ecosystem services linked to the natural hydrological functions, including groundwater recharge, surface water flows, and the role of soils and vegetation in regulating water retention and purification.

Energy – targeting energy generation (e.g. integration of renewable energy sources), energy demand and use in the water and farming/food components, infrastructure and buildings. It also includes energy efficiency measures, the resilience of energy supply systems, and the potential for energy recovery from water and agricultural processes.

Farming/Food – in the CARDIMED project, not all DEMOs incorporating agricultural activities generate food thus, a broader term is used (farming) to capture these activities as well. This component targets agricultural and land-use practices, including crop cultivation, agroforestry, and regenerative farming. It focuses on land management practices, sustainable crop production, agricultural inputs such as fertilizers and organic amendments, and farming system efficiency. Additionally, it considers resource optimization and the integration of innovative techniques for sustainable agriculture.

Ecosystem (dis)services – targeting soil health and fertility, nutrient cycling, biodiversity, emissions to air, water, and soil, as well as the natural water cycle. This component also addresses risks related to drought and flooding, climate regulation (such as temperature moderation and carbon sequestration), and the role of green and blue infrastructure in enhancing urban resilience and ecological connectivity.

3.1 Climate Resilience Solutions for Urban Areas

The CARDIMED project develops eight DEMOs in urban areas around Europe and their analysis is presented in the following sub-sections.

3.1.1 DEMO 4.1 in Catania (Sicily, Italy)

The first CARDIMED DEMO implemented in an urban area is the **DEMO 4.1** in **Catania**, Italy. Catania, located on Sicily's eastern coast, is an urban centre that faces several climate-related challenges that impact both its urban infrastructure and residents. Extreme heat events are becoming more frequent, exacerbating the urban heat island effect and increasing energy demands for cooling. The city is also vulnerable to drought, which affects water availability, and heavy rainfall, which can lead to flooding due to its coastal location and aging drainage systems. Addressing these climate-related challenges requires resilient urban planning, efficient water management, and infrastructure adaptations to protect Catania's population and economy from these environmental pressures. Responding to these challenges, **CARDIMED DEMO 4.1** focuses on enhancing stormwater management in urban areas using NBS. Targeting runoff from Alessandro Doria Avenue and Via del Bosco, the system captures, retains, and infiltrates water through bioswales and bioretention cells, including rain gardens. Infiltration shafts have been added to green spaces around Tondo Gioeni to further improve water infiltration. To prevent overloading of the sewer system during heavy rainfall events, the implemented NBS are supported by a separated sewer system that channels stormwater independently from wastewater, ***reducing flood risks***, ***improving water quality management***, and ***strengthening Catania's urban sustainability and resilience***.

Table 1 summarises important information of **DEMO 4.1** from a nexus point of view, using colour codes for the different nexus components – i.e. ecosystem services related information uses green colour, water related information uses blue colour, and energy related information uses amber colour.

Table 1. *Summary information of CARDIMED DEMO 4.1*

Name of CARDIMED DEMO	DEMO 4.1
Area Type	Urban areas
Applicable to	Streets, roads and districts
Main objectives	Enhancement of urban green spaces for: Water regulation (flood risk reduction) Water purification (water quality improvement)
Main targeted nexus component(s)	Ecosystem services
Additional (indirect) benefits	Water volume reduction to sewer system Energy reduction in WWTP Energy reduction for emergency pumping Urban biodiversity
Indirectly targeted nexus component(s)	Water Energy Ecosystem services
Type of nexus in the DEMO	**E-W-E**

3.1.2 DEMO 4.2 in Ferla (Sicily, Italy)

The second CARDIMED DEMO implemented in an urban area is **DEMO 4.2** in **Ferla**, Italy. Ferla, a small town in southeastern Sicily, is recognized for its commitment to sustainable urban practices as a designated "slow city." Despite its structured urban environment and emphasis on sustainability, Ferla faces climate-related challenges, including water scarcity during increasingly hot and dry summers and vulnerabilities to extreme weather events that strain local infrastructure and surrounding agricultural activities. To address these challenges, **CARDIMED DEMO 4.2** focuses on sustainable water management at the Instituto Comprensivo Statale Valle dell'Anapo primary school. A wall-based green facade system is installed on three building facades, integrating degreasing, UV disinfection units, and storage tanks to treat greywater from washbasins, repurposing it for toilet flushing and significantly reducing freshwater consumption. Spanning a vertical surface of 30 m², the green facade may additionally contribute to thermal regulation by reducing heat absorption in warmer months and minimizing heat loss during colder seasons, lowering the energy demand for heating and cooling of the building. By combining ***water conservation***, ***energy efficiency***, and ***climate-resilient infrastructure***, CARDIMED DEMO 4.2 offers an innovative model for addressing local environmental challenges while promoting sustainable urban development.

Table 2 summarises important information of **DEMO 4.2** from a nexus point of view, using colour codes for the different nexus components – i.e. water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 2. *Summary information of CARDIMED DEMO 4.2*

Name of CARDIMED DEMO	DEMO 4.2
Area Type	Urban areas
Applicable to	Buildings (schools, houses, offices, etc.)
Main objectives	Reduction of freshwater consumption through greywater reuse
Main targeted nexus component(s)	Water
Additional (indirect) benefits	Energy reduction in buildings Urban biodiversity through green facades
Indirectly targeted nexus component(s)	Energy Ecosystem services
Type of nexus in the DEMO	**W-E-E**

3.1.3 DEMO 5.1 in Saint-Jérôme (Marseille, France)

The **CARDIMED DEMO 5.1** is implemented in **Saint-Jérôme**, located in the northern part of Marseille in France. Saint-Jérôme faces several climate-related challenges, including extreme heat exacerbated by the urban heat island effect, drought conditions that strain water resources, and heavy rainfall events that lead to localized flooding and stress drainage infrastructure. To address these challenges, **CARDIMED DEMO 5.1** focuses on sustainable water management and climate resilience by transforming impermeable surfaces at a university site into a multifunctional green infrastructure solution. Waterproof asphalt has been removed from the university's forecourt, access roads, and car parks, reducing surface runoff. Part of the unsealed area has been replaced with porous asphalt and porous concrete to maintain access paths while improving water infiltration. Terraced landscaping is also utilised in this DEMO to reduce stormwater runoff and erosion, while bioswales planted with cover crops further enhance water management. Additionally, terracing has been implemented to reshape the landscape, reducing stormwater runoff. Three bioswales have been installed and planted with cover crops to further enhance water retention and filtration. An urban micro-forest, planted on the main bioswale and an unsealed area, contributes to improving air quality, enhancing biodiversity, and potentially mitigating the urban heat island effect in the long term once the trees are fully grown. The use of biodegradable mulch films and drip irrigation supports tree growth, while the overall soil unsealing reduces stormwater discharge into the sewer system. Smart irrigation systems, remote sensing, and advanced soil health monitoring aim to optimize water usage and environmental conditions, supported by a weather station and air quality sensors to track microclimatic changes. Spanning 4,500 m² of university land, with an additional 1,000 m² to be unsealed during winter, this NBS approach demonstrates how sustainable infrastructure can ***reduce heat***, ***manage stormwater*** efficiently, and ***support urban biodiversity*** while fostering a resilient and environmentally friendly campus environment.

Table 3 summarises important information of **DEMO 5.1** from a nexus point of view, using colour codes for the different nexus components – i.e. ecosystem services related information uses green colour, energy related information uses amber colour, and water related information uses blue colour.

Table 3. *Summary information of CARDIMED DEMO 5.1*

Name of CARDIMED DEMO	DEMO 5.1
Area Type	Urban areas

Applicable to	Public and private open spaces
Main objectives	Enhancement of urban green spaces for: Water regulation (stormwater runoff reduction and infiltration increase) Climate regulation (urban heat island effect mitigation) Urban biodiversity Air quality
Main targeted nexus component(s)	Ecosystem services
Additional (indirect) benefits	(Energy reduction in buildings) Optimisation of water usage for irrigation of green spaces
Indirectly targeted nexus component(s)	Energy Water
Type of nexus in the DEMO	**E-W-(E)**

3.1.4 DEMO 5.2 in Saint Charles (Marseille, France)

The **CARDIMED DEMO 5.2** is implemented in the **Saint Charles** district, a highly urbanized area in Marseille, France, near the city's main train station. Saint Charles is characterized by limited available space and a high volume of visitors, restricting the extent of possible transformations. It faces several climate-related challenges, including an intense urban heat island effect, heavy rainfall that leads to flooding due to minimal permeable surfaces, and air pollution exacerbated by dense transportation networks. To address these challenges, **CARDIMED DEMO 5.2** focuses on targeted NBS, following a similar approach to DEMO 5.1 but on a smaller scale. Surface unsealing and terracing will be carried out to enhance stormwater management, while porous asphalt and concrete will be installed on pedestrian areas, roads, and parking spaces to improve water infiltration while maintaining accessibility. In the next phase, an urban micro-forest will be planted to enhance air quality by capturing microparticles and other pollutants through vegetation. Mulching, supported by biodegradable mulch films, will help retain soil moisture and regulate soil temperature around newly planted trees. Smart irrigation, remote sensing, and advanced soil health monitoring will also be implemented to optimize water use for irrigation. Despite the constraints of the site, this demonstration highlights how NBS can be integrated into dense urban environments. Spanning a small but strategically significant area, this NBS approach demonstrates how sustainable infrastructure can ***improve stormwater management***, ***reduce air pollution***, ***moderate urban heat over time***, and ***foster urban biodiversity***, creating a resilient, multifunctional green corridor in the heart of Saint Charles.

Table 4 summarises important information of **DEMO 5.2** from a nexus point of view, using colour codes for the different nexus components – i.e. ecosystem services related information uses green colour, energy related information uses amber colour, and water related information uses blue colour.

Table 4. *Summary information of CARDIMED DEMO 5.2*

Name of CARDIMED DEMO	DEMO 5.1
Area Type	Urban areas
Applicable to	Streets, roads and districts

Main objectives	Enhancement of urban green spaces for: Water regulation (stormwater runoff reduction and infiltration increase) Climate regulation (urban heat island effect mitigation) Urban biodiversity Air quality
Main targeted nexus component(s)	Ecosystem services
Additional (indirect) benefits	(Energy reduction in buildings) Optimisation of water usage for irrigation of green spaces
Indirectly targeted nexus component(s)	Energy Water
Type of nexus in the DEMO	**E-W-(E)**

3.1.5 DEMO 6.2 in Zaragosa (Aragon, Spain)

The **CARDIMED DEMO 6.2** is implemented in **Zaragoza**, the capital of Aragon in northeastern Spain. Zaragoza's city centre is characterized by a densely built urban environment, facing several climate-related challenges such as water scarcity due to its semi-arid climate, rising temperatures that intensify the urban heat island effect, and flash flooding caused by intense rainfall overwhelming drainage systems. To address these challenges, **CARDIMED DEMO 6.2** is implemented at two primary schools, *CEIP Maria Moliner* and *CEIP Vadorrey*, focusing on sustainable water management and climate resilience through NBS. At *CEIP Maria Moliner*, surface unsealing and bioretention cells have been implemented to manage stormwater effectively, while *CEIP Vadorrey* features a vegetated pergola with shading vines to provide natural cooling. Both schools utilize rainwater harvesting systems to collect and store rainwater, supporting efficient irrigation and reducing reliance on external water sources. Additionally, urban biodiversity is enriched through the installation of insect hotels, bird and bat houses, and amphibian ponds, creating habitats that enhance the ecological value of the school grounds. Spanning a total of 7,500 m² of public space, this initiative demonstrates how sustainable infrastructure can ***improve stormwater management***, ***mitigate heat***, and ***support urban biodiversity*** while fostering greener, climate-adaptive environments for urban schools in Zaragoza.

Table 5 summarises important information of **DEMO 6.2** from a nexus point of view, using colour codes for the different nexus components – i.e. ecosystem services related information uses green colour, energy related information uses amber colour, and water related information uses blue colour.

Table 5. *Summary information of CARDIMED DEMO 6.2*

Name of CARDIMED DEMO	DEMO 6.2
Area Type	Urban areas
Applicable to	Public and private open spaces
Main objectives	Water regulation (stormwater runoff reduction and infiltration increase – *CEIP Maria Moliner*) Climate regulation (natural cooling – *CEIP Vadorrey*) Urban biodiversity (*both*)

	Freshwater use reduction through rainwater harvesting (*both*)
Main targeted nexus component(s)	Ecosystem services Water
Additional (indirect) benefits	-
Indirectly targeted nexus component(s)	Energy *(energy is indirectly targeted in this system through potential energy consumption of the different solutions)*
Type of nexus in the DEMO	**E-W-(E)**

3.1.6 DEMO 9.1 in Nicosia (Cyprus)

The **CARDIMED DEMO 9.1** is implemented in Makrigiannis Park in **Nicosia**, Cyprus. As the largest and most densely populated city on the island, Nicosia faces significant climate-related challenges, including water scarcity exacerbated by prolonged droughts and declining freshwater reserves. To address these challenges, **CARDIMED DEMO 9.1** introduces a large-scale photobioreactor (PBR) system designed to treat groundwater for irrigating urban green spaces. The PBR system features a closed tubular or flat panel design that removes salinity, nitrates, and hardness from groundwater, which is initially disinfected by UV. Microalgae within the PBR treat the water, which is then sent to a settling tank for microalgal biomass harvesting through flocculation, flotation, or sedimentation. The treated water is stored in a buffer tank for irrigation use or recirculation. By ***improving groundwater quality*** and enabling sustainable irrigation practices, this NBS enhances the resilience of urban green spaces in Nicosia, addressing critical water management challenges in the region.

Table 6 summarises important information of **DEMO 9.1** from a nexus point of view, using colour codes for the different nexus components – i.e. water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 6. *Summary information of CARDIMED DEMO 9.1*

Name of CARDIMED DEMO	DEMO 9.1
Area Type	Urban areas
Applicable to	Public and private open spaces (urban parks)
Main objectives	Water treatment for irrigation
Main targeted nexus component(s)	Water
Additional (indirect) benefits	Generation of biomass for further utilisation Supporting urban green spaces
Indirectly targeted nexus component(s)	Energy *(potential energy generation through biomass & energy consumption of systems)* Ecosystem services
Type of nexus in the DEMO	**W-E-E**

3.1.7 DEMO 9.2 in Nicosia (Cyprus)

The **CARDIMED DEMO 9.2** is implemented in a hydro-pocket urban park in **Nicosia**, Cyprus, addressing the city's persistent water scarcity and the need for sustainable irrigation practices. This DEMO focuses on a subsurface rainwater harvesting system integrated with a filter drain design to optimize water use and support aquifer recharge. Rainwater is collected and transferred through a hydraulic pipeline network into storage units, such as detention vaults and tanks. The harvested rainwater is used to irrigate green areas and recharge natural aquifers. Equipped with online weather stations, water level sensors, water quality sensors, soil moisture sensors, and smart irrigation systems, the system ensures efficient water resource management and continuous monitoring. Spanning 860 m² of urban public land, this NBS provides a sustainable solution to rainwater resource management for urban green spaces in Nicosia, promoting climate resilience and water efficiency.

Table 7 summarises important information of **DEMO 9.2** from a nexus point of view, using colour codes for the different nexus components – i.e. water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 7. *Summary information of CARDIMED DEMO 9.2*

Name of CARDIMED DEMO	DEMO 9.2
Area Type	Urban areas
Applicable to	Public and private open spaces (urban parks)
Main objectives	Reduction of freshwater use for irrigation Water use reduction for irrigation Water provision (aquifer recharge)
Main targeted nexus component(s)	Water Ecosystem services
Additional (indirect) benefits	Supporting urban green spaces
Indirectly targeted nexus component(s)	Energy *(potential energy consumption of systems)*
Type of nexus in the DEMO	**W-E-E**

3.1.8 DEMO 9.3 in Nicosia (Cyprus)

The **CARDIMED DEMO 9.3** is implemented in **Nicosia**, Cyprus, featuring a 500 m² wall-based green facade aimed at enhancing urban sustainability and local food resilience. The system uses UV-disinfected water, primarily sourced from tap water, with the potential integration of greywater under evaluation. Drip irrigation ensures ***efficient water distribution*** to the facade, while temperature sensors with internal data loggers monitor environmental conditions critical to the system's operation. Installed on privately-owned but publicly accessible urban property, this NBS supports ***urban agriculture*** by utilizing vertical space for food production, ***reducing the need for food transport*** and ***associated emissions***. By combining water efficiency with urban greening and food resilience, **DEMO 9.3** contributes to Nicosia's climate adaptation and sustainability goals.

Table 8 summarises important information of **DEMO 9.3** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 8. *Summary information of CARDIMED DEMO 9.3*

Name of CARDIMED DEMO	DEMO 9.3
Area Type	Urban areas
Applicable to	Buildings (schools, houses, offices, etc.)
Main objectives	Urban agriculture Efficient water use for irrigation
Main targeted nexus component(s)	Food/Farming Water
Additional (indirect) benefits	Urban biodiversity Energy reduction in buildings
Indirectly targeted nexus component(s)	Ecosystem services Energy
Type of nexus in the DEMO	W-E-F-E

3.1.9 Summary of Findings of CARDIMED DEMOs for Urban Areas

The CARDIMED DEMOs implemented in urban areas aim to address a variety of climate-related and sustainability challenges, including water scarcity, flooding, urban heat, and urban biodiversity loss. These challenges are tackled through tailored NBS designed to optimize water management, stormwater management, improve energy efficiency, mitigate urban heat island effect, and enhance biodiversity in urban areas. The main nexus targeted in the urban CARDIMED DEMOs is the Water-Energy-Ecosystems (WEE) nexus, while only DEMO 9.3 targets the Water-Energy-Food/Farming-Ecosystems (WEFE) nexus.

The CARDIMED DEMOs for urban areas are applied across various urban settings with two DEMOs implemented in buildings (i.e. DEMO 4.2 in Ferla and DEMO 9.3 in Nicosia), two DEMOs implemented in streets and districts (i.e. DEMO 4.1 in Catania and DEMO 5.2 in Saint Charles), and four DEMOs implemented in open spaces – either parks or yards (i.e. DEMO 5.1 in Saint-Jérôme, DEMO 6.2 in Zaragoza, DEMO 9.1 and DEMO 9.2 in Nicosia).

DEMO 4.2 and DEMO 9.3 implemented in buildings apply the same NBS (i.e. green façade in the building walls) but for different purposes. DEMO 4.2 uses the green façade for treating greywater and reusing it for toilet flushing, reducing freshwater requirements, while DEMO 9.3 uses the green façade for urban agriculture, using potable water for irrigation and drip irrigation systems as a water saving technology. The plant coverage of the building walls in both cases can potentially reduce the energy demand for cooling and heating of the buildings, while also contributing to urban biodiversity. In both cases, the nexus created (either WEE in DEMO 4.2 or WEFE in DEMO 9.3) is localised, primarily affecting the building itself.

Both DEMOs implemented in streets and roads (i.e. DEMO 4.1 in Catania and DEMO 5.2 in Saint Charles) focus on stormwater management and urban biodiversity. They address flooding as a key urban challenge by improving water infiltration and reducing runoff. DEMO 4.1, applied to streets and roads, uses bioswales and bioretention cells to reduce sewer system overload and improve water quality. Similarly, DEMO 5.2 integrates unsealing, bioswales, and an urban micro-forest to enhance water infiltration, reduce stormwater discharge into the sewer system, and improve air quality. These approaches demonstrate how NBS can be tailored to different urban settings under the WEE nexus, adapting solutions to site-specific constraints and opportunities.

The remaining four DEMOs implemented in open spaces (i.e. DEMO 5.1 in Saint-Jérôme, DEMO 6.2 in Zaragoza, DEMO 9.1 in Nicosia, and DEMO 9.2 in Nicosia) focus on either stormwater or water management, and directly or indirectly on urban biodiversity enhancement. DEMO 5.1 and DEMO 6.2 address stormwater management, using measures like surface unsealing, porous materials, and bioretention cells to reduce runoff and improve infiltration. DEMO 9.1 – implemented in a public park – treats groundwater for irrigation, while DEMO 9.2 introduces subsurface rainwater harvesting and aquifer recharge to address water scarcity. Despite some shared objectives, these DEMOs apply tailored solutions to meet specific local needs – for example, DEMO 5.1 incorporates a micro-forest for urban cooling, while DEMO 6.2 integrates vegetated pergolas in schoolyards for natural cooling. DEMO 9.1 and DEMO 9.2 while not directly implementing urban greening they support it indirectly as treated water in both cases is used for irrigation of public green spaces. All four DEMOs implemented in open spaces target the WEE nexus with primarily localised impacts.

3.2 Climate Resilience Solutions for Peri-Urban Areas

3.2.1 DEMO 2 in Oinofyta (Beotia, Greece)

The **CARDIMED DEMO 2** is implemented in **Oinofyta**, Greece, an industrial hub located in the region of Boeotia, approximately 50 kilometres from Athens. Oinofyta is characterized by its significant industrial activity, particularly in sectors like chemicals, metallurgy, and food processing, which coexists with residential and agricultural zones, giving the area distinct peri-urban characteristics. Despite its industrial growth, Oinofyta faces pressing environmental challenges, primarily water pollution in the Asopos River, which has been heavily contaminated by industrial waste. This pollution, combined with periods of water scarcity, has impacted local water availability for consumption and irrigation, raising concerns for both human health and agricultural productivity. To address these challenges, **CARDIMED DEMO 2** establishes smart water management through an innovative NBS designed to transform industrial water use in this peri-urban industrial zone. The system integrates biofiltration columns and a bioswale to treat and reuse rainwater, peri-urban runoff, and industrial wastewater. Separate treatment units ensure compliance with regulations prohibiting the mixing of rainwater and wastewater, while additional components like rainwater harvesting systems, buffer tanks, and UV disinfection support the treatment process. By recovering and reusing water for industrial activities such as cooling, cleaning, and storage, the system ***reduces reliance on external water sources*** and ***addresses water scarcity***. With the potential to meet over 70% of the area's industrial water needs, this Demand-Driven Industrial Water Symbiosis System (DDIWSS) dynamically optimizes water sourcing, management, and distribution. By removing contaminants, including heavy metals, and enabling water reuse, CARDIMED Demo 2 offers a sustainable approach to industrial water management that reduces environmental impact, promotes resource efficiency, and supports Oinofyta's resilience against climate challenges.

Table 9 summarises important information of **DEMO 2** from a nexus point of view, using colour codes for the different nexus components – i.e. water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 9. *Summary information of CARDIMED DEMO 2*

Name of CARDIMED DEMO	DEMO 2
Area Type	Peri-urban areas
Applicable to	Industrial sites
Main objectives	Diversification of water sources for reduction of freshwater consumption
Main targeted nexus component(s)	Water
Additional (indirect) benefits	Reduction of stormwater runoff

	Reduction of water pollution (reusing instead of discharging industrial WW)
Indirectly targeted nexus component(s)	Ecosystem services Energy (*energy consumption of systems*)
Type of nexus in the DEMO	**W-E-E**

3.2.2 DEMO 3 in Alghero (Sardinia, Italy)

The **CARDIMED DEMO 3** is implemented in the peri-urban area of **Alghero**, located on the northwest coast of Sardinia, Italy. This region intersects urban development with agricultural activities and essential infrastructure, such as wastewater treatment plants (WWTPs). Agriculture plays a vital role in the local economy, with vineyards, olive groves, and various horticultural crops. However, the area faces significant climate-related challenges, including water scarcity during dry summer months, changing rainfall patterns, and prolonged droughts, threatening crop yields, soil health, and water availability for both agriculture and domestic use. To address these challenges, **CARDIMED DEMO 3** proposes an integrated system to support sustainable agriculture, while enhancing water resource efficiency and environmental sustainability. Over a five-year crop rotation cycle, wheat, maize, and alfalfa will be cultivated using treated wastewater from the San Marco WWTP, which has been upgraded with advanced oxidation, UV disinfection, and sand filtration to meet Class A water quality standards as per EU regulations. Solar panels will power both the wastewater treatment and irrigation systems, aligning with renewable energy goals and reducing reliance on fossil fuels. Agricultural runoff and drainage will be managed through a free water surface wetland and riparian buffer, which will treat nutrients and contaminants before water is discharged into nearby rivers. A pilot PBR and aquaculture area within the wetland further enhance sustainable water management and productivity. Spanning 6-8 hectares of peri-urban private land, this innovative system demonstrates how ***sustainable agriculture***, powered by ***renewable energy*** and supported by ***advanced water management*** technologies, can promote agricultural resilience, ***protect surface waters***, and ***decarbonize Sardinian agriculture***.

Table 10 summarises important information of **DEMO 3** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 10. *Summary information of CARDIMED DEMO 3*

Name of CARDIMED DEMO	DEMO 3
Area Type	Peri-urban areas
Applicable to	WWTPs, agriculture
Main objectives	Sustainable crop production (crop rotation, treated wastewater irrigation, renewable energy) Soil health improvement (crop rotation) Reduction of freshwater use for irrigation (treated wastewater) Efficient water use for irrigation (crop rotation)
Main targeted nexus component(s)	Food/Farming Water

Additional (indirect) benefits	Biodiversity enhancement (wetlands, riparian buffers) Water purification (wetlands, riparian buffers, PBR) Renewable energy use (solar-powered systems)
Indirectly targeted nexus component(s)	Ecosystem services Energy
Type of nexus in the DEMO	W-E-F-E

3.2.3 Summary of Findings of CARDIMED DEMOs for Peri-Urban Areas

The CARDIMED DEMOs implemented in peri-urban areas address distinct environmental and sustainability challenges, reflecting the diverse pressures of urban, industrial, and agricultural activities in such transitional zones. Both DEMO 2 in Oinofyta, Greece, and Demo 3 in Alghero, Italy, share a focus on water resource management and sustainability but differ significantly in their targeted nexus components and objectives due to their respective contexts.

DEMO 2 primarily targets the Water-Energy-Ecosystems (WEE) nexus, addressing water scarcity in an industrial zone through advanced water reuse technologies and pollution control. Its emphasis lies in optimizing industrial water use while minimizing environmental impacts. By focusing on water treatment and reuse, the system ensures resource efficiency within a heavily industrialized context, with secondary benefits for local ecosystems through reduced pollution. However, food or farming is not part of the nexus, and the system's impacts remain localized to the industrial zone.

In contrast, DEMO 3 focuses on the Water-Energy-Food/Farming-Ecosystems (WEFE) nexus, reflecting its agricultural context. The integration of treated wastewater for irrigation, renewable energy systems, and sustainable farming practices (e.g., crop rotation) creates a holistic approach to climate-resilient agriculture. Unlike DEMO 2, which centres on industrial applications, Demo 3's impacts extend to agricultural productivity, soil health, and water quality, aligning closely with the broader WEFE framework.

Both DEMOs share the primary objective of addressing **water scarcity**, but the scope and scale of their interventions vary. DEMO 2 concentrates on reducing industrial reliance on freshwater resources, while DEMO 3 combines sustainable water use with soil health improvement and renewable energy to support long-term agricultural resilience. Additionally, biodiversity is indirectly supported in both cases, but through different mechanisms: wetlands and riparian buffers in DEMO 3 and pollution reduction in DEMO 2.

This comparison highlights how peri-urban DEMOs under the CARDIMED project tailor their interventions to their specific contexts. DEMO 2 offers a focused solution for industrial water management, while DEMO 3 adopts a broader, integrated approach to support agricultural sustainability. These differences highlight the need for high adaptability of the CARDIMED nexus methodology to address diverse challenges in peri-urban areas.

3.3 Climate Resilience Solutions for Rural Areas

3.3.1 DEMO 1.1 in Antissa Village (Lesvos island, Greece)

The **CARDIMED DEMO 1.1** is implemented in **Antissa**, a small, traditional village located in the Eresos-Antissa municipal unit on the island of Lesvos, Greece. Known for its agricultural heritage and reliance on local food production, Antissa faces significant climate-related challenges, including water scarcity, agricultural vulnerability, and ecosystem degradation. Heavy reliance on groundwater for domestic and agricultural use, coupled with increasingly common droughts and changing rainfall patterns, has strained the village's water resources, threatening crop yields, soil health, and food security. Addressing these challenges, **CARDIMED DEMO 1.1** integrates a hybrid system (combining NBS with grey infrastructure) at the village's wastewater treatment plant, focusing on water reuse, nutrient recycling, and sustainable agriculture. Raw sewage is

treated through a combination of anaerobic UASB reactors and constructed wetlands, followed by filtration and disinfection, enabling reclaimed water to be safely used for irrigation. An alternative scenario employs electroactive wetlands for higher water treatment efficiency and reduced spatial requirements, though it sacrifices the biogas recovery achieved by UASB reactors. The biogas generated through the UASB process can potentially be used to produce energy, contributing to reduced reliance on external energy sources and advancing circular resource management. The treated water supports a polyculture cropland spanning 1 hectare, where diverse crops are cultivated to enhance biodiversity and build resilience against crop-specific risks. This system supports soil health, water retention, and local food production while fostering habitats for pollinators and beneficial organisms. Additionally, the sludge from the treatment process is dewatered using drying reed beds and composted into nutrient-rich material. While its application to cropland is not permitted, the composted sludge can be utilized in other ways, such as for landscaping or soil improvement in non-agricultural areas. Spanning 10,000 m², this system demonstrates a holistic approach to addressing key rural challenges through ***enhancing water reuse for irrigation***, ***promoting sustainable resource management***, and ***supporting biodiversity through diversified cropping systems***. By integrating treated wastewater for irrigation, improving water quality, and exploring potential applications for composted sludge, the system addresses water scarcity, reduces environmental impact, and builds resilience against climate-related pressures. These objectives reflect the potential of NBS to create sustainable and efficient resource management practices in rural areas.

Table 11 summarises important information of **DEMO 1.1** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 11. *Summary information of CARDIMED DEMO 1.1*

Name of CARDIMED DEMO	DEMO 1.1
Area Type	Rural areas
Applicable to	WWTPs, agriculture
Main objectives	Reduction of freshwater use for irrigation (treated wastewater) Efficient water use for irrigation (diversified crops, water-saving irrigation systems) Circular resource management (composted sludge, biogas potential) Sustainable crop production (diversified cropping system)
Main targeted nexus component(s)	Water Food/Farming
Additional (indirect) benefits	Biodiversity enhancement (polyculture cropland) Soil health support (diversified cropping) Potential energy recovery (biogas)
Indirectly targeted nexus component(s)	Ecosystem services Energy
Type of nexus in the DEMO	**W-E-F-E**

3.3.2 DEMO 1.2 (A and B) in Ano Mera (Mykonos island, Greece)

The **CARDIMED DEMO 1.2A** is implemented in **Ano Mera**, a village on the island of Mykonos, Greece. While Ano Mera retains its agricultural heritage, it faces increasing pressures from growing tourism, which has transformed it into a blend of rural and urban land use. The village struggles with significant climate-related challenges, particularly water scarcity, which is exacerbated during the dry summer months due to rising demands for agricultural irrigation and domestic use driven by seasonal visitors. Traditional farming practices, such as oregano cultivation, are vulnerable to shifting rainfall patterns and extreme weather events, threatening crop yields and local agriculture. To address these challenges, **DEMO 1.2A** integrates a sub-surface rainwater collection system to sustainably manage water resources. Rainwater is captured via a shallow filter drain, treated, and stored in detention vaults and tanks before being distributed through a smart irrigation system that optimizes water use. Spanning 4,500 m² of private rural land, the system provides a reliable water source for irrigating a 0.4-hectare oregano field, reducing reliance on external water supplies and enhancing agricultural resilience. By promoting ***efficient water use*** and ***climate-adaptive farming practices***, DEMO 1.2A demonstrates a scalable solution for sustainable resource management in rural areas transitioning toward tourism-driven economies.

Table 12 summarises important information of **DEMO 1.2A** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 12. *Summary information of CARDIMED DEMO 1.2A*

Name of CARDIMED DEMO	DEMO 1.2A
Area Type	Rural areas
Applicable to	Agriculture
Main objectives	Reduction of freshwater use for irrigation (harvested rainwater) Efficient water use for irrigation (water-saving irrigation systems) Revitalizing rural agricultural practices (oregano cultivation)
Main targeted nexus component(s)	Water Food/Farming
Additional (indirect) benefits	Support for the natural water cycle (reducing runoff, enhancing infiltration) Soil moisture conservation (smart irrigation systems) Reducing energy consumption (water collected via gravity, reduced pumping needs)
Indirectly targeted nexus component(s)	Ecosystem services Energy
Type of nexus in the DEMO	**W-E-F-E**

The **CARDIMED DEMO 1.2B** is also implemented in **Ano Mera**, focusing on sustainable water management for both agricultural and domestic applications. The village's growing tourism sector has intensified demands on

water resources, creating a need for innovative solutions to ensure long-term water security. **DEMO 1.2B** features a rainwater harvesting system that captures rainwater from rooftops and yards, channelling it to tanks for storage in order to be used for non-potable domestic use. Stormwater from yards is also collected through a different collection system and is stored for irrigation of a 0.2-hectare lavender field, supported by smart irrigation technology to optimize water efficiency. Additionally, a bioswale integrated into the system facilitates aquifer recharge during wet seasons, while improving water availability for irrigation during dry periods. This system significantly ***reduces reliance on external water sources*** by ensuring sustainable rainwater harvesting and efficient irrigation practices, directly supporting local agriculture and enhancing resilience to seasonal water scarcity. By prioritizing resource efficiency and sustainable water management, DEMO 1.2B addresses interconnected challenges, offering a scalable and adaptable solution for rural areas experiencing increasing pressures from tourism and climate change.

Table 13 summarises important information of **DEMO 1.2B** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 13. *Summary information of CARDIMED DEMO 1.2B*

Name of CARDIMED DEMO	DEMO 1.2B
Area Type	Rural areas
Applicable to	Houses, agriculture
Main objectives	Reduction of freshwater use for irrigation (harvested rainwater) Reduction of freshwater use for non-potable domestic purposes (harvested rainwater) Efficient water use for irrigation (smart irrigation systems) Revitalizing rural agricultural practices (lavender cultivation)
Main targeted nexus component(s)	Water Food/Farming
Additional (indirect) benefits	Support for the natural water cycle (aquifer recharge, reducing runoff, enhancing infiltration) Soil moisture conservation (smart irrigation systems) Reducing energy consumption (water collected via gravity, reduced pumping needs)
Indirectly targeted nexus component(s)	Ecosystem services Energy
Type of nexus in the DEMO	**W-E-F-E**

3.3.3 DEMO 1.3 in Kamares basin (Sifnos island, Greece)

The **CARDIMED DEMO 1.3** is implemented in the **Kamares Basin** on Sifnos Island, Greece, a rural area known for its traditional landscapes, terraced hillsides, and small-scale agriculture. Despite its natural beauty and agricultural heritage, the Kamares Basin faces significant climate-related challenges, including water scarcity during the dry summer months, irregular rainfall patterns, and extended droughts that threaten crop yields

and soil health. Seasonal tourism further intensifies water demand, straining local resources. Addressing these challenges, **CARDIMED DEMO 1.3** integrates an NBS system focused on enhancing water retention, flood mitigation, and biodiversity conservation within this arid ecosystem. The project involves constructing more than 100 traditional dry stone dams along two main streams, Rema Skafis Taxiarchi and Rema Tria Pigadia, combining ancient stone-dam techniques with modern conservation strategies to suit the unique conditions of Sifnos. These structures are designed to slow water flow, ***promoting soil infiltration*** and ***aquifer recharge***, which are critical for maintaining local water supplies and supporting small-scale agriculture. The dry stone dams also ***create habitats for native wildlife***, including birds, amphibians, and aquatic plants, contributing to biodiversity conservation in the region. Additionally, small water storage ponds aid in ***water retention for agricultural irrigation***, while low rock barriers are implemented to control soil erosion. Spanning 10,000 m² of public and private land, this system demonstrates a sustainable approach to water resource management and ecological resilience. By improving water retention, mitigating flood risks, and supporting biodiversity, DEMO 1.3 addresses the interconnected challenges of water scarcity and environmental degradation in rural Cycladic landscapes.

Table 14 summarises important information of **DEMO 1.3** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, and ecosystem services related information uses green colour.

Table 14. *Summary information of CARDIMED DEMO 1.3*

Name of CARDIMED DEMO	DEMO 1.3
Area Type	Rural areas
Applicable to	Streams
Main objectives	Support for the natural water cycle (aquifer recharge, reducing runoff, enhancing infiltration) Flood mitigation (slowing water flow, controlling erosion) Water provision for small-scale agriculture (water retention through water storage ponds)
Main targeted nexus component(s)	Ecosystem services Water
Additional (indirect) benefits	Biodiversity conservation (habitat creation for wildlife) Support for small-scale agriculture
Indirectly targeted nexus component(s)	Ecosystem services Food/Farming
Type of nexus in the DEMO	**W-E-(F)**

3.3.4 Summary of Findings of CARDIMED DEMOs for Rural Areas

The CARDIMED DEMOs implemented in rural areas address key challenges related to water scarcity, agricultural resilience, and ecosystem degradation, reflecting the diverse pressures and opportunities found in rural landscapes. Each DEMO applies tailored NBS to promote sustainable water use, enhance agricultural practices, and support biodiversity conservation, though their focus, scale, and targeted nexus components differ significantly.

DEMO 1.1, implemented in Antissa, Lesvos, focuses on integrating advanced wastewater treatment technologies with polyculture cropland to address water scarcity and promote sustainable agriculture. By reusing treated wastewater for irrigation and supporting nutrient recycling, this DEMO demonstrates a comprehensive approach to resource efficiency and circular management. Its impacts are closely tied to agricultural resilience, soil health improvement, and localized water reuse, highlighting its contribution to the WEFE nexus. Unlike DEMO 3 in Alghero, which applies wastewater reuse to a larger peri-urban agricultural area using renewable solar energy, DEMO 1.1's rural context allows for the use of extensive constructed wetlands due to available space but operates on a smaller population equivalent, resulting in lower reclaimed water volumes and localized impacts.

In contrast, DEMO 1.2 (A and B), implemented in Ano Mera, Mykonos, focuses on rainwater harvesting and smart irrigation to manage water scarcity and support agricultural practices under increasing pressures from tourism. DEMO 1.2A targets the irrigation needs of an oregano field, while DEMO 1.2B extends the benefits of rainwater harvesting to both agricultural (lavender cultivation) and non-potable domestic applications. Both systems indirectly enhance the natural water cycle by reducing runoff, promoting aquifer recharge, and supporting soil moisture conservation. Their contribution to the WEFE nexus lies in their emphasis on efficient water use and revitalization of rural agriculture. While DEMO 1.2B focuses on water management across agriculture and domestic uses, urban DEMOs like 4.2 and 9.3 apply similar technologies (e.g. green facades for water efficiency and greywater reuse) but within urban settings, creating highly localized impacts confined to individual buildings with less available space.

DEMO 1.3, implemented in the Kamares Basin, Sifnos, emphasizes ecosystem resilience and hydrological balance in an arid Cycladic landscape. By constructing traditional dry-stone dams and incorporating small water storage ponds, this DEMO targets flood mitigation, aquifer recharge, and biodiversity conservation, aligning primarily with the WE nexus. Unlike the other rural DEMOs, DEMO 1.3 focuses less on agricultural productivity and more on restoring natural water cycles and habitats, making it unique in its emphasis on ecological sustainability.

Despite their differences, all rural DEMOs share a common objective of addressing water scarcity through sustainable water management practices. DEMO 1.1 applies advanced technologies for wastewater reuse, DEMO 1.2 adopts rainwater harvesting to reduce reliance on freshwater sources, and DEMO 1.3 leverages traditional methods to enhance water retention and ecological resilience.

3.4 Climate Resilience Solutions for Natural Areas

3.4.1 DEMO 6.1 near Alcañiz (Aragon, Spain)

The **CARDIMED DEMO 6.1** is implemented in a rural-to-wilderness transition area near **Alcañiz**, Spain, a vast landscape characterized by rolling hills, dense forests, and limited agricultural activity. This region serves as a critical buffer between managed rural lands and more remote natural ecosystems, emphasizing ecological preservation and sustainable resource management. Despite its natural beauty and ecological value, the area faces significant climate-related challenges, including increasing temperatures, prolonged droughts, and heightened wildfire risks. These conditions have also facilitated the spread of invasive mistletoe, which weakens native trees, reduces biodiversity, and exacerbates the vulnerability of forest ecosystems. To address these challenges, **CARDIMED DEMO 6.1** focuses on mitigating the impacts of mistletoe infestation and restoring forest health across 45,000 hectares of public forest land. The project employs advanced mapping and monitoring tools, such as GIS, drones, and remote sensing, to assess infestation levels and guide targeted control measures like pruning and thinning. These efforts aim to enhance forest resilience, promote biodiversity, and reduce competition for limited resources. Additionally, the project explores the economic potential of removed biomass, offering opportunities to support the local economy while advancing sustainable practices. By integrating ***ecological restoration***, ***invasive species control***, and ***community involvement***, DEMO 6.1 demonstrates a comprehensive approach to addressing climate-related challenges and promoting long-term environmental sustainability in rural-to-wilderness landscapes.

This DEMO does not directly target any nexus components, as its primary focus is ecological restoration and biodiversity conservation. If the removed biomass is utilized for energy production, it could create a temporary Ecosystem-Energy (E-E) nexus; however, this would be limited to the duration of biomass availability and would not represent a long-term systemic nexus impact.

Table 15 summarises important information of **DEMO 6.1** from a nexus point of view, using colour codes for the different nexus components – i.e. ecosystem services related information uses green colour, and energy related information uses amber colour.

Table 15. *Summary information of CARDIMED DEMO 6.1*

Name of CARDIMED DEMO	DEMO 6.1
Area Type	Rural-to-wilderness transition areas
Applicable to	Forest ecosystems
Main objectives	Forest health restoration (pruning and thinning invasive mistletoe) Biodiversity enhancement (restoration of native species) Climate resilience (reducing wildfire risks)
Main targeted nexus component(s)	Ecosystem services
Additional (indirect) benefits	Potential economic value from biomass removal
Indirectly targeted nexus component(s)	None (*Energy component could appear temporarily if biomass is used for energy production*)
Type of nexus in the DEMO	None (**E-E** possible temporarily)

3.4.2 DEMO 7 in Central Alentejo - streams (7.1) and montado (7.2) ecosystems (Portugal)

The **CARDIMED DEMOs 7.1 and 7.2** are implemented in Central Alentejo, Portugal, a region renowned for its rich ecological and cultural heritage, particularly its montado system and Mediterranean water streams. These areas face growing pressures from biodiversity loss, climate change, and the abandonment of traditional land management practices, leading to increased wildfire risks and ecological degradation. To address these challenges, the two DEMOs employ NBS tailored to restore ecological balance, enhance biodiversity, and promote climate resilience. **CARDIMED DEMO 7.1** focuses on the conservation and restoration of riparian woodlands and Mediterranean streams, critical ecosystems that play a vital role in supporting biodiversity and maintaining regional hydrology. This DEMO implements NBS across 50,277 m² of public rural land, including the establishment of green corridors and riparian buffers, the restoration of native vegetation, and the control of invasive alien species over 707 m². Additionally, fauna refuges and nesting areas spanning 30 m² are created to support wildlife. Rainwater serves as the primary source for maintaining these green areas, ensuring the sustainability of the interventions. These measures collectively strengthen ecological balance, contribute to climate change mitigation, and reflect regional conservation priorities. **CARDIMED DEMO 7.2** focuses on the restoration and enhancement of the montado ecosystem, a neighbouring habitat closely tied to Mediterranean streams. This DEMO targets 26,287 m² of private rural land, implementing key NBS interventions such as restoring native vegetation, deploying agroforestry practices, and creating fauna refuges and nesting areas. These efforts aim to improve habitat connectivity, restore ecological balance, and reduce wildfire risks in the montado landscape. Like DEMO 7.1, rainwater is used for the natural maintenance of green areas, aligning with sustainable resource use principles. By addressing the challenges of biodiversity loss and climate vulnerability, DEMO 7.2 promotes ecosystem resilience and supports sustainable land use practices.

Together, **DEMOs 7.1 and 7.2** demonstrate a comprehensive approach to ***ecological restoration*** and ***climate resilience*** in Central Alentejo. While DEMO 7.1 emphasizes the conservation of riparian ecosystems, DEMO 7.2 focuses on enhancing the montado landscape. These complementary interventions contribute to biodiversity conservation, sustainable resource management, and long-term environmental sustainability, ensuring the preservation of Central Alentejo's unique natural and cultural heritage.

Table 16 summarises important information of **DEMO 7.1** and **DEMO 7.2** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, water related information uses blue colour, energy related information uses amber colour, and ecosystem services related information uses green colour.

Table 16. *Summary information of CARDIMED DEMO 7.1 and DEMO 7.2*

Name of CARDIMED DEMO	DEMO 7.1 & DEMO 7.2
Area Type	Natural areas
Applicable to	Riparian ecosystems, montado landscapes, agroforestry
Main objectives	Native vegetation restoration and invasive species control (in both riparian woodlands and Montado ecosystem) Water regulation and purification (natural hydrological processes, riparian buffers) Climate resilience (wildfire risk mitigation, habitat connectivity) Agroforestry for land productivity and resilience
Main targeted nexus component(s)	Ecosystem services Food/Farming
Additional (indirect) benefits	Biodiversity conservation (habitat creation, fauna refuges) Soil erosion prevention (vegetation cover, stabilizing riparian zones) Improving landscape connectivity (between DEMO 7.1 and DEMO 7.2) Eliminating irrigation water use for food production in agroforestry (relying solely on rainwater for natural irrigation)
Indirectly targeted nexus component(s)	Ecosystem services Water Energy (*energy consumption of activities*)
Type of nexus in the DEMO	**W-E-F-E**

3.4.3 DEMO 8 in Gediz delta ecosystem (Izmir, Turkey)

The **CARDIMED DEMO 8** is implemented in the Gediz **Delta** region in western Turkey, a dynamic landscape where agricultural, urban, and natural elements interact, shaping the ecological health of the delta. Located along the Aegean coast, the delta is a critical habitat for migratory birds, fish, and endemic species, serving as a natural buffer that supports biodiversity, filters water, and acts as a carbon sink. However, increasing pressures from agricultural water diversion, urban expansion, pollution, and climate change – particularly

rising temperatures and prolonged droughts – threaten the delicate balance of this coastal ecosystem. Addressing these challenges, **CARDIMED DEMO 8** integrates a comprehensive coastal wetland restoration plan using diverse NBS to enhance ecological resilience and promote sustainable land and water management. Key interventions include the establishment of riparian buffer zones to ***improve wastewater treatment***, freshwater diversion channels to lower salinity levels and ***restore wetland habitats***, and **green corridors** to strengthen ecological connectivity. Additionally, invasive species are controlled, and native fauna, such as buffaloes, are reintroduced to ***boost biodiversity***. Lagoon restoration techniques further mitigate erosion, while sustainable grazing practices are implemented to balance ecosystem pressures. To support these restoration efforts and ensure the long-term sustainability of the wetland management system, renewable energy solutions are integrated into the DEMO. Photovoltaic (PV) panels provide clean energy for monitoring stations, irrigation systems, and essential infrastructure, reducing reliance on external energy sources. Additionally, biogas units process organic waste from grazing activities and wetland biomass, generating sustainable energy while contributing to circular resource management. These energy solutions enhance the self-sufficiency of the restoration plan, minimizing environmental impact and ensuring continuous ecosystem monitoring and maintenance. By ***revitalizing coastal wetlands*** and strengthening biodiversity conservation efforts, DEMO 8 aims to ensure the long-term ecological sustainability of the Gediz Delta, demonstrating the effectiveness of integrated restoration strategies in complex, multi-use landscapes.

Table 17 summarises important information of **DEMO 8** from a nexus point of view, using colour codes for the different nexus components – i.e. food/farming related information uses brown colour, and ecosystem services related information uses green colour.

Table 17. *Summary information of CARDIMED DEMO 8*

Name of CARDIMED DEMO	DEMO 8
Area Type	Coastal wetland ecosystems
Applicable to	Wetlands, riparian zones, lagoons
Main objectives	Wetland restoration and conservation (riparian buffers, freshwater diversion channels) Biodiversity conservation (reintroduction of native fauna, invasive species control) Water purification for ecosystem restoration (riparian buffers)
Main targeted nexus component(s)	Ecosystem services
Additional (indirect) benefits	Climate change mitigation (wetlands as carbon sinks) Soil erosion prevention (restored lagoon ecosystems) Ecological connectivity (green corridors, habitat linkages) Sustainable grazing and ecosystem balance (introduction of buffalo grazing) Integration of renewable energy for sustainable ecosystem management (solar panels, biogas units)
Indirectly targeted nexus component(s)	Ecosystem services Food/Farming Energy
Type of nexus in the DEMO	**E-(F)-E**

3.4.4 Summary of Findings of CARDIMED DEMOs for Natural Areas

The CARDIMED DEMOs implemented in natural areas offer unique insights into the challenges and opportunities of applying NBS in ecosystems where human intervention is minimal. However, from a nexus perspective, these DEMOs demonstrate limited or indirect contributions to interconnected resource systems, focusing predominantly on ecological restoration and biodiversity conservation.

DEMO 6.1, implemented in a rural-to-wilderness transition area near Alcañiz, Spain, and DEMO 8 in the Gediz Delta, Turkey, both prioritize ecosystem restoration without directly targeting nexus components. DEMO 6.1 addresses forest health by removing invasive mistletoe, restoring native vegetation, and reducing wildfire risks. DEMO 8 focuses on coastal wetland conservation through interventions like riparian buffers, freshwater diversion channels, lagoon restoration, and the integration of renewable energy solutions (solar panels and biogas units) to support monitoring, maintenance, and sustainable wetland management. While both DEMOs offer indirect contributions to ecosystem services, such as biodiversity enhancement and carbon sequestration, DEMO 8 also engages with the Energy (E) nexus by incorporating decentralized renewable energy sources to enhance the efficiency and resilience of restoration activities. For instance, DEMO 6.1 only temporarily engages with the Ecosystem-Energy (E-E) nexus if biomass is utilized for energy, while DEMO 8 indirectly supports the Food/Farming (F) component through sustainable grazing practices and directly contributes to energy self-sufficiency by generating on-site renewable energy for ecosystem monitoring and restoration efforts. Neither DEMO reintroduces treated water or resources into human-managed systems, but DEMO 8 distinguishes itself by reducing dependence on external energy sources, reinforcing its systemic nexus impact beyond ecological functions.

In contrast, DEMOs 7.1 and 7.2 in Central Alentejo, Portugal, provide a broader nexus perspective by integrating interventions across riparian ecosystems and the montado landscape. These DEMOs contribute to the Water-Energy-Food/Farming-Ecosystems (W-E-F-E) nexus through measures like agroforestry, native vegetation restoration, and riparian buffer establishment. However, the extensive scale of these DEMOs, spanning thousands of square meters, combined with the focus on ecological restoration, presents significant challenges for nexus evaluation. The ecological benefits, such as improved habitat connectivity, soil stabilization, and hydrological regulation, may take years or even decades to manifest fully. This delay complicates the assessment of nexus impacts, as measurable outcomes may rely heavily on historical baseline data and long-term monitoring efforts. Without these, evaluating the effectiveness of these DEMOs from a nexus perspective becomes speculative and highly dependent on projected benefits rather than observed results.

Moreover, the broad geographical scope of DEMO 7 raises practical concerns about capturing localized nexus interlinkages. For instance, while agroforestry practices in the montado might enhance soil health and water retention, quantifying these benefits at the scale of the entire DEMO requires robust data collection and analysis. Similarly, the hydrological improvements achieved through riparian buffers and green corridors are dispersed across large areas, making it difficult to assess their aggregated impact on the water cycle or biodiversity at a systemic level.

Ultimately, while DEMOs 7.1 and 7.2 appear to offer broader nexus integration than DEMO 6.1 and Demo 8, their scale and focus on long-term ecological processes render immediate nexus evaluations challenging. In comparison, DEMO 6.1 and DEMO 8, with their narrower scope, provide clear but limited ecosystem service benefits. These findings highlight the need for tailored evaluation frameworks that account for the unique temporal and spatial dynamics of NBS in natural areas.

4 Methodology

4.1 Development of the WEFE Nexus Framework

The development of the CARDIMED WEFE Nexus framework is essential for understanding and optimizing the impacts of the diverse NBS implemented across the project's DEMOs. It encompasses the activities related to Task 5.1.1, Task 5.1.2, Task 5.1.3, Task 5.1.4 and Task 5.2 holistically as the first focuses on the theoretical development and visualization of interactions, and the rest focus on the implementation of the framework and the actual quantification. This deliverable develops and presents the overall WEFE nexus methodology and presents the qualitative results obtained from the implementation of the first two steps of the developed methodology.

Unlike conventional WEFE Nexus models, which often focus on broad regional assessments or sector-specific interactions, CARDIMED requires a tailored approach that accounts for the unique scales, spatial contexts, and targeted nexus components of each DEMO. The project spans urban, peri-urban, rural, and wilderness areas, each presenting distinct environmental and socio-economic dynamics. The scale of interventions varies significantly, from building-level urban green facades to landscape-scale wetland restoration and agroforestry systems. Furthermore, the targeted nexus components differ across DEMOs, with some focusing on water and energy, others on food production and ecosystem services, and some primarily emphasizing ecosystem restoration with indirect nexus effects. This heterogeneity makes the application of existing nexus models impractical, as they are typically designed for more homogenous, large-scale resource systems and lack the adaptability required for localized, context-specific evaluations.

Moreover, CARDIMED presents a unique opportunity for WEFE Nexus research through its extensive monitoring campaign, which will generate high-resolution, site-specific data across multiple indicators. While many WEFE Nexus models remain largely conceptual or constrained by data limitations, CARDIMED's empirical approach enables a more robust and data-driven assessment of nexus interactions, ensuring that the framework is grounded in real-world observations rather than theoretical assumptions. The ability to integrate real-time data on water availability, energy consumption, food production, biodiversity changes, and climate resilience makes it possible to conduct a more precise and dynamic evaluation of the interlinkages, synergies, and trade-offs across different DEMOs. However, to fully leverage this extensive dataset, it is necessary to develop a methodology that can systematically capture these interactions, analyse their causal relationships, and enable the prediction of future dynamics under different scenarios.

To address these complexities while leveraging the available data, CARDIMED adopts a stepwise methodology for WEFE Nexus assessment, integrating qualitative systems thinking with quantitative causal inference techniques. This structured approach enables a comprehensive understanding of the interlinkages between nexus components, supports scenario analysis, and provides a decision-support tool for optimizing NBS deployment. The developed stepwise methodology for the CARDIMED WEFE nexus is presented in ***Figure 1***.

The first step of ***Figure 1*** involves the development of causal loop diagrams to structure and visualize the interconnections between water, energy, food, and ecosystems within each DEMO. These diagrams provide a system-level representation of feedback loops, dependencies, and potential trade-offs, incorporating expert knowledge and stakeholder insights. CLDs are widely used in systems thinking to capture the dynamic interactions within complex systems, helping to identify feedback structures that drive system behaviour (Sterman, 2000). This qualitative modelling approach is particularly useful in identifying key leverage points where interventions may have the most significant impact, while also helping to define system boundaries and contextualize external drivers such as climate change, policy constraints, and socio-economic factors that influence NBS performance. Recent studies have also explored the use of network-based methods, such as graph theory, to pinpoint critical leverage points in energy and resource management systems (Rozhkov, 2024).

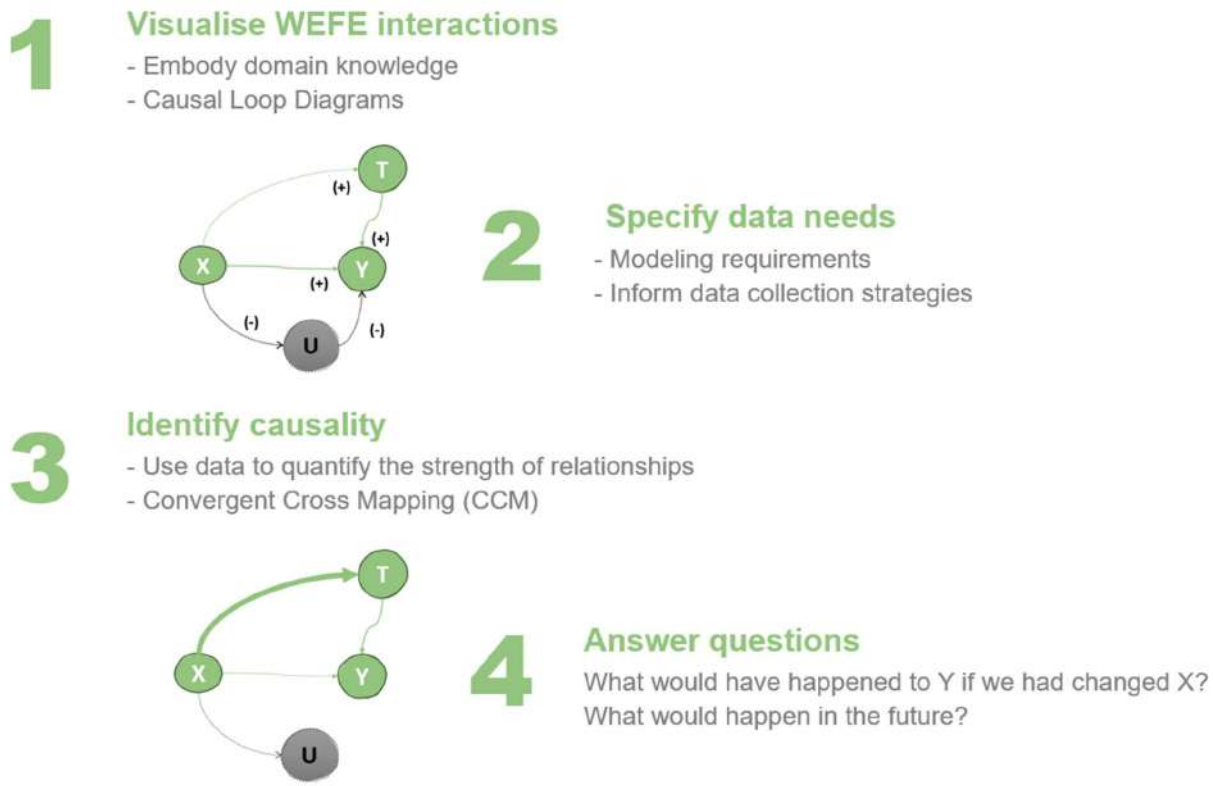

Figure 1. *Stepwise methodology of the CARDIMED WEFE nexus*

Once the qualitative relationships are established, the next step focuses on assessing data requirements (step 2 of the methodology). This involves defining the specific observational data that need to be monitored across each WEFE component and ensuring that they align with the causal loop diagram structure. The monitoring campaign provides a valuable data source, covering aspects such as water availability and quality, energy demand and production, food yield, biodiversity indicators, and climate resilience metrics. By aligning the monitored indicators with the causal loop diagram variables, this step ensures that the data collection strategy is systematic and targeted, facilitating robust quantitative analysis in later stages.

The third step of ***Figure 1*** moves beyond qualitative representation by employing Convergent Cross Mapping (CCM), a causal inference method that quantifies the strength and directionality of relationships between nexus components. This approach allows for the detection of true causal linkages by analysing empirical time-series data, distinguishing genuine dependencies from mere correlations. By applying this technique, it becomes possible to validate or refine the qualitative causal relationships identified in the previous step, providing evidence-based confirmation of how changes in one component, such as water availability, influence others, such as crop yield, energy demand, or biodiversity levels.

The final step presented in ***Figure 1*** leverages the identified causal relationships to develop predictive models that explore different intervention scenarios. These models are constructed by considering the entire network of relationships as a dynamic system, without relying on explicit mathematical formulations, and by exploiting existing data to build an equation-free framework (see also discussion in Section 4.5). In this context, as data are amassed from the implementation of the DEMOs, the approach assembles a “library” of system states – where the complete nexus is treated as the system – thereby facilitating the observation and prediction of transitions between states. In this way, by populating the library of system states, the approach enables the simulation of future system dynamics and the evaluation of how changes in policy, climate conditions, or resource availability might impact NBS performance over time.

By integrating both qualitative insights from causal loop diagrams and quantitative causality analysis through CCM, this approach provides a powerful tool for assessing potential trade-offs and optimizing NBS strategies for long-term sustainability. The ability to simulate different scenarios enhances the decision-making process by allowing for a more adaptive management of the WEFE Nexus, ensuring that interventions remain effective under changing environmental and socio-economic conditions.

It should be noted that the results of the first and second steps are presented in this deliverable while, the more quantitative results of steps three and four will be presented in deliverable D5.2.

The stepwise methodology developed in CARDIMED offers several advantages over conventional WEFE Nexus models. It allows for context-specific analysis that is adaptable to different spatial scales and environmental settings, ensuring relevance across all DEMOs. The integration of empirical data from CARDIMED's extensive monitoring infrastructure enables a data-driven validation of nexus interactions, reducing the reliance on assumptions and theoretical generalizations. By combining qualitative systems thinking with advanced causal inference techniques, this approach ensures that both expert knowledge and empirical evidence are incorporated into the assessment, enhancing the accuracy and robustness of the framework. Furthermore, the ability to simulate different intervention scenarios provides a forward-looking perspective, supporting informed decision-making and ensuring that NBS strategies are optimized for long-term resilience and sustainability.

The development of this framework represents a significant advancement in the application of the WEFE Nexus approach to NBS. By moving beyond conceptual models and integrating real-world data with predictive analytics, the CARDIMED WEFE Nexus framework establishes a new standard for evaluating the complex interdependencies between water, energy, food, and ecosystems. The stepwise methodology ensures that the analysis is both comprehensive and actionable, allowing stakeholders to assess the effectiveness of NBS interventions, anticipate potential trade-offs, and design more resilient and integrated solutions for addressing climate challenges in the Mediterranean region.

4.2 Causal Loop Diagram (CLD) Development

The causal loop diagram (CLD) approach was implemented to assess the WEFE Nexus in each DEMO. CLDs serve to identify and represent causal influences among variables, providing a visual tool that facilitates the understanding of system dynamics (Littlejohns et al., 2021). In these diagrams, the structure consists of nodes and edges, where nodes denote variables, and edges represent the causal interactions between them. The directional links indicate cause-and-effect relationships, where a change in one variable impacts another (i.e., cause → effect). Each link is assigned either a positive (+) or negative (-) sign to denote whether the cause-and-effect variables change in the same or opposite directions, respectively. A positive causal link signifies that both variables increase or decrease together, whereas a negative causal link indicates that an increase in the cause variable results in a decrease in the effect variable.

After establishing variables and their causal connections, feedback loops naturally emerge in the system. These loops are categorized as reinforcing and balancing feedback loops. A reinforcing feedback loop consists entirely of either positive or negative causal links moving in the same direction, leading to self-reinforcing effects that may amplify changes in the system. If a variable increases within a reinforcing loop, the effects propagate through the system and return to further amplify the original variable. This mechanism has the potential to drive instability in the system if unchecked. In contrast, a balancing feedback loop consists of both positive and negative causal links within a cycle. In these loops, an increase in one variable eventually results in a decrease in the original variable, promoting system stability and equilibrium. By capturing these feedback structures, CLDs provide valuable insights into systemic interactions and potential trade-offs.

CLDs are particularly well-suited for analysing the complex interactions within the WEFE Nexus (Purwanto et al., 2019; Giordano & De Stefano, 2020; Coletta et al., 2024). As previously discussed, the WEFE Nexus is inherently intricate, with numerous interdependencies and feedback mechanisms across water, energy, food, and ecosystem components. These components function as an interconnected system, where changes in one domain trigger cascading effects across others. The CLD methodology is instrumental in mapping these

interdependencies, making it possible to identify key drivers, synergies, and trade-offs within the WEFE Nexus at the level of each NBS DEMO. The ability to visualize these relationships provides a qualitative foundation for evaluating NBS interventions, particularly in assessing their contributions to climate resilience by improving water availability, energy efficiency, food security, and ecosystem services.

To construct the CLDs, a stepwise participatory approach was adopted within Task 5.1.1 of the CARDIMED project. Unlike previous studies that employed group model building (GMB) to develop CLDs through direct stakeholder workshops, the CARDIMED project followed an expert-driven participatory methodology. The process began with Imperial College London (ICL) conducting a preliminary identification of relevant variables and their causal interconnections for each of the 17 DEMOs. This initial framework was built using all available documentation, descriptions of the DEMOs, and existing knowledge on NBS functionalities. The preliminary CLDs were then shared with the other WP5 participants (CET, CREAF, and ALEA), who reviewed and refined the variables and linkages based on their expertise in specific WEFE components. The revised CLDs were subsequently submitted to the DEMO leaders, who provided final validation and further refinements based on their contextual knowledge of each demonstration site.

The outcome of this iterative process was the development of tailored CLDs for each of the 17 DEMOs across the 9 demonstration sites. The final CLDs capture both internal (endogenous) and external (exogenous) factors, ensuring a comprehensive representation of the dynamics shaping each NBS DEMO. Endogenous variables include site-specific elements directly influenced by the implemented NBS, such as water retention capacity, vegetation cover, nutrient cycling, and energy requirements. These variables interact within the system and define the direct impacts of NBS interventions on the WEFE nexus components. In contrast, exogenous variables, such as climatic conditions (e.g., temperature, rainfall patterns), regulatory frameworks, and socio-economic drivers, represent external influences that shape the boundary conditions of the system but cannot be directly controlled by the implemented solutions.

Considering both endogenous and exogenous factors is essential for accurately depicting the complex interdependencies within each DEMO. Endogenous interactions define how the NBS functions within the site, while exogenous influences determine the system sensitivity to broader environmental and policy changes. For example, the ability of a riparian buffer to regulate water quality and enhance biodiversity depends not only on its internal characteristics (e.g., plant species composition, soil permeability) but also on external pressures such as seasonal droughts, upstream pollution loads, and land-use policies. Similarly, urban green infrastructures designed to reduce heat stress must account for external climatic variables that dictate their cooling effectiveness under different temperature scenarios.

By systematically integrating both levels of influence, the developed CLDs provide a realistic, site-specific understanding of how NBS interventions function within their broader environmental and regulatory contexts. These CLDs are presented in this deliverable, forming the qualitative basis for subsequent causal analysis using CCM. By incorporating expert knowledge with local insights, the CLD development process ensures that the WEFE interactions are represented as accurately and comprehensively as possible, providing a robust foundation for scenario exploration and predictive analysis.

The developed CLDs also serve as a visualization tool, making it easier to identify the key interactions and feedback loops that drive system behaviour. This is particularly relevant for understanding how different WEFE components interact within specific NBS interventions. This process is illustrated in ***Figure 2***, which presents a stepwise approach for developing the CLDs across all CARDIMED DEMOs. The figure highlights key system variables such as crop water requirements, irrigation water availability, and energy consumption for water use, showcasing the integration of water, energy, food, and ecosystem components into a single causal structure. While DEMO 1.2(a) in Mykonos is used as an example, the methodology applies universally across all DEMOs, following a structured representation of interdependencies that facilitates the next stage of causal inference analysis. The results of this step and the CLDs developed for each CARDIMED DEMO are presented in Section 5 of this deliverable.

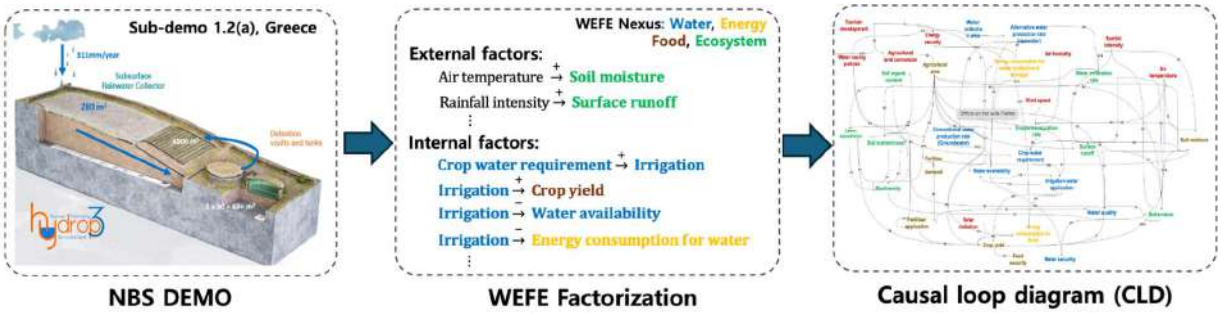

Figure 2. *Causal loop diagram application into CARDIMED DEMOs for WEFE Nexus assessment, using DEMO 1.2A as an example.*

4.3 Data Needs Specification

A crucial aspect of developing the WEFE Nexus framework is ensuring that the data used for modelling, causal analysis, and scenario exploration is comprehensive, and tailored to the diverse NBS implemented in the CARDIMED project. The specification of data needs must align with the multi-scale and multi-sectoral approach required to assess interactions between water, energy, food, and ecosystem components across 17 DEMOs spanning urban, peri-urban, and rural contexts. The methodology follows a structured process to ensure that the collected data supports the qualitative and quantitative assessments required in subsequent steps, such as CLD development and CCM.

Building on the structured monitoring approach established in Deliverable D2.2, the project benefits from a comprehensive monitoring plan that prescribes data collection processes across all the relevant WEFE sectors. Each DEMO has a detailed monitoring plan, listing observational data and key performance indicators (KPIs) relevant to water availability, energy use, food production, biodiversity, and ecosystem health. These KPIs were selected through an iterative process, ensuring that both systemic interlinkages and site-specific considerations are captured. Data collection is tailored to each NBS to ensure that the assessment of synergies and trade-offs within the WEFE Nexus remains as accurate and context specific as possible. Additionally, Deliverable D2.2 outlines the methodologies employed to gather such data, detailing aspects such as sampling frequency, instrumentation, and stakeholder involvement. By leveraging both existing datasets and direct measurements, the project ensures that the selected indicators can be used to quantify interactions within the Nexus and support scenario modelling efforts. These indicators span diverse categories, including hydrological parameters (rainwater harvesting efficiency, infiltration rates), energy-related indicators (renewable energy production, energy use for irrigation), food system dynamics (crop yields, fertilizer use), and ecosystem services (biodiversity enhancement, carbon sequestration). This ensures that both direct impacts of NBS implementation and indirect systemic effects are captured.

A critical challenge in defining data needs is accounting for temporal and spatial heterogeneity. Given the variability in climatic conditions, land use, and policy environments across the Mediterranean region, it is essential to consider how data can be harmonized to allow for meaningful cross-comparisons. The inclusion of both exogenous (external) and endogenous (internal) variables is fundamental to achieving a holistic assessment. Exogenous factors such as climate variability, regulatory frameworks, and socio-economic conditions influence NBS performance but are often beyond the direct control of stakeholders. Endogenous variables, on the other hand, include direct interventions within the NBS, such as water reuse efficiency, local energy generation, and soil health improvements. The ability to distinguish between endogenous and exogenous drivers enables a more nuanced interpretation of causality in the WEFE Nexus and enhances the predictive capacity of the framework.

The data needs specification process serves as the foundation for subsequent analysis steps. The integration of CLDs with monitored data will allow for identifying key leverage points in each DEMO, ensuring that decision-makers can effectively design interventions that enhance sustainability and resilience. Furthermore, the extensive monitoring campaign established within CARDIMED provides an opportunity to apply advanced

causal inference techniques, such as CCM, to quantify the strength and directionality of interactions within the WEFE Nexus. The methodological approach for data specification also aligns with the broader objectives of WP2 and WP4, which focus on refining project specifications, consolidating requirements, and ensuring data interoperability across different assessment frameworks. By leveraging these established monitoring frameworks, the WEFE Nexus framework is designed to be adaptive, evidence-based, and capable of informing policy and decision-making for nature-based solutions in diverse Mediterranean contexts.

The selection of variables and factors in the CLDs aligns with the data collection strategies and monitoring frameworks detailed in Deliverable D4.1 and the validation approaches outlined in Deliverable D2.2. These deliverables define the available data sources for assessing the performance of each NBS intervention across the demonstration sites. This deliverable (D5.1) does not repeat the detailed data requirements but instead focuses on linking the qualitative relationships identified in the CLDs with the quantitative datasets outlined in D4.1 and D2.2. The process ensures that key CLD variables correspond to measurable indicators, highlights any missing data required for a complete system analysis, and prepares for the next methodological step: quantifying causal relationships using CCM. This structured approach translates the qualitative understanding developed through CLDs into a robust, data-driven assessment of WEFE Nexus interactions in subsequent analyses.

4.4 Identification of causality

Assessing the causality within the WEFE Nexus is a fundamental step in understanding how different components interact dynamically over time. In complex, non-linear systems such as those involving NBS implementations, traditional correlation-based methods are insufficient to establish causal relationships because variables may exhibit shifting dependencies, delayed effects, or even misleading correlations. As outlined by Ye et al. (2015), the co-occurrence of events should not imply that they are causally related, and vice versa; the lack of correlation should not translate in absence of causality. Nonetheless, traditional correlation-based approaches are commonly used to suggest causality.

The CCM method overcomes these limitations by providing a statistical approach to infer causality from time series data (Sugihara et al., 2012). CCM enables us to determine whether one variable contains predictive information about another, thereby establishing causal linkages that are not always apparent through correlation analysis alone.

Unlike correlation, which measures the strength of association between two variables but does not establish directionality or underlying mechanisms, CCM relies on the principles of dynamical systems theory and state-space reconstruction (Deyle & Sugihara, 2011). According to Takens' theorem (Takens, 1981), in a dynamic system where multiple variables are interdependent, the past values of one variable inherently encode information about others, even if their interactions are not directly observable. This means that if variable X is causally influencing variable Y, we should be able to reconstruct the behaviour of X using time-lagged observations of Y. The strength of this reconstruction improves as more data are incorporated, which is the key principle of convergence in CCM.

The application of CCM within the CARDIMED project follows a structured process. First, expert-driven CLDs were developed to map qualitative relationships between variables within each NBS DEMO. These relationships were then quantitatively tested using monitored data, ensuring that inferred causalities align with real-world observations. The methodological process follows three key steps (Ye et al., 2015): (i) embedding time series data into a reconstructed state space, (ii) quantifying the ability of one variable to predict another, and (iii) assessing convergence over extended time horizons to confirm causality. By comparing the predictive power of different variables, CCM allows us to distinguish true causal influences from indirect or deceptive associations.

The advantages of CCM are particularly relevant for assessing NBS-driven interventions. Many WEFE interactions exhibit nonlinear and time-dependent behaviours, where short-term correlations may not accurately reflect long-term causal effects. For instance, urban heat island (UHI) mitigation through increased vegetation cover may not immediately lower temperatures but could exhibit delayed or seasonal impacts due

to changes in evapotranspiration and shading effects. Similarly, agricultural water demand may be causally influenced by precipitation patterns and soil moisture levels, but these relationships may only become apparent when analysed over extended time scales. Moreover, CCM enables us to uncover hidden dependencies within the WEFE system, ensuring that critical feedback loops – such as the interplay between water availability, energy consumption, and ecosystem resilience – are captured with high accuracy.

A notable limitation of CCMs is that it struggles with bidirectional causality or with strong unidirectional causality that leads to synchrony (i.e., a phenomenon where two or more variables become synchronized due to strong coupling or dynamic resonance; this emerges when the dynamics of a response variable become dominated by those of a driving variable making their behaviours indistinguishable). In our case, we will use the extension of CCMs as introduced by Ye et al. (2015), who, by explicitly considering different lags for cross mapping, managed to determine whether a driving variable acts with some time delay on a response variable.

By applying CCM systematically across the 17 DEMOs, the CARDIMED project enhances its capacity to evaluate synergies and trade-offs, guiding decision-making on the most effective nature-based solutions for climate resilience.

The methodological process and conceptual framework are illustrated in ***Figure 3***, which outlines how expert beliefs (captured in CLDs) are validated and refined using CCM, ultimately leading to a data-driven causal network. This approach ensures that the interactions identified within the WEFE Nexus framework are not only theoretically plausible but also empirically verified, forming the basis for scenario analysis and predictive modelling in subsequent methodological steps.

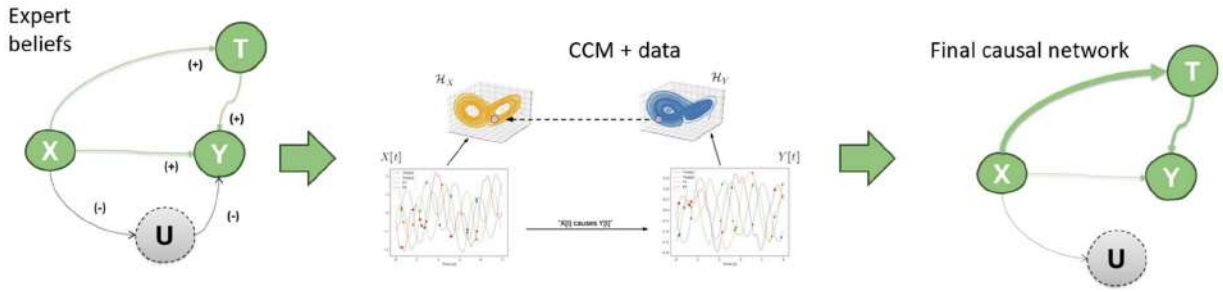

Figure 3. *Process of Identifying Causal Relationships Using Convergent Cross Mapping (CCM)*

4.5 System Behaviour Prediction

The predictive capacity of the WEFE Nexus framework relies on the integration of key indicators across water, energy, food, and ecosystem components, combined with causal discovery methods such as CCM. Nonetheless, diverse future scenarios – including seasonal variations, extreme weather events, and long-term climate change effects – should be explored to assess how NBS dynamically interact with the WEFE Nexus under evolving conditions.

A core component of this predictive approach involves the use of Empirical Dynamic Models (EDMs) as a merely data-driven and non-parametric approach to understanding the complex, nonlinear interactions within the WEFE Nexus. Causal discovery techniques, particularly CCM, complement EDMs by retrospectively identifying and quantifying causal relationships among WEFE indicators. Once these causal dependencies are established, they provide a critical basis for forward-looking simulations, ensuring that system projections account for the most influential interactions.

EDMs are equation-free methods that leverage time-series data to uncover causal relationships (Chang et al., 2017), allowing for dynamic forecasting and scenario analysis of dynamic systems. Unlike traditional models that rely on predefined equations, EDMs reconstruct system dynamics directly from observed data, making them particularly effective for nonlinear, high-dimensional, and non-equilibrium systems such as the WEFE

nexus (Sugihara et al., 2012). In simple terms, instead of relying on fixed equations, EDMs reconstruct how a system evolves over time using patterns found directly in observed data. This is done through state-space reconstruction, which allows us to capture the hidden structure of a system without making assumptions about how its parts interact. One key technique in EDMs is called time-delay embedding, where past values of a system are used to predict its future state. This works by treating different points in time as separate dimensions, creating a multi-dimensional "map" that represents how the system behaves. By analysing this map, EDMs can identify how different variables influence each other and even predict future changes (Clark et al., 2015). Finally, EDMs include adaptive forecasting methods, such as Simplex Projection and S-map models (Cenci & Saavedra, 2019), which adjust their predictions based on how relationships between variables change over time.

EDMs are great at dealing with nonlinear and unpredictable changes (Deyle & Sugihara, 2011). In the context of CARDIMED, water, energy, food, and ecosystems will not follow simple, fixed rules – rainfall patterns shift, crop yields vary, and ecosystems adapt over time. Traditional system dynamics models often assume steady relationships, but EDMs allow us to see how these interactions change dynamically and adapt their predictions accordingly. Another advantage is that EDMs do not require an a priori formulation of the equations that define the system. But these processes are often too complex to be captured by a simple set of equations. EDMs, on the other hand, learn directly from real-world data, letting the system reveal its own patterns without forcing it into a predefined framework. Finally, EDMs work well with real-world data, even if it does require careful considerations when handling missingness or noise (Munch et al., 2020). Information about water, energy, food, and ecosystems often comes from different sources, is collected at different times, and sometimes has missing or noisy values. EDMs can handle imperfect data, making them practical for analysing real environmental systems.

EDMs require adequate historical data to generate reliable predictions, making them most effective in systems with well-documented time-series records. The sufficiency of data depends on the underlying system dynamics and cannot be predefined prior to analysis. As additional data are collected, the reconstructed state-space of the WEFE Nexus is continuously refined, enhancing model reliability and improving the accuracy of inferred system interactions over time. For these data-related challenges, the reader is advised to refer to Section 7.

Ultimately, by incorporating scenario-based predictive modelling rationale (stepping on EDMs), the CARDIMED WEFE Nexus framework provides valuable insights for stakeholders, guiding the design, installation, and operation of NBS to enhance climate resilience. The ability to anticipate how NBS solutions will perform under varying conditions ensures that decision-making processes are informed by data-driven projections rather than reactive measures. This predictive capability ultimately strengthens the long-term sustainability and effectiveness of NBS implementations across different spatial contexts, from urban environments to remote wilderness areas.

5 CARDIMED WEFE Nexus Framework Results

This section presents the results of this deliverable, summarizing the factors co-selected for the CARDIMED DEMOs, their interactions as visualized through CLDs, the required data along with their sources, and the preliminary scenario development for each DEMO. The selection of factors was carried out in collaboration with DEMO leaders, ensuring their relevance to the specific challenges and objectives of each demonstration case.

Table 18-

Table 22 presents the endogenous ecosystem-related factors identified within the CARDIMED DEMOs, highlighting their applicability across different demonstration sites. These factors include vegetation cover, soil and water interactions, biodiversity, climate regulation, pollution control, and carbon sequestration. They reflect both ecosystem services, which provide benefits such as improved air quality, flood control, and biodiversity conservation, and ecosystem disservices, such as soil erosion, invasive species proliferation, and pollution.

The integration of these factors within DEMOs allows for a better understanding of how NBS, land management, and ecosystem restoration contribute to the WEFE nexus. The DEMOs addressing ecosystem factors are grouped into the following categories:

- **DEMOs Managing Vegetation Cover and Green Infrastructure**: DEMOs 2, 3, 4.1, 4.2, 5.1, 5.2, 6.2, 7.2, and 9.2 integrate green spaces, permeable surfaces, or vegetated areas; DEMOs 4.2 and 9.3 implement green facades; and DEMOs 3 and 7.1 maintain riparian buffer zones.
- **DEMOs Impacting the Natural Water Cycle**: DEMOs 1.1, 1.2a, 1.2b, 1.3, 2, 3, 4.1, 4.2, 5.1, 5.2, 6.2, 7.1, 7.2, 8 and 9.2 directly affect the natural water cycle; and DEMOs 1.3, and 4.2 aim to mitigate flood risk.
- **DEMOs Impacting Soil**: DEMOs 1.1, 1.2a, 1.2b, 2, 7.1, and 7.2 address soil related functions.
- **DEMOs for Biodiversity Conservation and Restoration**: DEMOs 6.1, 7.1, 7.2, and 8 aim to restore native vegetation and control invasive alien species; and DEMOs 1.1, 1.2a, 1.2b, 1.3, 2, 3, 4.1, 4.2, 5.1, 5.2, 6.1, 7.1, 7.2, 8, 9.1, 9.2, and 9.3 aim to enhance urban and natural biodiversity.
- **DEMOs for Microclimate and Thermal Regulation**: DEMOs 4.2, 5.1, 5.2, 7.1, and 9.3 implement measures that can potentially moderate local temperatures, improve air circulation, and enhance thermal comfort in the surrounding buildings.
- **DEMOs for Climate Mitigation and Pollution Control**: DEMOs 1.1, 1.2a, 1.2b, 2, 4.2, 5.1, 5.2, 6.1, 7.1, 7.2, 8, 9.1, 9.2, and 9.3 implement measures that can potentially enhance carbon sequestration, monitor and mitigate water and soil pollution, track GHG emissions, and assess air quality, contributing to climate change mitigation and improved environmental conditions.

For DEMOs integrating green infrastructure, biodiversity conservation, and pollution control, the end node of ecosystem-related factors is the net balance between ecosystem services and disservices. Positive contributions occur in DEMOs that increase green spaces, improve water infiltration, enhance biodiversity, and reduce pollution, leading to climate resilience, habitat conservation, and improved urban sustainability. Negative contributions occur in DEMOs where soil erosion, pollution, or habitat degradation reduce ecosystem health, leading to biodiversity loss, decreased air and water quality, and increased climate vulnerability.

Table 22 provide a structured summary of the key factors used across the DEMOs, including their definitions, their role within the WEFE nexus, and their relevance in different DEMOs. These tables also indicate the specific DEMOs in which each factor is considered, allowing for a comparative understanding of their application across various contexts.

The sections that follow present the results for each DEMO, detailing the selected factors, the CLDs capturing their interactions, the associated data needs, and the preliminary scenario development. These results are structured according to the application areas of the DEMOs, categorized as urban, peri-urban, rural, and remote or wilderness areas. This classification allows for a clearer understanding of how different settings influence the dynamics of the WEFE nexus and the applicability of specific interventions.

Table 18 presents the **exogenous factors** identified as relevant to the CARDIMED DEMOs and highlights their applicability across different demonstration sites. Exogenous factors are external drivers that influence the DEMOs but are not directly controlled within the system. These factors shape environmental conditions, regulatory contexts, resource availability, and socio-economic conditions that impact the performance and design of the DEMOs.

It should be noted that exogenous factors related to energy and water are case-specific, as some DEMOs are externally influenced by these factors, while in other DEMOs, these factors may become endogenous. For instance, in DEMOs where energy is solely supplied from external grids, energy security and prices remain exogenous. However, in DEMOs implementing local renewable energy production or decentralized water treatment and reuse, these factors become part of the internal system dynamics, influencing feedback loops and decision-making processes rather than merely acting as external constraints.

Climatic Factors

Climatic variables such as air temperature, air humidity, rainfall intensity, solar radiation, and wind speed are widely applicable across most DEMOs. These factors play a crucial role in shaping environmental conditions, influencing water availability, energy demand, and ecosystem interactions. Rainfall intensity, in particular, is relevant across all DEMOs, as it directly impacts water resource management, flooding potential, and agricultural productivity. Other climatic factors, such as solar radiation and wind speed, are particularly significant for DEMOs integrating renewable energy solutions.

Policy-Related Factors

Policy drivers, including water-saving policies, water quality standards, and water reuse regulations, are relevant for multiple DEMOs, particularly those focusing on sustainable water management and circular economy approaches. Tourism development and agricultural land conversion are factors affecting specific DEMOs where land-use changes are prominent. Additionally, biodiversity and habitat conservation laws are key considerations for DEMOs addressing ecosystem restoration and conservation, while stormwater management regulations influence flood control and runoff treatment solutions.

Demographic Factors

Demographic elements, including population fluctuations, number of inhabitants, and number of students, influence water demand, wastewater generation, and overall resource consumption patterns. These factors are critical in DEMOs involving urban or peri-urban settlements, where population density and seasonal variations significantly impact system performance.

Land Cover

Upstream impervious surface area is an essential consideration for DEMOs dealing with urban runoff, stormwater management, and flood risk reduction. The extent of impermeable surfaces upstream influences the volume of water entering each DEMO, shaping infrastructure design and water retention strategies.

External Water Inputs (Natural and Human-Managed)

Several DEMOs receive wastewater, groundwater, and surface runoff as external inputs, requiring specific treatment measures. Wastewater generation and quality impact DEMOs focused on water reuse and treatment efficiency. Groundwater quality is a crucial factor for DEMOs relying on groundwater abstraction, determining treatment needs before use. Additionally, agricultural and industrial water demand are critical in DEMOs that integrate irrigation and production activities. The management of surface runoff is relevant in multiple DEMOs, with specific attention given to its generation, capture by existing sewer systems, treatment, and direct discharge without treatment.

In DEMOs where water is primarily externally supplied (e.g., from municipal sources, centralized wastewater treatment plants, or regional reservoirs), it remains an exogenous factor. However, in DEMOs integrating decentralized water treatment, storage, or reuse systems, water availability and quality become endogenous as they are actively managed within the system.

External Energy Factors

Energy security and energy prices are external factors influencing DEMOs reliant on stable and affordable energy access. DEMOs integrating energy-intensive processes, renewable energy systems, or industrial activities must account for potential energy price fluctuations and supply reliability. However, as mentioned earlier, in DEMOs implementing on-site renewable energy production, energy supply shifts from being exogenous to endogenous, as local generation and storage systems influence energy availability within the DEMO.

Table 18. *Exogenous factors and their applicability to CARDIMED's DEMOs*

Factor		Description	DEMO 1.1	DEMO 1.2a	DEMO 1.2b	DEMO 1.3	DEMO 2	DEMO 3	DEMO 4.1	DEMO 4.2	DEMO 5.1	DEMO 5.2	DEMO 6.1	DEMO 6.2	DEMO 7.1	DEMO 7.2	DEMO 8	DEMO 9.1	DEMO 9.2	DEMO 9.3
Climatic	Air temperature	The measure of how hot or cold the air is, typically measured in degrees Celsius (°C). It influences weather patterns, plant growth, human comfort, and energy demand.	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Air humidity	The amount of water vapor present in the air. It is commonly expressed as relative humidity (%) and affects weather conditions, human comfort, and evaporation rates.	✓	✓	✓	✓		✓		✓	✓	✓		✓		✓	✓	✓	✓	✓
	Rainfall intensity	The rate at which rain falls over a given period, usually measured in millimetres per hour (mm/h). It is important for flood prediction, water resource management, and agriculture.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Solar radiation	The energy emitted by the sun that reaches	✓	✓	✓	✓		✓		✓	✓	✓		✓		✓	✓	✓	✓	✓

		the Earth's surface, measured in watts per square meter (W/m^2). It affects climate, weather patterns, and energy production (e.g. solar panels).																	
	Wind speed	The rate at which air moves across the Earth's surface, typically measured in meters per second (m/s) or kilometres per hour (km/h). It influences weather patterns, air quality, and renewable energy generation (wind power).	✓	✓	✓	✓		✓		✓	✓	✓		✓		✓	✓	✓	✓	✓
Policy-related	Water saving policies	Strategies, regulations, and initiatives implemented by governments, organizations, or communities to reduce water consumption, promote efficient water use, reuse water, and conserve water resources. These policies aim to address water scarcity, improve water management, and ensure the sustainable use of	✓	✓	✓		✓	✓										✓		✓

		water for current and future needs																	
	Water quality standards and water reuse regulations	Regulatory benchmarks ensuring safe water use, particularly for reuse, by defining physical, chemical, and biological quality standards.	✓				✓	✓		✓							✓		✓	
	Tourism development	Expansion of tourism-related infrastructure and services to attract visitors and boost local economies.		✓	✓															
	Agricultural land conversion	Transformation of farmland for other uses like urban expansion, industrial development, or reforestation.		✓																
	ESG compliance and alignment with relevant standards	Integration of environmental, social, and governance (ESG) principles into business operations to enhance sustainability.					✓													
	Biodiversity and habitat conservation laws	Legal measures to protect ecosystems, species diversity, and natural habitats.										✓	✓	✓	✓	✓				
	Local development	Strategies promoting economic growth,										✓								

	& economic enhancement	improved infrastructure, and balanced social-environmental development.																	
	Stormwater management regulations	Policies regulating runoff and infiltration to mitigate flooding and enhance water resource management, influencing the design of solutions.						✓		✓	✓		✓						
Demographic	Population fluctuations	Changes in population size due to migration, tourism, or urbanization, impacting resource demand and waste generation.	✓					✓											
	Number of inhabitants	Total residents in the area, influencing water and energy consumption.			✓														
	Number of students	Primary users of school facilities, affecting water demand and wastewater generation.							✓										
Land cover	Upstream Impervious surface area	Total non-porous area upstream the specific DEMO, reducing water infiltration and increasing runoff entering the DEMO.			✓		✓		✓		✓	✓							

External water (nature and human managed)	Wastewater generated	Volume of wastewater produced in a given area and timeframe, treated or untreated. The DEMO receives it as external input.	✓					✓									✓			
	Quality of Wastewater generated	Physical, chemical, and biological properties determining treatment and discharge requirements.	✓					✓									✓			
	Groundwater quality	Levels of salinity, nitrates, and hardness, influencing water treatment needs.																✓		
	Agricultural water demand	Water required for irrigation and farming activities.				✓									✓	✓				
	Industrial water demand	Total water needed for industrial operations.					✓													
	Volume of surface runoff generated	Water from precipitation that flows over impervious surfaces without infiltrating, entering the DEMO as external input.							✓		✓	✓								
	Volume of surface runoff captured by existing sewer system (combined or separated)	Runoff released into the environment without pollution control, affecting ecosystems.							✓		✓	✓								

	Volume of surface runoff discharged without treatment	Runoff released into the environment without pollution control, affecting ecosystems.							✓		✓	✓							
	Volume of surface runoff treated	Runoff processed to remove contaminants for safe discharge or reuse.							✓		✓	✓							
External energy	Energy security	The availability of a reliable, affordable, and sustainable energy supply, minimizing risks from supply disruptions and geopolitical dependencies.		✓	✓		✓			✓	✓	✓		✓				✓	✓	✓
	Energy prices	The cost of energy, influenced by supply and demand, geopolitical factors, market regulations, and production costs, impacting consumers and industries.								✓										✓

Table 19 presents the **endogenous water-related factors** identified within the CARDIMED DEMOs, highlighting their applicability across different demonstration sites. Endogenous factors are those that are actively managed within the system, influenced by internal processes, and subject to decision-making within each DEMO. These factors include water availability, wastewater generation and treatment, rainwater and stormwater management, irrigation needs, and water security, among others. Their inclusion in the analysis helps define the internal water dynamics of each DEMO and their role within the WEFE nexus.

It is important to note that the water-related factors summarized in this table focus on the human-managed water system, meaning they refer to water that is collected, treated, reused, or allocated for specific uses such as irrigation, domestic consumption, or industrial processes. In contrast, water factors related to the nature-managed system – such as precipitation infiltration, groundwater recharge, and river ecosystem functioning – are included in the ecosystem component of the nexus rather than in this table. This distinction ensures a clear differentiation between engineered water interventions and natural hydrological processes influencing the DEMOs.

Additionally, it should be noted that exogenous factors related to energy and water are case-specific, as some DEMOs are externally influenced by these factors, while in other DEMOs, these factors may become endogenous. For instance, in DEMOs where water is passively received from external sources, it remains exogenous. However, in DEMOs that actively manage water treatment, reuse, and irrigation within the system, water becomes an endogenous factor, directly affecting system feedback loops and decision-making processes.

Several DEMOs incorporate water as a key component, engaging in water treatment, alternative water production, irrigation, and water reuse. These include:

- **DEMOs with wastewater and greywater management**: DEMOs 2, 4.1, 5.1, 6.1, 7.1, 8, and 9.3 actively manage wastewater generation, treatment, and discharge, addressing water reuse potential and treatment efficiencies.
- **DEMOs incorporating rainwater and surface runoff management**: DEMOs 1.2a, 1.2b, 2, 3, 4.2, 5.1, 5.2, 6.1, 7.1, 9.1, and 9.3 focus on capturing, treating, or utilizing rainwater and stormwater for various purposes, contributing to sustainable water use and reducing runoff impacts.
- **DEMOs managing irrigation needs and water demand**: DEMOs 1.1, 1.2a, 1.2b, 3, 4.1, 5.1, 5.2, 6.1, 7.1, 8, 9.1, 9.2, and 9.3 include factors such as crop and vegetation water requirements, irrigation demand, and ecosystem water provision, linking water availability with agricultural and environmental sustainability.
- **DEMOs affecting water security**: All DEMOs incorporating water-related factors contribute to water security (DEMOs 1.1, 1.2a, 1.2b, 2, 3, 4.1, 6.1, 7.1, 7.2, 8, and 9.3), making it a key outcome variable that integrates the effects of water use, efficiency, and management across the system.

Water security serves as the end node for all water-related factors, meaning that every DEMO that integrates the water component of the nexus ultimately contributes – positively or negatively – to its internal water security. Water security reflects the sustainable access to adequate water for human, economic, and environmental needs, encompassing both quantity and quality considerations. Positive contributions to water security occur when an DEMO enhances water efficiency, increases alternative water sources, reduces losses, and improves treatment and reuse processes. For instance, DEMOs that incorporate rainwater harvesting, wastewater reuse, or efficient irrigation strengthen local water security by reducing reliance on conventional sources and minimizing external dependencies. Negative contributions to water security arise when an DEMO increases water demand, depletes resources, discharges untreated wastewater, or reduces water quality. DEMOs with high water consumption and inadequate treatment systems may exacerbate water scarcity, pollute receiving water bodies, or introduce inefficiencies in the water cycle, ultimately diminishing water security.

Table 19. *Endogenous water-related factors and their applicability to CARDIMED's DEMOs*

Factor	Description	DEMO 1.1	DEMO 1.2a	DEMO 1.2b	DEMO 1.3	DEMO 2	DEMO 3	DEMO 4.1	DEMO 4.2	DEMO 5.1	DEMO 5.2	DEMO 6.1	DEMO 6.2	DEMO 7.1	DEMO 7.2	DEMO 8	DEMO 9.1	DEMO 9.2	DEMO 9.3
Volume of wastewater generated internally	Total wastewater produced within a system or facility.					✓			✓										
Volume of greywater generated internally	Amount of lightly used wastewater from sinks, showers, and washing machines.								✓										
Volume of wastewater to be treated (based on treatment capacity)	Quantity of wastewater directed for treatment, depending on system capacity.	✓				✓	✓												
Volume of rainwater to be captured	Amount of rainwater collected for storage and reuse.					✓												✓	
Volume of surface runoff captured by the implemented solution	Runoff intercepted and managed by implemented infrastructure.					✓	✓	✓		✓	✓								
Volume of groundwater to be treated	Quantity of extracted groundwater requiring treatment before use.																✓		
Alternative water production rate (wastewater, greywater, rainwater, stormwater)	Rate of alternative water sources generated within the system.	✓	✓	✓		✓	✓		✓				✓			✓		✓	
Quality of wastewater / greywater generated	Physical, chemical, and biological characteristics	✓				✓	✓		✓										

	affecting treatment and reuse potential.																	
Wastewater / Greywater / Water treatment efficiency	Effectiveness of treatment processes in removing contaminants.	✓				✓	✓		✓									✓
Rainwater collection area	Surface area designated for rainwater harvesting.		✓	✓		✓							✓					
Quality of rainwater harvested	Purity and pollutant levels in collected rainwater.					✓							✓					
Rainwater treatment efficiency	Effectiveness of processes in improving harvested rainwater quality.					✓												
Stormwater collection area / Surface runoff collection area	Designated space for capturing stormwater and runoff.			✓		✓	✓											
Quality (incl. pollutant load) of surface runoff collected	Contaminant levels in captured runoff affecting treatment needs.					✓	✓	✓		✓	✓							
Surface runoff treatment efficiency	Performance of systems in improving runoff quality before reuse or discharge.					✓	✓											
Water quality of (alternative) water source (treated wastewater / greywater, rainwater, stormwater, water in ponds, streams, groundwater)	Condition of treated wastewater, rainwater, stormwater, or natural water sources.	✓	✓	✓	✓	✓	✓		✓					✓		✓	✓	✓	

(Internal) Water Availability	Usable (accepted quality) water volume within the system for various needs.	✓	✓	✓	✓	✓	✓		✓				✓	✓	✓	✓	✓	✓	
Crop / vegetation water requirement	Water needed for plant growth.	✓	✓	✓			✓						✓		✓			✓	✓
Water demand for irrigation (agricultural area, green areas, green façade)	Volume required to irrigate specific landscapes, considering irrigation losses, etc.	✓	✓	✓			✓	✓	✓	✓	✓		✓		✓		✓	✓	✓
Water demand for energy production	Water used in power generation processes.	✓					✓												
Water demand for industrial production	Total water needed for manufacturing and industrial processes.					✓													
Water demand for domestic potable water	Safe drinking water requirements for households.			✓					✓										
Water demand for domestic non-potable water	Water used for non-drinking purposes like flushing and cleaning.			✓															
Volume of conventional water sources to meet the demand	Water drawn from traditional sources such as rivers, lakes, groundwater or municipal supply.	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓				✓	✓	✓
Volume of alternative water sources to meet the demand	Water obtained from non-traditional sources like treated wastewater and rainwater.	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓					✓	
Wastewater discharged	Volume of treated or untreated wastewater released into the environment.	✓				✓	✓												
Ecosystem water provision (aquifer	Water allocated to maintain natural			✓	✓		✓	✓		✓	✓			✓		✓		✓	

recharge, water in ponds, in river)	ecosystems and groundwater recharge.																		
Water security	Assurance of sustainable access to adequate water for human, economic, and environmental needs.	✓	✓	✓	✓	✓	✓		✓				✓	✓		✓	✓	✓	

Table 20 presents the **endogenous energy-related factors** identified within the CARDIMED DEMOs, highlighting their applicability across different demonstration sites. These factors include biogas and bio-based energy production, renewable energy generation, energy use in water management, energy consumption in agriculture and green spaces, energy efficiency measures, and overall system energy demand and self-sufficiency. Their inclusion in the analysis allows for an assessment of how each DEMO integrates energy production, consumption, and efficiency measures within its operation.

Several DEMOs actively manage energy production and consumption, contributing to the energy component of the WEFE nexus by either generating their own energy, improving energy efficiency, or optimizing energy use in key processes. Other DEMOs do not manage energy internally but instead rely on external energy sources, meaning energy remains an exogenous factor for them.

- **DEMOs Generating Energy**: DEMO 1.1 and DEMO 3 incorporate biogas production and solar energy generation, respectively. DEMO 1.1 produces biogas and bio-based energy from organic waste, while DEMO 3 integrates renewable energy production, primarily through solar power. These DEMOs contribute to energy self-sufficiency by reducing reliance on external energy sources.
- **DEMOs Consuming Energy for Water Treatment**: DEMOs 1.1, 2, 3, 4.1 (saves energy for water treatment), 4.2, 9.1 and 9.3 require energy for wastewater treatment and water management processes, including filtration, purification, water collection, storage, and distribution. These DEMOs highlight the water-energy nexus, where energy demand is directly linked to water treatment and supply operations.
- **DEMOs Consuming Energy for Agriculture**: DEMOs 1.1, 1.2a, 1.2b, and 3 use energy for irrigation, agricultural machinery, and crop-related activities. The energy demand in these DEMOs is associated with pumping water, operating irrigation systems, and mechanized farming processes.
- **DEMOs Consuming Energy for Green Spaces**: DEMOs 4.2, 9.1, and 9.2 require energy for the maintenance of parks, gardens, and green façades. These DEMOs focus on urban sustainability and green infrastructure, where energy is used for irrigation, lighting, and the operation of green space management systems.
- **DEMOs Impacting Thermal Regulation**: DEMOs 4.2, 5.1, 5.2, 6.2, and 9.3 incorporate factors such as building surface temperature, heating and cooling degree days, energy savings from thermal regulation, and net energy savings. These DEMOs contribute to reducing energy demand through improved insulation, passive heating/cooling, and energy-efficient building designs.

For DEMOs that integrate energy production, consumption, and efficiency measures, **energy security** serves as the end node of energy-related factors. Energy security reflects the reliability, affordability, and sustainability of energy supply, ensuring that DEMOs can operate without significant disruptions due to external dependencies, price fluctuations, or supply limitations. Positive contributions to energy security occur in DEMOs that generate their own energy (e.g., biogas, renewables), improve efficiency, and reduce dependency on external energy sources. These DEMOs enhance their energy resilience, lowering operational risks. Negative contributions to energy security arise when DEMOs are highly dependent on external energy sources without local production or efficiency measures, making them vulnerable to price increases, energy shortages, or grid failures.

DEMOs that do not incorporate energy related factors include DEMOs 1.3, 6.1, 7.1, 7.2, and 8.

Table 20. *Endogenous energy-related factors and their applicability to CARDIMED's DEMOs*

Factor	Description	DEMO 1.1	DEMO 1.2a	DEMO 1.2b	DEMO 1.3	DEMO 2	DEMO 3	DEMO 4.1	DEMO 4.2	DEMO 5.1	DEMO 5.2	DEMO 6.1	DEMO 6.2	DEMO 7.1	DEMO 7.2	DEMO 8	DEMO 9.1	DEMO 9.2	DEMO 9.3
Biogas generation	Amount of produced methane-rich gas from organic waste.	✓														✓			
Biogas treatment efficiency	Effectiveness of processes in purifying and upgrading biogas for energy use.	✓																	
Biobased energy production	Generation of energy from biological sources like biomass and biofuels.	✓														✓			
Renewable energy production	Energy generated from sustainable sources such as solar, wind, hydro, and biomass.						✓									✓			
Energy for (waste)water treatment	Power required for wastewater treatment processes, including filtration and purification.	✓				✓	✓		✓								✓		✓
Energy for water collection, storage, distribution	Energy used to extract, store, and deliver water.	✓	✓	✓		✓							✓					✓	
Energy consumption for agricultural production (irrigation, machinery, etc.)	Power used for farming activities, including irrigation and equipment operation.	✓	✓	✓			✓												
Energy consumption for green spaces (irrigation, machinery, etc.)	Energy needed to maintain parks, gardens, and green façades.												✓				✓	✓	✓

Energy for energy generation	Internal energy use in power plants or renewable energy systems.	✓													✓			
Heating and Cooling Degree Days	Measurement of temperature variations influencing heating and cooling demand.											✓				✓		
Building surface temperature	External temperature of buildings affecting energy efficiency and thermal comfort.							✓										✓
Energy savings from thermal regulation	Reduction in energy demand due to improved insulation and passive heating/cooling.							✓										✓
Net energy savings	Total reduction in energy use after implementing efficiency measures.							✓										
Total energy consumption in the system (operation, maintenance, etc.)	Overall energy demand for system functioning, upkeep, and operation.			✓		✓		✓	✓	✓					✓			✓
Energy self-sufficiency	The extent to which a system meets its energy needs through internal generation without external reliance.	✓					✓								✓			
Energy security	The availability of a reliable, affordable, and sustainable energy supply, minimizing risks from supply disruptions and geopolitical dependencies.	✓					✓								✓			

Table 21 presents the **endogenous farming-related factors** identified within the CARDIMED DEMOs, highlighting their applicability across different demonstration sites. The term "farming" is used instead of "food" because not all DEMOs incorporating agricultural activities are directly involved in food production. While DEMOs 1.1, 3, and 7.2 produce food crops, others, such as DEMOs 1.2a and 1.2b, focus on the cultivation of aromatic plants, which are not considered food crops but still contribute to agricultural activities. Additionally, DEMOs 6.1 and 9.1 generate biomass for further utilization, such as soil enrichment, feed, or bioenergy production, further supporting sustainable farming systems. These DEMOs, along with those cultivating aromatic plants, play an important role in land management, soil enhancement, and resource cycling, even if they are not directly involved in food production.

Several DEMOs actively manage farming-related activities, influencing land use, productivity, and input efficiency. These activities include biomass production, composting, fertilizer application, and resilience-building measures that contribute to sustainable agricultural systems.

- **DEMOs Managing Agricultural Land and Farming Activities**: DEMOs 1.1, 1.2a, 1.2b, 3, and 7.2 actively manage agricultural areas, supporting crop cultivation, irrigation, and farming infrastructure. These DEMOs integrate agriculture as a key land use, contributing to food and non-food crop production, ecosystem services, and resource-efficient farming systems.
- **DEMOs Managing Biomass and Compost Production**: DEMOs 6.1, and 9.1 incorporate harvested biomass production, which includes microalgal and organic biomass for energy, feed, or soil enrichment. Additionally, DEMO 1.1 contributes to compost production, converting organic waste into nutrient-rich soil amendments that support soil fertility and crop productivity.
- **DEMOs Integrating Communal Grazing**: DEMO 8 incorporates communal grazing, where multiple livestock owners share grazing land. This DEMO explores the interactions between land use, livestock management, and ecosystem sustainability, contributing to grassland management and biodiversity conservation.

For DEMOs that integrate farming practices, resource inputs, and productivity measures, **agricultural output resilience** serves as the end node of farming-related factors. Agricultural resilience reflects the ability of farming systems to sustain yields despite climate variability, economic pressures, and resource constraints. Positive contributions to agricultural resilience occur in DEMOs that optimize fertilizer use, improve compost production, enhance soil quality, and implement adaptive farming practices. These DEMOs strengthen long-term productivity, food security, and land sustainability. Negative contributions to agricultural resilience arise in DEMOs where land degradation, poor soil fertility management, or inefficient farming practices reduce agricultural sustainability, increasing vulnerability to environmental and market fluctuations.

Some DEMOs do not actively manage agricultural activities, meaning that farming is either non-existing or remains an **exogenous factor** for them. These DEMOs may focus on water, energy, or ecosystem restoration without direct agricultural interventions. DEMOs that do not integrate farming-related factors include 1.3 (farming is exogenous), 2, 4.1, 4.2, 5.1, 5.2, 6.2, 7.1, and 9.2. DEMOs 6.1 and 9.1 do not involve agricultural activities but they just generate biomass that could be used in agricultural activities.

Table 21. *Endogenous farming-related factors and their applicability to CARDIMED's DEMOs*

Factor	Description	DEMO 1.1	DEMO 1.2a	DEMO 1.2b	DEMO 1.3	DEMO 2	DEMO 3	DEMO 4.1	DEMO 4.2	DEMO 5.1	DEMO 5.2	DEMO 6.1	DEMO 6.2	DEMO 7.1	DEMO 7.2	DEMO 8	DEMO 9.1	DEMO 9.2	DEMO 9.3
Sludge generation	Volume of produced solid byproducts from wastewater treatment processes.	✓																	
Sludge treatment efficiency	Effectiveness of processes in reducing sludge volume and improving its quality for disposal or reuse.	✓																	
Harvested Biomass (microalgal, organic)	Amount of biological material collected, including microalgae or organic crops, for energy, feed, or other uses.											✓					✓		
Agricultural area	Total land designated for farming activities, including crop cultivation and livestock.	✓	✓	✓			✓												
Compost production	Amount of organic waste converted into nutrient-rich compost for soil enhancement.	✓																	
Fertilizer demand	Quantity of nutrients required to support plant growth in agricultural or green systems.	✓	✓	✓			✓												
Fertilizer application	The rate at which fertilizers are applied to crops for optimal yield.	✓	✓	✓			✓												
Crop yield	The total harvested production per unit area, measuring agricultural productivity.	✓	✓	✓			✓								✓				

Communal grazing	Shared use of grazing land by multiple livestock owners or communities.														✓				
Agricultural Output Resilience	The ability of an agricultural system to maintain productivity despite environmental or economic disruptions.	✓	✓	✓			✓							✓	✓				✓

Table 22 presents the endogenous ecosystem-related factors identified within the CARDIMED DEMOs, highlighting their applicability across different demonstration sites. These factors include vegetation cover, soil and water interactions, biodiversity, climate regulation, pollution control, and carbon sequestration. They reflect both ecosystem services, which provide benefits such as improved air quality, flood control, and biodiversity conservation, and ecosystem disservices, such as soil erosion, invasive species proliferation, and pollution.

The integration of these factors within DEMOs allows for a better understanding of how NBS, land management, and ecosystem restoration contribute to the WEFE nexus. The DEMOs addressing ecosystem factors are grouped into the following categories:

- **DEMOs Managing Vegetation Cover and Green Infrastructure**: DEMOs 2, 3, 4.1, 4.2, 5.1, 5.2, 6.2, 7.2, and 9.2 integrate green spaces, permeable surfaces, or vegetated areas; DEMOs 4.2 and 9.3 implement green facades; and DEMOs 3 and 7.1 maintain riparian buffer zones.
- **DEMOs Impacting the Natural Water Cycle**: DEMOs 1.1, 1.2a, 1.2b, 1.3, 2, 3, 4.1, 4.2, 5.1, 5.2, 6.2, 7.1, 7.2, 8 and 9.2 directly affect the natural water cycle; and DEMOs 1.3, and 4.2 aim to mitigate flood risk.
- **DEMOs Impacting Soil**: DEMOs 1.1, 1.2a, 1.2b, 2, 7.1, and 7.2 address soil related functions.
- **DEMOs for Biodiversity Conservation and Restoration**: DEMOs 6.1, 7.1, 7.2, and 8 aim to restore native vegetation and control invasive alien species; and DEMOs 1.1, 1.2a, 1.2b, 1.3, 2, 3, 4.1, 4.2, 5.1, 5.2, 6.1, 7.1, 7.2, 8, 9.1, 9.2, and 9.3 aim to enhance urban and natural biodiversity.
- **DEMOs for Microclimate and Thermal Regulation**: DEMOs 4.2, 5.1, 5.2, 7.1, and 9.3 implement measures that can potentially moderate local temperatures, improve air circulation, and enhance thermal comfort in the surrounding buildings.
- **DEMOs for Climate Mitigation and Pollution Control**: DEMOs 1.1, 1.2a, 1.2b, 2, 4.2, 5.1, 5.2, 6.1, 7.1, 7.2, 8, 9.1, 9.2, and 9.3 implement measures that can potentially enhance carbon sequestration, monitor and mitigate water and soil pollution, track GHG emissions, and assess air quality, contributing to climate change mitigation and improved environmental conditions.

For DEMOs integrating green infrastructure, biodiversity conservation, and pollution control, the end node of ecosystem-related factors is the net balance between ecosystem services and disservices. Positive contributions occur in DEMOs that increase green spaces, improve water infiltration, enhance biodiversity, and reduce pollution, leading to climate resilience, habitat conservation, and improved urban sustainability. Negative contributions occur in DEMOs where soil erosion, pollution, or habitat degradation reduce ecosystem health, leading to biodiversity loss, decreased air and water quality, and increased climate vulnerability.

Table 22. *Endogenous factors related to ecosystem (dis)services and their applicability to CARDIMED's DEMOs*

Factor	Description	DEMO 1.1	DEMO 1.2a	DEMO 1.2b	DEMO 1.3	DEMO 2	DEMO 3	DEMO 4.1	DEMO 4.2	DEMO 5.1	DEMO 5.2	DEMO 6.1	DEMO 6.2	DEMO 7.1	DEMO 7.2	DEMO 8	DEMO 9.1	DEMO 9.2	DEMO 9.3
Green / permeable / vegetated area	Land covered with vegetation or permeable surfaces that support water infiltration and reduce runoff.					✓		✓		✓	✓		✓	✓			✓	✓	
Vegetated area of building	Green roofs, facades, or planted areas on buildings that enhance insulation and biodiversity.								✓										✓
Riparian buffer area	Area of vegetated zones along water bodies that protect against erosion, filter pollutants, and support biodiversity.						✓							✓					
Evaportranspiration / Evaporation rate	The combined water loss from soil and plant transpiration, influencing climate and soil moisture.	✓	✓	✓	✓		✓		✓				✓				✓	✓	
Soil moisture	The amount of water retained in the soil, essential for plant growth and ecosystem health.	✓	✓	✓			✓		✓				✓					✓	
(Remaining) Surface runoff	The portion of rainwater that does not infiltrate the soil and flows over the surface.	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	
Water infiltration rate	The speed at which water penetrates the soil, affecting groundwater recharge and flood control.	✓	✓	✓	✓	✓		✓		✓	✓		✓	✓				✓	
Flood risk	The likelihood of flooding due to heavy rainfall, poor drainage, or high surface runoff.			✓	✓	✓		✓		✓	✓						✓	✓	

Soil organic content	The proportion of decomposed plant and animal material in soil, crucial for fertility and water retention.	✓	✓	✓			✓						✓	✓	✓			
Soil nutrient level	The concentration of essential nutrients like nitrogen and phosphorus, influencing plant growth.	✓	✓	✓			✓							✓	✓			
Soil erosion	The loss of soil due to water, wind, or human activities, impacting land productivity and water quality.												✓					
Invasive alien species control	Measures to prevent or manage non-native species that threaten local ecosystems.										✓		✓	✓				
Restoration of native vegetation	Efforts to reintroduce indigenous plants to improve biodiversity and ecosystem resilience.										✓			✓	✓			
(Urban) Biodiversity	The variety of species in urban or natural environments, supporting ecological balance and ecosystem services.	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓
Vegetation / Forest health	The condition of plant life, including resistance to disease, climate stress, and human impact.										✓	✓		✓	✓	✓	✓	
Microclimate / Thermal regulation	Local climate conditions influenced by vegetation, water bodies, and built environments.							✓	✓	✓		✓				✓	✓	✓
Carbon sequestration	The capture and storage of atmospheric CO_2 by plants, soil, and ecosystems.	✓	✓						✓	✓	✓	✓		✓	✓	✓	✓	
Water / Soil pollution	Contamination of water and soil due to chemicals, waste, or human activities.	✓	✓	✓			✓								✓	✓	✓	

GHG emissions	The release of greenhouse gases such as CO_2 and methane, contributing to climate change.	✓	✓	✓			✓									✓	✓	✓	
Air quality	The level of pollutants in the air, affecting human health and environmental conditions.									✓	✓		✓				✓	✓	✓

5.1 Urban Areas: Findings for all relevant DEMOs

5.1.1 DEMO 4.1 in Catania (Sicily, Italy)

Nexus Interlinkages and Causal Loop Diagram for DEMO 4.1

The CLD in **Figure 4** illustrates the nexus interlinkages within DEMO 4.1, incorporating key components of the WEFE nexus. This DEMO directly engages with the water and ecosystems components, focusing on stormwater management, flood risk reduction, water quality improvement, and urban biodiversity enhancement. The implementation of bioretention cells (rain gardens) serves as an NBS that influences hydrological processes, pollutant filtration, and urban ecological functions, improving resilience in an urban environment affected by pluvial flooding risks.

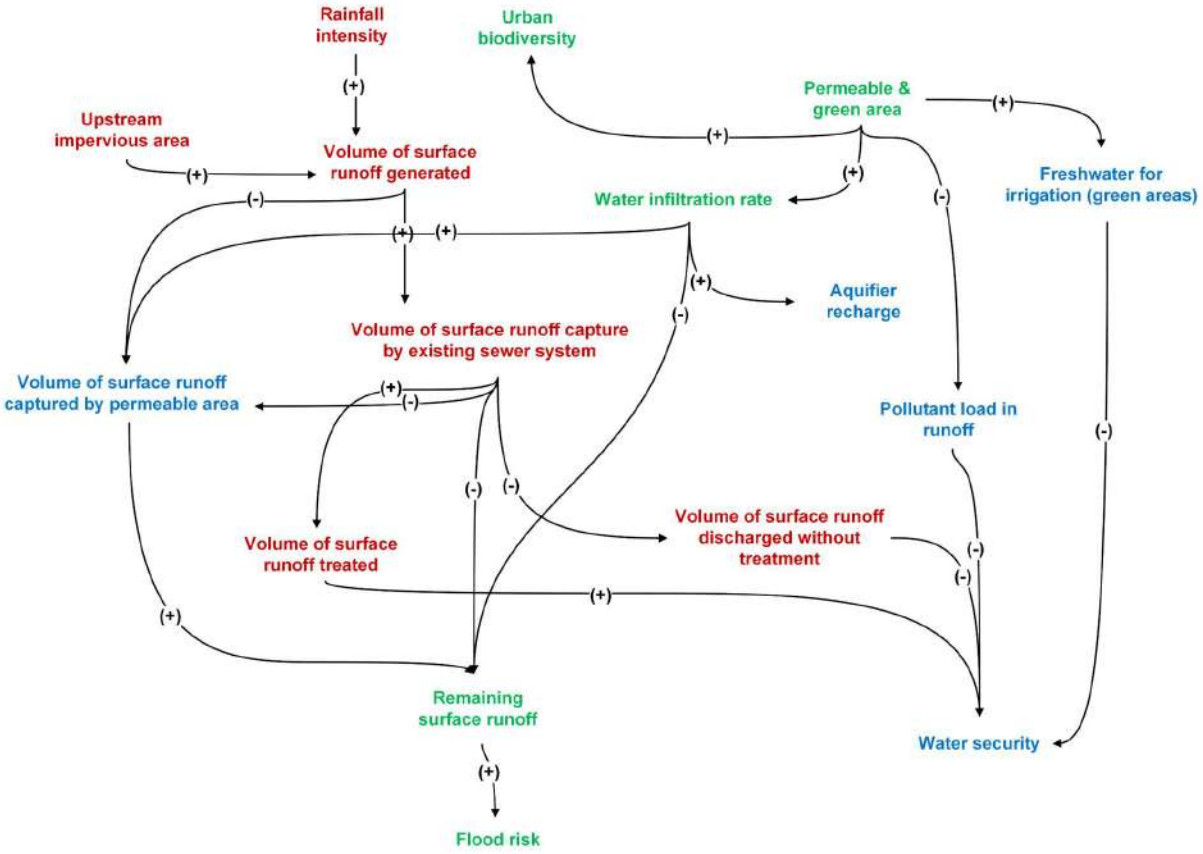

Figure 4. *CLD of DEMO 4.1*

The hydrological dynamics of stormwater runoff are central to this DEMO. Rainfall intensity and the extent of upstream impervious areas directly increase the volume of surface runoff generated. Without effective management, this runoff contributes to increased flood risk and places a burden on urban drainage infrastructure. The implementation of permeable and green areas, such as bioretention cells, captures part of this runoff, leading to an increase in water infiltration rates and a reduction in remaining surface runoff. Higher infiltration rates further contribute to aquifer recharge, enhancing groundwater sustainability and reducing reliance on external water resources. At the same time, less remaining runoff means a lower volume of surface runoff captured by the existing sewer system, decreasing the risk of drainage overload.

Another critical nexus interlinkage highlighted in the CLD is the impact of bioretention cells on water quality. The pollutant load in runoff is directly affected by the amount of untreated surface runoff discharged. When runoff bypasses treatment and enters the environment, it negatively affects water security. However, by

intercepting runoff, bioretention cells serve as a filtration mechanism, reducing pollutant loads in runoff and subsequently improving water security. Additionally, a portion of the captured runoff undergoes treatment, further lowering the volume of untreated discharges.

Beyond flood and water quality management, DEMO 4.1 generates synergies with biodiversity conservation and urban water use efficiency. The integration of permeable and green areas supports urban biodiversity by creating green spaces that enhance habitat availability. Furthermore, the captured and treated stormwater can serve as an alternative water source for irrigation in green areas, reducing the demand for freshwater for irrigation purposes. This interconnected system links stormwater management with ecosystem services, promoting urban sustainability.

The reinforcing and balancing feedback loops in the CLD illustrate the self-regulating nature of this system. A reinforcing loop exists where an increase in runoff capture by permeable areas leads to higher water infiltration rates, which in turn enhances aquifer recharge, further reducing surface runoff and mitigating flood risk. Another reinforcing loop occurs where a higher volume of surface runoff treated leads to lower pollutant loads in runoff, thereby improving water security.

Conversely, balancing feedback loops regulate the system to prevent excessive runoff and pollution. A higher water infiltration rate decreases the volume of surface runoff captured by the existing sewer system, ensuring that drainage systems are not overwhelmed. Additionally, reducing the pollutant load in runoff lowers the negative impact on water security, stabilizing the long-term sustainability of urban water resources.

The implementation of bioretention cells within DEMO 4.1 exemplifies how NBS can transform stormwater management, strengthening climate adaptation, urban resilience, and sustainability in flood-prone environments.

Scenario Development for DEMO 4.1

The scenario development for DEMO 4.1 aims to assess the impact of bioretention cells (rain gardens) on stormwater management, flood risk reduction, and urban water security under different conditions. This includes a baseline scenario representing the current urban drainage conditions and future scenarios that incorporate climate change projections.

The **baseline scenario** development process focuses on analysing existing stormwater dynamics, considering current rainfall intensity, impervious surface coverage, urban drainage infrastructure, and flood risks. The baseline assessment evaluates the volume of surface runoff generated, the capacity of existing sewer systems to capture runoff, pollutant loads in runoff, and the frequency of urban flooding events. It provides a reference against which future interventions can be assessed.

Future scenarios incorporate climate change impacts, including projected increases in extreme rainfall events, shifts in infiltration rates due to soil degradation or urban expansion, and changing hydrological patterns. These scenarios examine how increased rainfall intensity could amplify surface runoff and flood risks, requiring enhanced stormwater management strategies.

Data Needs Summary of DEMO 4.1

Data requirements revolve around the hydrological and urban biodiversity aspects of the DEMO. The primary data requirements for modelling the hydrological components of the nexus focus on rainfall intensity (both current and projected under climate change), surface runoff volumes, water infiltration rates in permeable and green areas, and aquifer recharge rates. These parameters, obtained through direct observations or estimations, are critical for understanding stormwater dynamics and their interactions with urban systems. Coupled with urban infrastructure data already mapped in Deliverable 4.1, these datasets allow for generating flood risk data.

Environmental quality data, particularly pollutant loads in surface runoff and overall water quality, will be collected in situ to ensure accuracy and representativeness. Urban biodiversity, an integral part of assessing ecosystem services, will be monitored in accordance with the prescribed monitoring plan. The high (5-30 m)

or very high (<5 m) spatial resolution of the majority of the data, as outlined in Deliverable 4.1, enables precise demo-level analyses, facilitating detailed assessments of NBS performance and its implications for urban water security, flood risk, and ecosystem health.

In conclusion, the most salient aspects of the WEFE nexus are accounted for within the project's monitoring plan and data ecosystem (outlined in Deliverables 2.2 and 4.1, respectively). The hydrological, environmental, and biodiversity components critical to nexus modelling are well-represented, with high-resolution data enabling precise analyses at the demo level.

5.1.2 DEMO 4.2 in Ferla (Sicily, Italy)

Nexus Interlinkages and Causal Loop Diagram for DEMO 4.2

The CLD in **Figure 5** illustrates the nexus interlinkages within DEMO 4.2, incorporating key components of the WEFE nexus. This DEMO integrates water, energy, and ecosystems, focusing on greywater reuse, water efficiency, thermal regulation, and urban biodiversity enhancement. The installation of a pot-based green facade not only treats and reuses greywater for non-potable applications but also contributes to building energy efficiency and microclimate regulation.

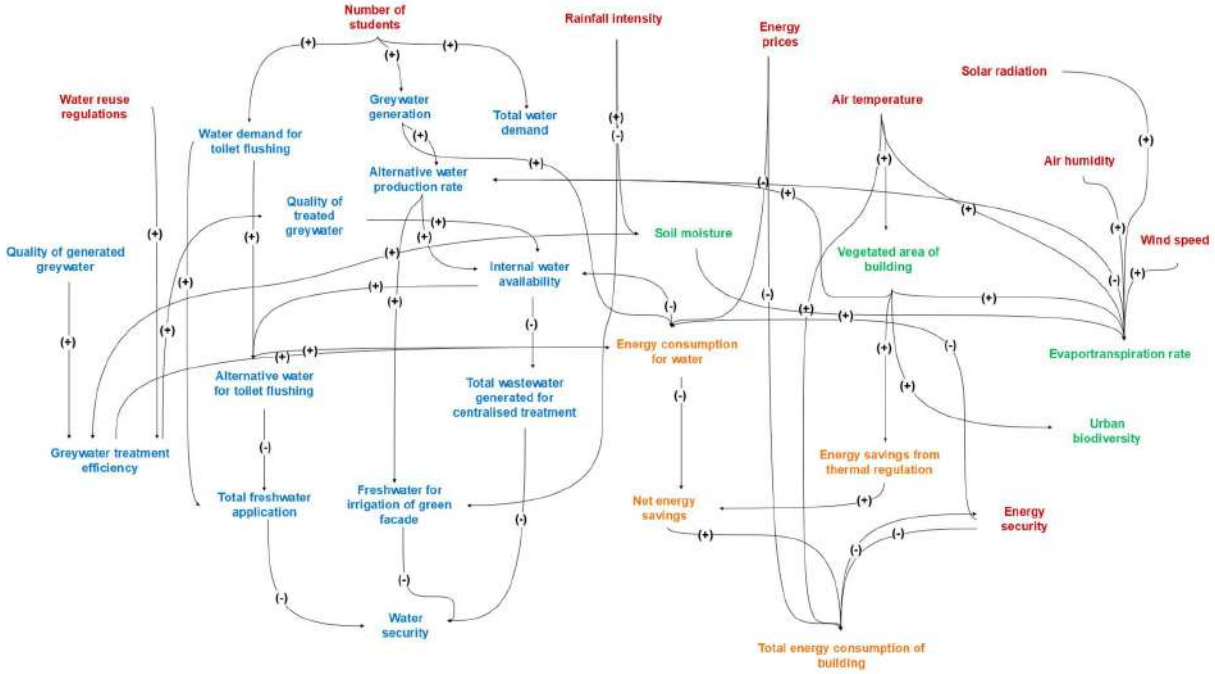

Figure 5. *CLD of DEMO 4.2*

The water component is represented through greywater reuse and water conservation strategies. The number of students directly influences greywater generation, which, when treated efficiently, contributes to the alternative water production rate. This alternative water source reduces freshwater application, thereby improving water security. A portion of the treated greywater is used as alternative water for toilet flushing, decreasing total water demand and minimizing the total wastewater generated for centralized treatment. Additionally, some treated water is allocated for irrigation of the green facade, supporting urban greenery while reducing irrigation water needs. The effectiveness of greywater reuse is influenced by water reuse regulations, which determine its feasibility and operational efficiency.

The energy component is closely linked to the water system. Energy consumption for water treatment and reuse is an important factor, as the need to process greywater affects overall net energy savings. Simultaneously, the green facade contributes to thermal regulation, reducing building surface temperatures

and leading to energy savings from thermal regulation. This results in lower total energy consumption of the building, reinforcing energy security.

The ecosystems component is reflected in the vegetated area of the building, which enhances urban biodiversity and contributes to microclimate regulation. The green facade influences evapotranspiration rates, which, in turn, affects soil moisture levels and local cooling effects. Climate variables such as air temperature, humidity, wind speed, solar radiation, and rainfall intensity interact with these processes, further shaping system performance.

The CLD in **Figure 5** highlights multiple reinforcing and balancing feedback loops. A reinforcing loop occurs where efficient greywater treatment increases the alternative water supply, reducing potable water demand and wastewater discharge, reinforcing water conservation efforts. Another reinforcing loop exists through the green facade, where enhanced thermal regulation leads to reduced building energy consumption, improving net energy savings.

Conversely, balancing loops regulate system performance. An increase in energy consumption for water treatment is offset by savings from thermal regulation, ensuring optimized energy efficiency. Similarly, evapotranspiration and soil moisture interactions regulate the cooling effect of the green facade, preventing excessive temperature fluctuations.

The implementation of greywater reuse and a green facade in DEMO 4.2 showcases a holistic approach to sustainable urban water and energy management, demonstrating how NBS can simultaneously address water conservation, energy efficiency, and biodiversity enhancement within the WEFE nexus.

Scenario Development for DEMO 4.2

The scenario development for DEMO 4.2 evaluates the effectiveness of greywater reuse and green facade integration in optimizing water and energy consumption while improving urban microclimates. The baseline scenario assesses the existing conditions, while future scenarios explore the impact of climate change and changes in hydrological conditions on the system's performance.

The **baseline scenario** development process analyses current water consumption patterns, greywater generation rates, and energy use for heating and cooling within the school building. It assesses the volume of greywater treated, alternative water available for reuse, and the corresponding reduction in freshwater demand. Additionally, the thermal performance of the green facade is evaluated, including its contribution to energy savings from thermal regulation and its effect on building surface temperature.

Future scenarios consider climate change impacts, including rising temperatures, increased evapotranspiration rates, and shifts in rainfall patterns affecting greywater availability and irrigation needs. These scenarios assess how climatic variations influence the efficiency of the greywater reuse system and the thermal regulation effect of the green facade. The impact of higher temperatures on building cooling demand and energy consumption is also examined, providing insights into the long-term resilience of the system under changing climatic conditions.

Through these scenarios, DEMO 4.2 is analysed in the context of the WEFE nexus, ensuring that water and energy efficiency strategies remain effective under evolving environmental conditions.

Data Needs Summary of DEMO 4.2

The water component of the nexus requires comprehensive mapping of water flows within the implemented NBS, focusing on both the volumetric dynamics water consumption and treatment, as well as the quality of untreated and treated greywater. These elements have been partially outlined in the monitoring plan (Deliverable 2.2). Therefore, the estimation of the water balance will rely on modeled assumptions, necessitating careful validation to minimize uncertainties. A robust framework for monitoring water quality parameters is essential to capture the influence of the NBS on water treatment outcomes and its contribution to improved water security.

For the energy component, assessing the impact of the green façade on building energy performance is a priority, as explicitly prescribed in the monitoring plan. However, a detailed breakdown of energy consumption across various uses, particularly wastewater treatment, is critical. This granular analysis will allow for the disentanglement of energy usage among nexus components, enabling the estimation of net energy savings achieved through NBS implementation. While some of this data may not be directly available, modeling efforts (through Task 5.1.4) will complement the existing monitoring plan (described in detail in D2.2) to fill in any information gaps, ensuring a comprehensive evaluation of the energy dimension within the WEFE nexus.

Regarding ecosystem services, urban biodiversity monitoring provides a direct means of quantifying the water-ecosystem links inherent in the NBS. By tracking biodiversity metrics, the monitoring framework will evaluate how green infrastructure enhances habitat availability, supports species richness, and contributes to ecosystem health.

As with the previous demo, the spatial resolution of both currently available and anticipated future data is sufficient to enable the mapping of the interlinkages within the WEFE nexus at the demo scale. This level of resolution ensures that the spatial variability of key components, such as water flows, energy distribution, and ecosystem services, can be accurately captured and analyzed.

5.1.3 DEMO 5.1 in Saint-Jérôme (Marseille, France)

Nexus Interlinkages and Causal Loop Diagram for DEMO 5.1

The CLD in **Figure 6** visualizes the nexus interlinkages within DEMO 5.1, incorporating key components of the WEFE nexus, particularly water, ecosystems, and energy. The removal of waterproof asphalt, the installation of bioswales, and the planting of a micro-forest contribute to stormwater management, urban biodiversity, climate mitigation, and air quality improvements. These NBS enhance urban resilience by reducing stormwater runoff, increasing water infiltration, and supporting carbon sequestration.

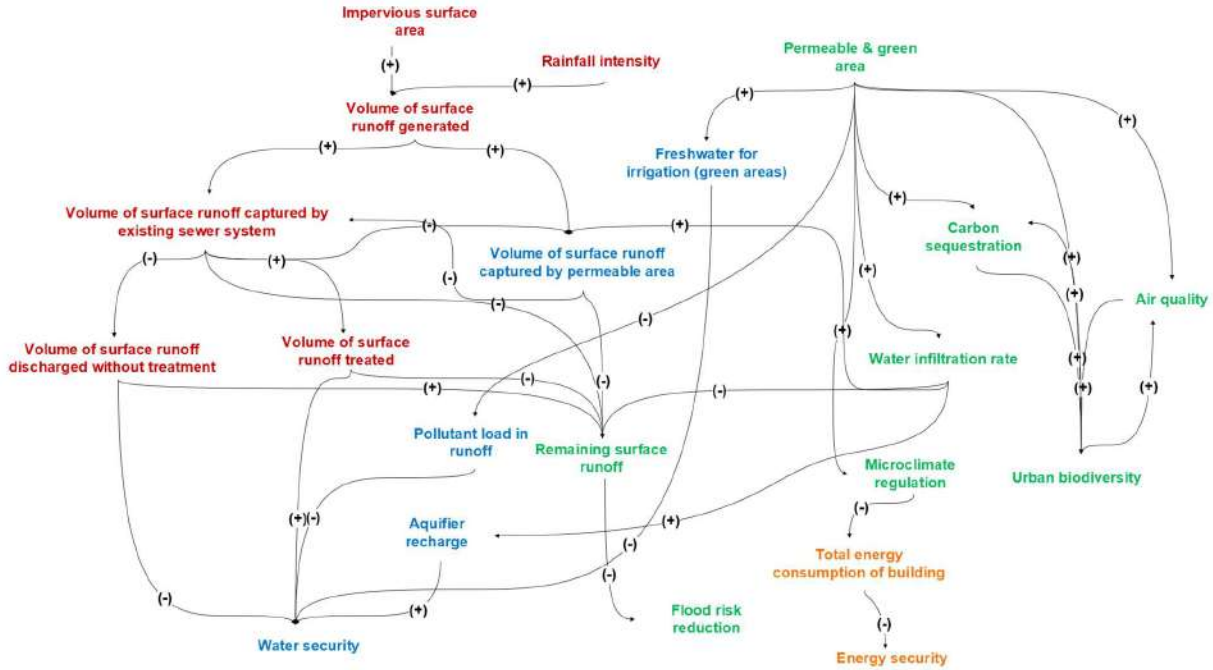

Figure 6. *CLD of DEMO 5.1*

The water component is represented through the management of stormwater runoff and water infiltration processes. The impervious surface area and rainfall intensity influence the volume of surface runoff generated, which, if not controlled, contributes to flood risk and urban drainage overload. By replacing impermeable

surfaces with permeable and green areas, DEMO 5.1 increases the volume of surface runoff captured by permeable areas, leading to higher infiltration rates and reduced remaining surface runoff. This process enhances aquifer recharge and reduces the volume of surface runoff captured by the sewer system, thus decreasing untreated discharges and improving water security.

The ecosystems component plays a critical role in climate regulation, biodiversity, and air quality. The introduction of permeable and green areas, including the micro-forest, enhances carbon sequestration, contributing to climate mitigation. Additionally, the vegetation supports urban biodiversity, providing a habitat for flora and fauna. Improved water infiltration and pollutant filtration within bioswales lead to lower pollutant loads in runoff, further enhancing environmental sustainability. Air quality improvements are also expected due to increased vegetation cover, reducing airborne pollutants and mitigating the urban heat island effect.

The energy component is linked to building microclimate regulation. The micro-forest and vegetated areas are expected to reduce building surface temperatures, leading to lower total energy consumption for cooling and contributing to energy security. However, it should be noted that these microclimate regulation effects are expected to materialize only once the trees have grown sufficiently, as their current size limits their impact on shading and temperature moderation.

The CLD in **Figure 6** highlights several reinforcing and balancing feedback loops that influence system stability. A reinforcing loop exists where increased permeable areas improve infiltration rates, enhancing aquifer recharge and further reducing surface runoff, contributing to flood risk reduction. Another reinforcing loop is observed in carbon sequestration and air quality improvements, where more green areas lead to better pollutant absorption, further improving environmental conditions.

Conversely, balancing loops regulate stormwater management. The increase in water infiltration reduces the volume of surface runoff captured by the sewer system, helping prevent urban drainage overload. Additionally, lower pollutant loads in runoff stabilize water quality improvements, ensuring long-term sustainability.

The implementation of bioswales, porous surfaces, and a micro-forest within DEMO 5.1 demonstrates how NBS can provide integrated solutions for water management, climate resilience, and biodiversity conservation, aligning with the WEFE nexus principles.

Scenario Development for DEMO 5.1

The scenario development for DEMO 5.1 assesses the impact of bioswales, soil unsealing, and micro-forest development on stormwater management, flood risk reduction, and climate mitigation. The baseline scenario establishes existing conditions, while future scenarios evaluate the potential impacts of climate change and changing hydrological conditions on the system's performance.

The **baseline scenario** development process analyses current rainfall patterns, stormwater runoff volumes, and infiltration rates in the modified urban landscape. It evaluates the effectiveness of bioswales and porous surfaces in capturing and treating runoff, as well as the initial contributions of the micro-forest to carbon sequestration and biodiversity. The baseline also considers air quality parameters and pollutant loads in runoff before and after the intervention.

Future scenarios focus on climate change impacts, particularly the increase in extreme rainfall events, prolonged drought periods, and rising temperatures. These scenarios explore how changing rainfall intensities affect surface runoff generation and infiltration processes, as well as how higher temperatures influence evapotranspiration rates and microclimate regulation. While the micro-forest is expected to enhance shading and cooling effects, these impacts will likely become more significant over time as trees mature. Therefore, the scenarios account for delayed microclimate regulation effects due to the small initial size of the trees.

Through these scenarios, DEMO 5.1 is analysed within the WEFE nexus, ensuring that the implemented NBS remain effective in the face of changing environmental conditions and contribute to long-term urban sustainability and resilience.

Data Needs Summary of DEMO 5.1

The water component in the monitoring framework focuses primarily on quantitative aspects, including the volume of surface runoff captured by permeable areas and infiltration rates. These metrics are critical for understanding the role of the NBS in mitigating flood risks and supporting aquifer recharge. By measuring these parameters, it is possible to quantify how effectively NBS reduces surface runoff and enhances groundwater sustainability. However, the absence of water quality data for runoff limits the analysis of pollutant load reduction and its implications for water security, leaving an aspect of the nexus unaddressed.

Air quality and microclimate regulation have been addressed within the monitoring plans (the reader is advised to refer to Deliverable 2.2), providing insights into the contribution of the NBS to local environmental improvements. Through microclimate regulation, indirect connections to the energy component can be established, as these processes influence energy demand for cooling and heating. Nevertheless, the absence of direct assessments of energy savings constrains to have a full and valid evaluation of this nexus aspect.

On the other hand, urban biodiversity support and soil-related parameters (e.g., soil fertility and organic content) are explicitly included in the monitoring plan, ensuring that the ecosystem-related impacts of the NBS are thoroughly documented.

The high spatial resolution of existing and future datasets, as outlined in Deliverable 4.1, allows for the detailed representation of these local dynamics, ensuring that the WEFE nexus interlinkages can be effectively portrayed at the demo scale.

5.1.4 DEMO 5.2 in Saint Charles (Marseille, France)

Nexus Interlinkages and Causal Loop Diagram for DEMO 5.2

The CLD in **Figure 7** illustrates the nexus interlinkages within DEMO 5.2, incorporating key components of the WEFE nexus, particularly water, ecosystems, and energy. This DEMO shares significant similarities with DEMO 5.1, as both focus on surface unsealing, stormwater management, and the integration of NBS to enhance urban resilience. However, DEMO 5.2 is located in a highly urbanized area with space constraints and high visitor flow, which limits the extent of modifications compared to DEMO 5.1. Despite these differences, both DEMOs implement porous materials, green spaces, and tree planting to improve stormwater management, air quality, and urban cooling.

The water component is addressed through stormwater runoff reduction and infiltration enhancement. Impervious surface area and rainfall intensity contribute to the volume of surface runoff generated, increasing flood risks and urban drainage pressures. By introducing permeable and green areas, DEMO 5.2 enhances infiltration rates, increases aquifer recharge, and decreases the remaining surface runoff, improving urban water security. Additionally, a portion of the captured and treated runoff is used for irrigation, reducing dependence on freshwater resources.

The ecosystems component is reinforced by the introduction of an urban micro-forest and expansion of green areas, which contribute to carbon sequestration, improved air quality, and increased urban biodiversity. The vegetation also plays a role in reducing pollutant loads in runoff, further supporting water security. The micro-forest is expected to have long-term effects on microclimate regulation and temperature moderation, although these benefits will only become significant once the trees have grown sufficiently, as their small initial size limits their immediate impact on urban cooling.

The energy component is linked to microclimate regulation and building energy efficiency. As the trees mature, they are expected to reduce building surface temperatures, lower cooling demand, and contribute to energy savings. This will enhance energy security by reducing reliance on external energy sources. However, similar to DEMO 5.1, these benefits will only become evident over time as the vegetation develops, meaning they are unlikely to be fully measurable within the CARDIMED project timeframe.

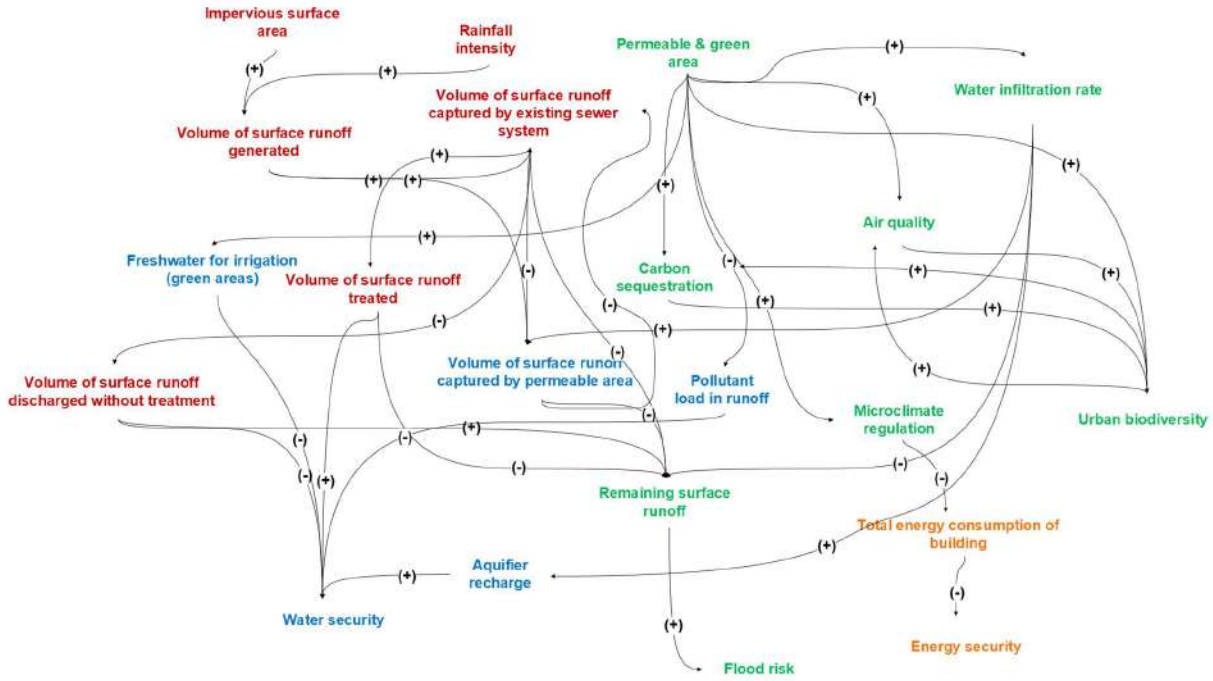

Figure 7. *CLD of DEMO 5.2*

The CLD in **Figure 7** highlights multiple reinforcing and balancing feedback loops within DEMO 5.2. A reinforcing loop is observed where increasing permeable and green areas enhance infiltration, which reduces surface runoff, decreases pollutant loads, and strengthens water security. Another reinforcing loop occurs in carbon sequestration and air quality improvements, where expanding vegetation further amplifies environmental benefits.

Conversely, balancing loops regulate stormwater interactions. Higher infiltration rates reduce the volume of runoff reaching the sewer system, helping to prevent urban drainage overload. Similarly, pollutant removal from runoff stabilizes water quality improvements, ensuring long-term benefits.

The implementation of surface unsealing, porous materials, and an urban micro-forest within DEMO 5.2 highlights how NBS can be effectively integrated into highly urbanized environments. Its similarities with DEMO 5.1 demonstrate the scalability of these solutions, reinforcing the WEFE nexus approach for urban resilience, climate adaptation, and stormwater management.

Scenario Development for DEMO 5.2

The scenario development for DEMO 5.2 evaluates the impact of surface unsealing, porous materials, and tree planting on stormwater management, climate mitigation, and air quality. Given the similarities with DEMO 5.1, the scenario development follows a parallel approach, with adjustments reflecting the high-density urban context and space limitations of DEMO 5.2.

The **baseline scenario** development process assesses existing stormwater dynamics, infiltration rates, and pollutant accumulation in runoff. It examines the effectiveness of porous materials in capturing and filtering runoff, the initial contributions of green areas to biodiversity, and early-stage air quality improvements. The potential for runoff reuse in irrigation is also included in the baseline framework.

Future scenarios focus on climate change impacts, particularly the increase in extreme rainfall events, prolonged droughts, and rising temperatures. These scenarios analyse how changing precipitation patterns influence runoff generation, infiltration capacity, and urban drainage performance. The impact of higher temperatures on urban cooling and energy demand is also considered. While the micro-forest is expected to enhance shading and cooling over time, its immediate effects will be limited due to the small size of the trees,

meaning that temperature regulation benefits will only materialize in the long term and are unlikely to be fully measurable within the CARDIMED project timeframe.

Through these scenarios, DEMO 5.2 is analysed within the WEFE nexus, ensuring that its NBS contribute effectively to urban resilience, water security, and climate adaptation, even under changing environmental conditions. Its similarities with DEMO 5.1 reinforce the value of NBS in diverse urban settings, providing insights into their adaptability and long-term benefits.

Data Needs Summary of DEMO 5.2

For Demo 5.2, data requirements closely mirror those identified in the previous demo. The volumetric aspects of water, such as the runoff captured by permeable areas and infiltration rates, are adequately addressed, providing a solid foundation for assessing flood risk mitigation and aquifer recharge. This is a key priority. While the pollutant load of runoff is less of a focus, additional data on water quality could further enhance the analysis.

Air quality and microclimate regulation are clearly incorporated into the monitoring plan, offering valuable insights into these aspects. The potential influence of microclimate regulation on direct energy savings is acknowledged but could be further explored to enhance the assessment of its impact on the energy component. While current monitoring efforts provide valuable insights, any remaining gaps will be addressed through modeling to ensure a more comprehensive evaluation. Lastly, parameters related to soil and urban biodiversity are well-covered, ensuring that the ecological contributions of the NBS are adequately captured.

5.1.5 DEMO 6.2 in Zaragosa (Aragon, Spain)

Nexus Interlinkages and Causal Loop Diagram for DEMO 6.2

The CLD in **Figure 8** visualizes the nexus interlinkages within DEMO 6.2, incorporating key components of the WEFE nexus, particularly water, ecosystems, and energy. This DEMO integrates NBS such as vegetated pergolas, permeable surfaces, rain gardens, and biodiversity-enhancing elements, all aimed at improving stormwater management, urban biodiversity, and microclimate regulation. Unlike other DEMOs focused on cooling effects at the building scale, DEMO 6.2 primarily provides localized heat mitigation under the pergolas, without significantly affecting the energy demand for heating or cooling in the school buildings.

The water component is addressed through rainwater infiltration, retention, and reuse strategies. The water collection area and the harvested rainwater storage capacity determine the alternative water production rate, which supports vegetation health and irrigation needs, reducing freshwater consumption. The implementation of permeable and green areas enhances water infiltration, increases soil moisture, and reduces surface runoff, contributing to flood risk mitigation and water security. The runoff retention capacity of the bioretention cells and permeable surfaces further reduces stormwater discharge into drainage systems, aligning with stormwater management regulations.

The ecosystems component is strengthened through biodiversity support measures. The presence of green and permeable areas contributes to soil nutrient levels and soil organic content, further enhancing carbon sequestration. Additionally, specific interventions such as insect hotels, birdhouses, bat houses, and amphibian ponds promote habitat creation and urban biodiversity, improving air quality and reinforcing ecosystem resilience.

The energy component is associated with localized microclimate regulation. The vegetated pergolas provide natural shading, reducing air temperature beneath them, which enhances thermal comfort for users in outdoor spaces. However, as this cooling effect is confined to shaded areas, it does not directly influence the total energy consumption of the school buildings for cooling or heating.

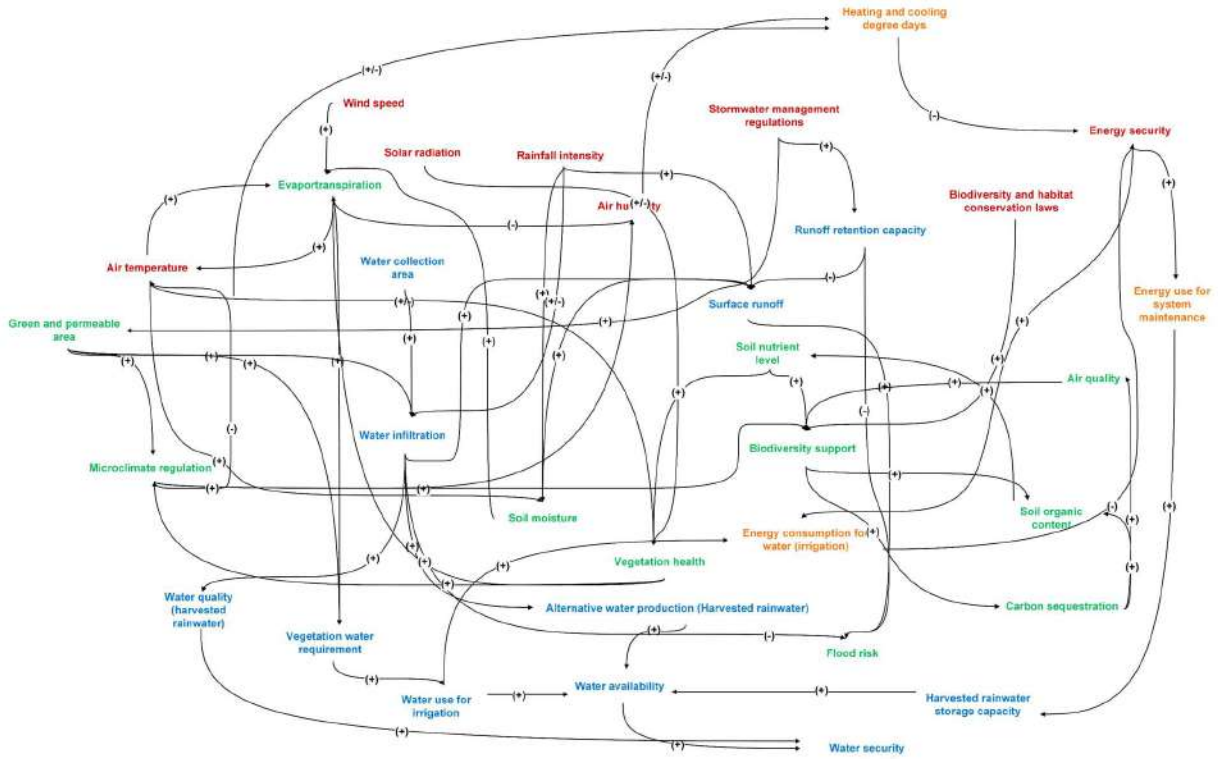

Figure 8. *CLD of DEMO 6.2*

The CLD in **Figure 8** highlights several reinforcing and balancing feedback loops that regulate system interactions. A reinforcing loop occurs where an increase in green and permeable areas leads to improved water infiltration, reducing surface runoff and enhancing soil moisture, which in turn supports vegetation health and further strengthens the system's ability to manage stormwater. Another reinforcing loop is seen in biodiversity support, where improved habitat availability increases urban biodiversity, which contributes to air quality improvements and ecosystem resilience.

Balancing loops help stabilize system interactions by counteracting reinforcing effects and maintaining system balance. Higher runoff retention capacity prevents excessive stormwater discharge, mitigating flood risks and improving water security. Similarly, efficient water use for irrigation ensures a balance between vegetation water demand and available rainwater resources, preventing overuse of freshwater supplies.

The implementation of vegetated pergolas, permeable surfaces, and biodiversity-enhancing features in DEMO 6.2 demonstrates how NBS can effectively improve stormwater management, microclimate regulation, and urban biodiversity while fostering environmental education within schools.

Scenario Development for DEMO 6.2

The scenario development for DEMO 6.2 evaluates the impact of rainwater management, vegetation-based cooling, and biodiversity interventions on urban resilience and sustainability. The baseline scenario represents current conditions, while future scenarios explore the effects of climate change on system performance without considering system upscaling.

The **baseline scenario** development process assesses existing water infiltration rates, runoff retention capacity, and vegetation water needs. It also evaluates the initial effects of vegetated pergolas on microclimate regulation, though these cooling effects are limited to shaded areas and do not influence the building's overall energy demand. Additionally, the impact of biodiversity-enhancing structures on species presence and habitat availability is included in the baseline framework.

Future scenarios focus on climate change impacts, including higher temperatures, prolonged droughts, and more intense rainfall events. These scenarios analyse how changes in rainfall patterns affect runoff generation, infiltration efficiency, and stormwater retention. Additionally, the impact of higher temperatures on evapotranspiration rates and vegetation water demand is examined to determine whether irrigation needs will increase under future climatic conditions.

Through these scenarios, DEMO 6.2 is analysed within the WEFE nexus, ensuring that the implemented NBS remain effective under changing environmental conditions, promoting long-term sustainability, biodiversity conservation, and water resilience.

Data Needs Summary of DEMO 6.2

The current monitoring plan, as described in Deliverable 2.2, emphasises the urban heat island effect and urban biodiversity support, reflecting a prioritization of these components within the NBS assessment framework. When complemented with soil-related indicators, the plan has the potential to sufficiently capture the energy-ecosystem interrelationship, particularly in terms of the contributions of green infrastructure to microclimate regulation and biodiversity enhancement. These elements provide a basis for understanding how the NBS fosters ecosystem services while indirectly influencing energy dynamics.

While the water component is primarily represented through measurements of infiltration rates and rainfall, these parameters provide a solid foundation for assessing the basic elements of the water balance within the NBS. Expanding the scope to include additional hydrological aspects could further enhance the analysis.

Air quality aspects, while absent from the monitoring plan, represent a less direct and evident impact of the NBS, which may justify its exclusion.

Conclusively, while there is a minor discrepancy between the complexity of the CLD and the scope of the monitoring plan, the latter enables the quantification of the most prominent water-energy-ecosystem interrelationships. This includes improved stormwater management, heat mitigation, and support for urban biodiversity, which are critical outcomes that underpin the objectives of the NBS.

5.1.6 DEMO 9.1 in Nicosia (Cyprus)

Nexus Interlinkages and Causal Loop Diagram for DEMO 9.1

The CLD in **Figure 9** visualizes the nexus interlinkages within DEMO 9.1, incorporating key components of the WEFE nexus, particularly water, ecosystems, and energy. This DEMO implements a photobioreactor (PBR) system to treat groundwater for irrigation, enhancing the sustainability of urban green spaces in Makrigiannis Park. By removing salinity, nitrates, and hardness from groundwater, the system provides a reliable water source for vegetation while simultaneously producing microalgal biomass that can be repurposed as a biofertilizer, further benefiting soil health and plant growth.

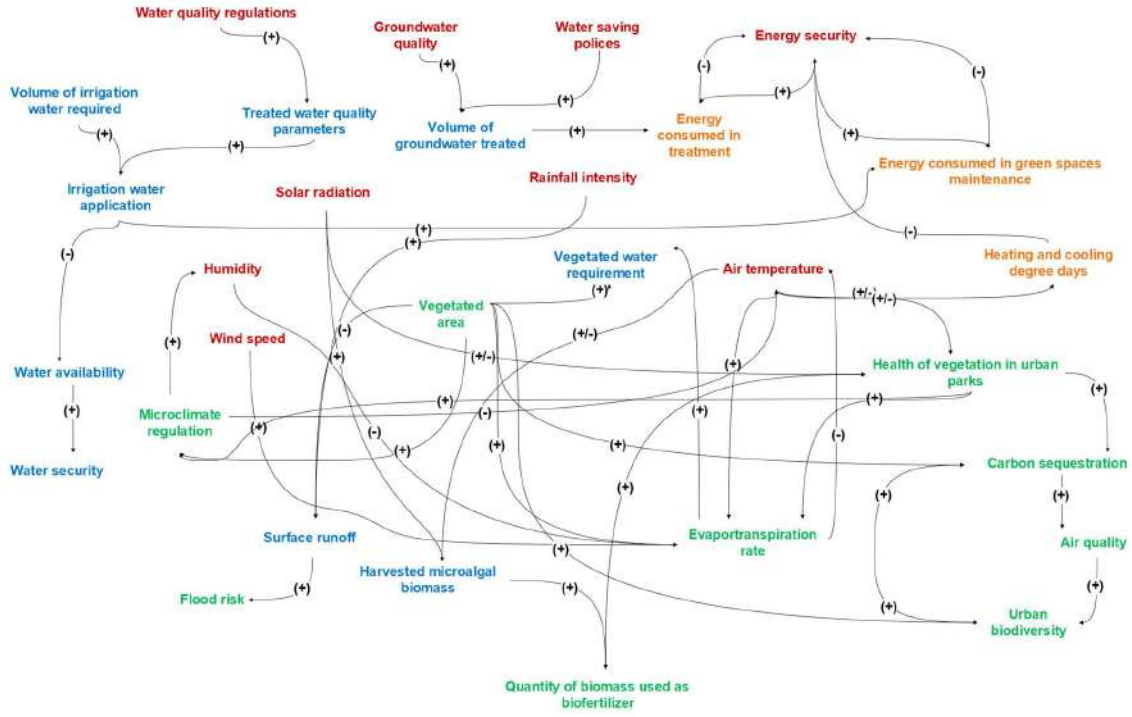

Figure 9. *CLD of DEMO 9.1*

The water component is centred around groundwater treatment and irrigation management. The volume of irrigation water required depends on factors such as vegetation water requirements, evapotranspiration rates, and climatic conditions. The PBR improves treated water quality parameters, ensuring that salinity and nutrient levels are suitable for irrigation. However, the reliance on groundwater for irrigation may pose a risk to water security, especially in regions prone to water scarcity. The balance between water availability and groundwater use is a critical consideration for the long-term sustainability of the system.

The ecosystems component is significantly strengthened through urban green space enhancement. The improved availability of treated irrigation water supports vegetation health in urban parks, contributing to carbon sequestration, improved air quality, and enhanced biodiversity. The integration of microalgal biomass as a biofertilizer further supports plant growth, improving soil nutrient levels and organic content. These combined effects create a positive feedback loop where better irrigation leads to healthier vegetation, which in turn contributes to cooling effects, biodiversity enhancement, and improved urban resilience.

The energy component is associated with PBR operation and irrigation system maintenance. The energy consumed in water treatment directly affects energy security, as increased energy demand can lead to higher operational costs and dependence on external energy sources. Additionally, energy consumed in green space maintenance, such as irrigation pumping and system operation, further influences the overall energy balance of the system.

The CLD in **Figure 9** highlights several reinforcing and balancing feedback loops. A reinforcing loop exists where the availability of treated water improves urban vegetation health, which enhances microclimate regulation, increasing evapotranspiration rates and reducing air temperatures, further supporting green space sustainability. Another reinforcing loop is observed in the role of harvested microalgal biomass as a biofertilizer, where its application enhances soil and plant health, reinforcing the benefits of irrigation.

Conversely, balancing loops regulate the system's water and energy dynamics. The extraction of groundwater for irrigation can negatively impact water security if not managed efficiently, requiring careful monitoring of groundwater availability. Similarly, the energy required for treatment and irrigation must be optimized to ensure that operational sustainability is maintained.

The implementation of a large-scale PBR system in DEMO 9.1 demonstrates how innovative NBS can improve urban water management, support vegetation health in parks, and contribute to biodiversity and climate resilience. However, the trade-offs between groundwater use, water security, and energy consumption must be carefully managed to ensure long-term viability.

Scenario Development for DEMO 9.1

The scenario development for DEMO 9.1 assesses the impact of groundwater treatment and irrigation on urban green spaces, water security, and energy consumption. The baseline scenario evaluates the current system performance, while future scenarios consider the effects of climate change and groundwater availability variations on irrigation sustainability.

The **baseline scenario** development process focuses on analysing current groundwater extraction rates, treatment efficiency, and irrigation water demand. It evaluates the effectiveness of the PBR in maintaining suitable water quality parameters for irrigation, as well as the initial contributions of treated irrigation water to vegetation health and urban biodiversity. Additionally, the role of microalgal biomass as a biofertilizer is assessed in terms of soil enhancement and plant growth support.

Future scenarios focus on climate change impacts, particularly rising temperatures, increased evapotranspiration rates, and potential groundwater depletion. These scenarios explore how higher temperatures influence irrigation demand and vegetation water requirements, as well as whether groundwater resources will remain sufficient to sustain long-term irrigation needs. Additionally, the energy required for water treatment and irrigation is analysed in relation to potential energy security challenges.

Through these scenarios, DEMO 9.1 is analysed within the WEFE nexus, ensuring that the PBR system continues to provide benefits for urban green spaces while minimizing risks to water security and energy sustainability. The findings will support informed decision-making regarding groundwater management, irrigation strategies, and long-term adaptation measures for urban resilience.

Data Needs Summary of DEMO 9.1

The data requirements for quantifying the NBS's performance encompass the dimensions of water, energy, and ecosystem services. Observational data on groundwater quality are critical to evaluating the efficacy of the PBR system in treating groundwater. Equally important are data on the water treatment process itself, such as the volume of groundwater treated and its post-treatment quality. These data are indispensable for assessing the impact of the PBR on irrigation practices, aquifer recharge, and the overall water availability. Furthermore, the ecological and environmental effects of the treated water, including its influence on sustaining nearby green urban spaces and, thereby, urban biodiversity, and microclimate regulation, must be monitored to fully understand the water-ecosystem dynamics and the broader benefits of intervention.

As noted in Deliverable 2.2, many of these data requirements, particularly groundwater quality and treatment performance, have been incorporated into the monitoring framework, with some attention also given to urban biodiversity. Energy-related data primarily accounts for energy consumption during the treatment process, which an integral part of the energy aspects of the nexus. Yet, energy-related data could be further expanded to provide a more comprehensive understanding of the broader energy implications of the NBS. Particularly, data could offer insight into how urban green space contributes to energy security in terms of trade-offs between energy consumption for water treatment and energy savings from microclimate regulation. While these aspects are not fully captured through direct monitoring, the monitoring plan allows for complementary modeling efforts that will bridge the gap, enabling a more integrated assessment of synergies and trade-offs within the water-energy-ecosystem nexus.

Overall, the major components of the NBS implementation are parts of the monitoring plan, allowing the subsequent evaluation of its more salient impacts. The slight misalignment between data requirements and the monitoring plan only partially limits the ability to explore the complex interdependencies depicted in the CLD, particularly concerning the long-term sustainability of the PBR system and its contribution to urban resilience in Nicosia. Lastly, as highlighted in Deliverable 4.1, the available data sources are of high spatial

resolution and are well-suited for demo-level analysis, offering a solid foundation for addressing at least the most critical aspects of the nexus.

5.1.7 DEMO 9.2 in Nicosia (Cyprus)

Nexus Interlinkages and Causal Loop Diagram for DEMO 9.2

The CLD in **Figure 10** visualizes the nexus interlinkages within DEMO 9.2, incorporating key components of the WEFE nexus, particularly water, ecosystems, and energy. This DEMO applies a subsurface rainwater harvesting system to enhance water security and optimize irrigation efficiency in an urban environment, adapting the approach previously implemented in the rural setting of DEMO 1.2a for application in a dense, city-based setting. By capturing and storing rainwater for irrigation, the system ensures reduced reliance on freshwater resources, directly addressing water scarcity challenges while maintaining sustainability and resilience.

The water component is central to the system, as it focuses on rainwater harvesting, storage, and reuse for irrigation. The rainfall intensity influences the amount of water collected, which is directed through a hydraulic pipeline network into storage units for later use. The stored rainwater contributes to alternative water production, enhancing water use efficiency and reducing the volume of conventional water required for irrigation. Additionally, by promoting higher water infiltration and aquifer recharge, this system supports long-term urban water security while reducing surface runoff and flood risk.

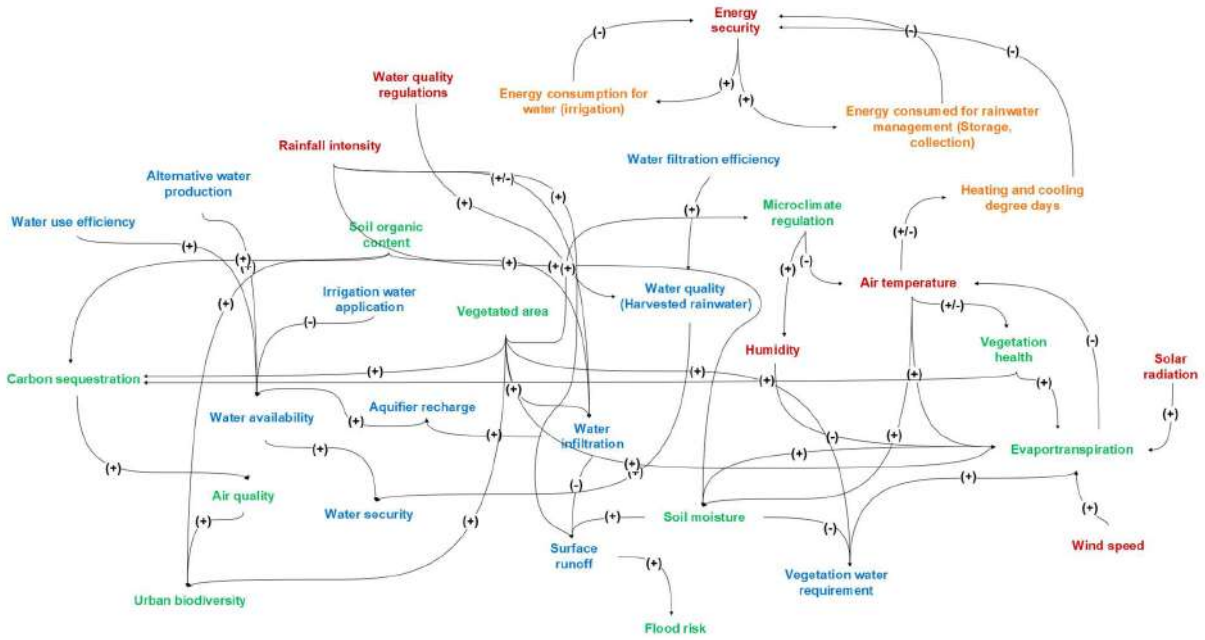

Figure 10. *CLD of DEMO 9.2*

The ecosystems component is strengthened through urban green space enhancement. The availability of harvested rainwater for irrigation ensures healthy vegetation, which contributes to carbon sequestration, improved air quality, and increased urban biodiversity. The improved vegetation cover supports soil organic content and nutrient levels, creating a positive feedback loop where enhanced irrigation leads to healthier plants, which further improve the surrounding microclimate and ecosystem services.

The energy component is linked to rainwater management and irrigation system operation. The energy consumed for rainwater storage and distribution influences energy security, as higher energy demand could increase operational costs. However, this system is designed to be low-cost and highly sustainable, minimizing long-term energy consumption while providing a reliable water source. Additionally, energy consumption for water filtration and irrigation processes must be optimized to ensure an efficient balance between water and energy use.

The CLD in **Figure 10** highlights several reinforcing and balancing feedback loops. A reinforcing loop occurs where increased rainwater harvesting improves water availability, supporting vegetation health, which in turn enhances carbon sequestration, air quality, and urban biodiversity. Another reinforcing loop is seen in microclimate regulation, where expanded vegetation improves evapotranspiration rates, further lowering urban temperatures and increasing overall ecosystem benefits.

Conversely, balancing loops regulate water and energy consumption. Increased energy use for rainwater storage and irrigation can impact energy security, requiring careful management to maintain system sustainability. Additionally, the rate of groundwater recharge versus water withdrawal must be balanced to ensure long-term water availability.

The implementation of a subsurface rainwater harvesting system in DEMO 9.2 demonstrates how NBS can be effectively integrated into urban environments, providing a scalable and efficient solution to water scarcity, urban resilience, and ecosystem enhancement. By adapting the approach from DEMO 1.2a, this DEMO highlights the flexibility and applicability of rainwater harvesting across different spatial contexts.

Scenario Development for DEMO 9.2

The scenario development for DEMO 9.2 evaluates the impact of rainwater harvesting, urban irrigation optimization, and climate resilience on water security and ecosystem enhancement. The baseline scenario assesses current conditions, while future scenarios consider the effects of climate change and variability in rainfall patterns on system performance.

The **baseline scenario** development process examines existing rainfall patterns, runoff generation, infiltration rates, and irrigation water demand. It evaluates the effectiveness of the rainwater harvesting system in reducing freshwater use for irrigation, as well as the initial contributions of enhanced irrigation to vegetation health and urban biodiversity. Additionally, the role of improved soil moisture retention in reducing the need for additional water inputs is included in the baseline framework.

Future scenarios focus on climate change impacts, particularly shifts in rainfall patterns, prolonged droughts, and increasing temperatures. These scenarios explore how changing precipitation levels affect rainwater harvesting potential and urban irrigation strategies, ensuring that the system remains resilient under varying climate conditions. Additionally, the impact of higher temperatures on urban cooling and vegetation water requirements is analysed to determine how irrigation demand may fluctuate in the future.

Through these scenarios, DEMO 9.2 is analysed within the WEFE nexus, ensuring that the subsurface rainwater harvesting system remains an effective solution for sustainable water management, urban greening, and climate adaptation. The adaptation of DEMO 1.2a to an urban setting reinforces the versatility of this NBS, showcasing its potential for broader implementation in cities facing water scarcity challenges.

Data Needs Summary of DEMO 9.2

In the context of the rainwater harvesting system within this DEMO, data collection and modelling efforts are aligned with the primary objectives of the system. These include reducing irrigation water use and enhancing aquifer recharge, thereby reinforcing the water and ecosystem components of the Water-Energy-Ecosystem nexus.

The existing data collection framework effectively captures both quantitative and qualitative aspects of water dynamics within the rainwater harvesting system and the urban green space it supports. This ensures a comprehensive representation of water flows, ecosystem benefits, and indirect environmental impacts. The only identified discrepancy concerns the potential for air quality improvements. However, the latter are not a core objective of the NBS implementation or the nexus assessment.

The energy dimension of the NBS is also integrated into the monitoring plan, encompassing both direct energy consumption associated with the operation of the system and indirect energy gains resulting from microclimate regulation provided by the urban green space. This approach facilitates a holistic evaluation of how the NBS interacts with and influences energy security.

As outlined in Deliverable 4.1, all data related to Demo 9 are collected in situ, eliminating the need for downscaling. This ensures high spatial accuracy in model development, as well as a precise representation of rainfall dynamics, infiltration rates, irrigation demand, and green space functionality.

5.1.8 DEMO 9.3 in Nicosia (Cyprus)

Nexus Interlinkages and Causal Loop Diagram for DEMO 9.3

The CLD in **Figure 11** visualizes the nexus interlinkages within DEMO 9.3, incorporating key components of the WEFE nexus, particularly water, energy, ecosystems, and food. This DEMO integrates a wall-based green facade to support urban farming, contributing to local food production, microclimate regulation, water efficiency, and energy savings in buildings. The system is currently irrigated using potable water, which may negatively impact water security, but the potential integration of greywater reuse, similar to DEMO 4.2, offers an opportunity for sustainable water management. The inclusion of urban farming adds an additional food component to this DEMO, reinforcing local food resilience and reducing emissions from food transport.

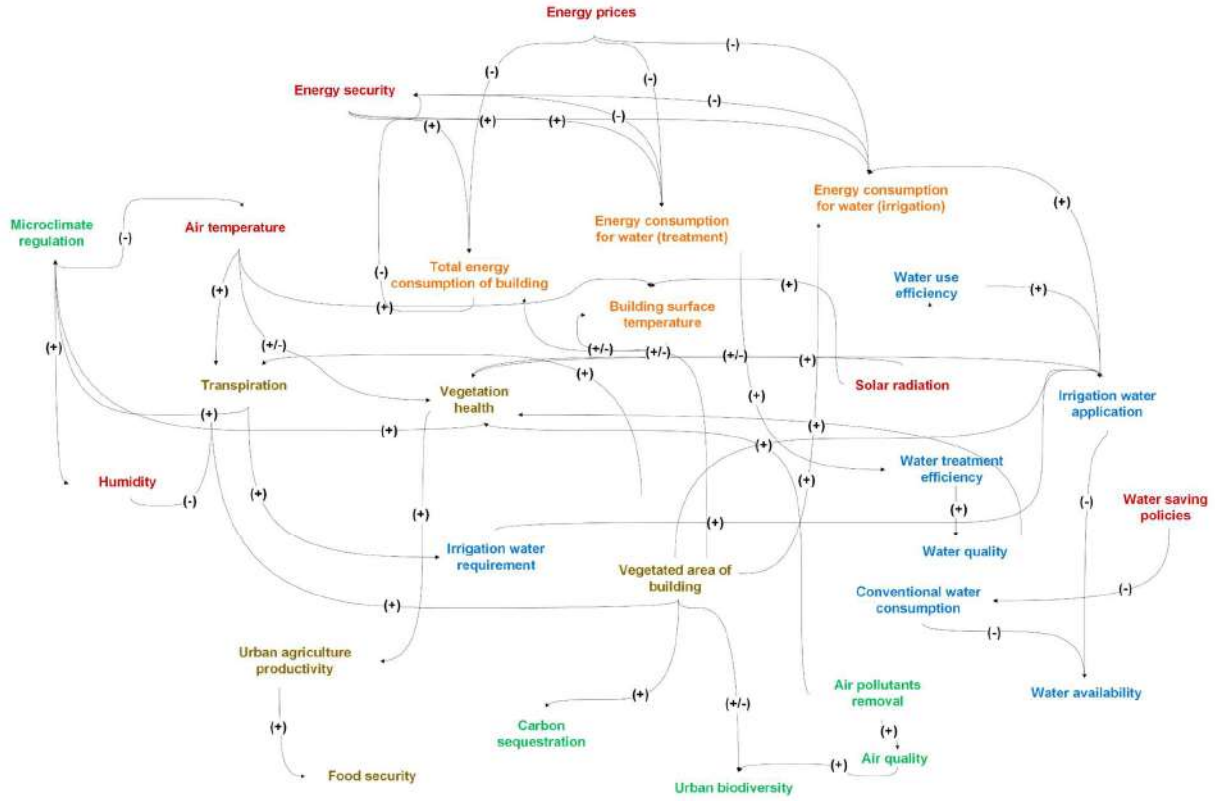

Figure 11. *CLD of DEMO 9.3*

The water component is primarily linked to irrigation efficiency and water treatment. The irrigation water requirement depends on factors such as vegetation health, transpiration rates, and climatic conditions. Currently, potable water is used for irrigation, increasing overall water consumption and potentially reducing water availability. However, introducing greywater as an alternative water source could significantly improve water use efficiency and reduce freshwater demand. Water treatment efficiency influences water quality, ensuring that the system maintains safe irrigation standards, while water-saving policies play a role in promoting responsible irrigation practices.

The energy component is directly linked to building thermal regulation and irrigation water management. The vegetated facade reduces building surface temperature, which lowers the total energy consumption for cooling and heating. This impact is particularly important in hot urban environments, where solar radiation and air temperature drive high energy demand for cooling. The presence of vegetation helps moderate air

temperature through transpiration, contributing to microclimate regulation. Additionally, energy is consumed in water treatment and irrigation, influencing overall energy security and operational efficiency.

The ecosystem component focuses on urban ecosystems and their services, including climate regulation, biodiversity support, and air quality improvement. The green facade contributes to carbon sequestration, air quality improvement, and urban biodiversity. Vegetation health plays a key role in these interactions, as healthier plants lead to higher carbon absorption, improved pollutant removal, and increased biodiversity support. The vertical nature of the system maximizes urban green space, enabling food production in limited areas, which reduces food transportation needs and associated emissions.

The food component is a key addition to this DEMO, as the green facade enables urban farming, strengthening local food resilience. By producing food locally, the system reduces dependence on imported food, lowering carbon emissions from food transport and enhancing food security. The integration of urban farming with vertical green infrastructure demonstrates the potential for multifunctional NBS in cities.

The CLD in **Figure 11** highlights several reinforcing and balancing feedback loops. A reinforcing loop occurs where increased vegetation area improves transpiration rates, leading to reduced air temperature, which enhances plant health, further promoting green coverage and ecosystem services. Another reinforcing loop is seen in energy efficiency, where improved building insulation due to vegetation reduces cooling demand, lowering energy consumption and enhancing energy security. A further reinforcing loop exists within urban farming, where higher food production strengthens local food resilience and reduces emissions from transportation, further promoting sustainability.

Conversely, balancing loops regulate water and energy dynamics. The use of potable water for irrigation can negatively impact water security, requiring a shift toward greywater reuse to ensure long-term sustainability. Similarly, the energy required for irrigation and treatment must be optimized to balance water efficiency with energy security.

The implementation of a green facade for urban farming in DEMO 9.3 demonstrates how NBS can address food resilience, building energy efficiency, and climate mitigation in urban environments. However, water security concerns related to potable water use highlight the need for alternative irrigation sources, such as greywater reuse, to enhance overall sustainability.

Scenario Development for DEMO 9.3

The scenario development for DEMO 9.3 evaluates the impact of urban farming, green facade thermal regulation, and irrigation efficiency on resource sustainability and climate resilience. The baseline scenario assesses current conditions, while future scenarios consider the effects of climate change and alternative water sourcing strategies on system performance.

The **baseline scenario** development process examines existing irrigation practices, vegetation health, and building energy consumption. It evaluates the effectiveness of the green facade in moderating building surface temperature and reducing cooling demand, as well as the contributions of urban farming to food resilience and emissions reduction. Additionally, the current reliance on potable water for irrigation is assessed in relation to overall water security concerns.

Future scenarios focus on the integration of greywater for irrigation, exploring its potential to reduce freshwater consumption while maintaining vegetation health and food production. The impact of climate change on irrigation demand and building energy efficiency is also considered, particularly in relation to rising temperatures and changing precipitation patterns. These scenarios analyse how increased heat stress may affect plant transpiration rates and water demand, as well as whether green facades can provide long-term cooling benefits under extreme climate conditions.

Through these scenarios, DEMO 9.3 is analysed within the WEFE nexus, ensuring that its green facade remains a viable solution for sustainable food production, building energy efficiency, and water conservation. The potential shift from potable water to greywater irrigation offers a critical opportunity to improve water security, reinforcing the importance of integrated resource management in urban sustainability strategies.

Data Needs Summary of DEMO 9.3

The data requirements for the UV-disinfection system and vertical green wall should primarily focus on three key areas: (i) water and energy footprint of the disinfection system, (ii) vegetation health as an indicator of the green wall condition, and (iii) the subsequent impacts on building energy efficiency and urban agricultural productivity. These components are essential for assessing the broader implications of the system within the WEFE nexus.

While the monitoring plan (Deliverable 2.2) accounts for the volumetric aspect of water disinfection, this approach is primarily suited for tap water applications. If greywater reuse is introduced into the system, the monitoring framework must be expanded to include water quality parameters. This would require an assessment of pre- and post-treatment water characteristics, including chemical contaminants, microbial load, turbidity, pH, and nutrient content. Such an update is necessary to ensure that the treated water meets safety and regulatory standards for both irrigation and building use, while also maintaining the integrity of the green wall ecosystem.

The energy fraction of the nexus is comprehensively addressed in the monitoring plan, allowing for a detailed evaluation of energy consumption and efficiency. However, some energy-related factors within the CLD, such as building surface temperature variations, may not be directly measurable. In such cases, these variables will need to be either simulated or substituted with proxy indicators, such as indoor air temperature fluctuations. These proxies can serve as reliable estimates for assessing the thermal regulation benefits provided by the green wall.

The urban farming and biodiversity components are well-documented within the monitoring plan. However, further clarification is required regarding the inclusion of vegetation health metrics. Since vegetation health serves as an intermediate variable linking water treatment and provision to the ecological and agricultural benefits of the green wall, it is essential that this aspect be explicitly integrated into data collection efforts. Key parameters such as leaf chlorophyll content, canopy density, or drought stress indicators could be incorporated to assess the overall performance of the system. The absence of such data would eventually add uncertainty primarily in the quantification of the link between the function of the green wall and its downstream impacts on the energy footprint of the building.

As already discussed in the other cases of Demo 9 (Demo 9.1 and 9.2), all data are available at a local scale, while the temporal resolution is sufficient to capture both short- and long-term impacts of the NBS implementation.

5.2 Peri-Urban Areas: Findings for all relevant DEMOs

5.2.1 DEMO 2 in Oinofyta (Beotia, Greece)

Nexus Interlinkages and Causal Loop Diagram for DEMO 2

The CLD in **Figure 12** illustrates the WEFE nexus interlinkages within DEMO 2, focusing on water management in an industrial peri-urban context. This DEMO integrates NBS to recover, treat, and reuse rainwater, peri-urban runoff, and industrial wastewater, reducing external water dependency and enhancing water security. The system operates within a regulatory framework that ensures compliance with water quality standards and ESG alignment, supporting sustainable industrial operations.

The water component is central to this DEMO, as it involves the treatment and reuse of multiple water sources. Rainwater harvesting, wastewater treatment, and runoff management contribute to alternative water production, reducing the demand for freshwater extraction. Industrial water demand influences the volume of water required, while regulatory policies ensure proper treatment and compliance with water quality standards. The efficiency of biofiltration columns and bioswales determines the quality of treated wastewater and harvested rainwater, impacting internal water availability. Additionally, surface runoff collection and rainwater infiltration support flood risk reduction and aquifer recharge, improving long-term water sustainability.

The energy component is linked to water treatment and distribution processes. Energy is consumed for wastewater treatment, rainwater filtration, and runoff processing, affecting energy security and overall industrial energy demand. The effectiveness of the treatment system influences total energy consumption, creating a balance between water reuse efficiency and energy requirements. Optimizing energy inputs is essential to ensure sustainability while maintaining high water treatment efficiency.

The ecosystem component plays a role through permeable areas and green infrastructure, enhancing water infiltration and reducing surface runoff. The presence of NBS such as bioswales improves stormwater management, preventing uncontrolled discharges and pollutant accumulation in water bodies. These ecosystem-based interventions contribute to water security and environmental resilience in the peri-urban industrial landscape.

The CLD in **Figure 12** showcases reinforcing and balancing feedback loops. A reinforcing loop occurs where improved wastewater treatment leads to increased alternative water production, which reduces external water dependency, further improving internal water availability and industrial sustainability. Another reinforcing loop is seen in surface runoff management, where increased water infiltration lowers flood risk and enhances water security, further supporting alternative water use.

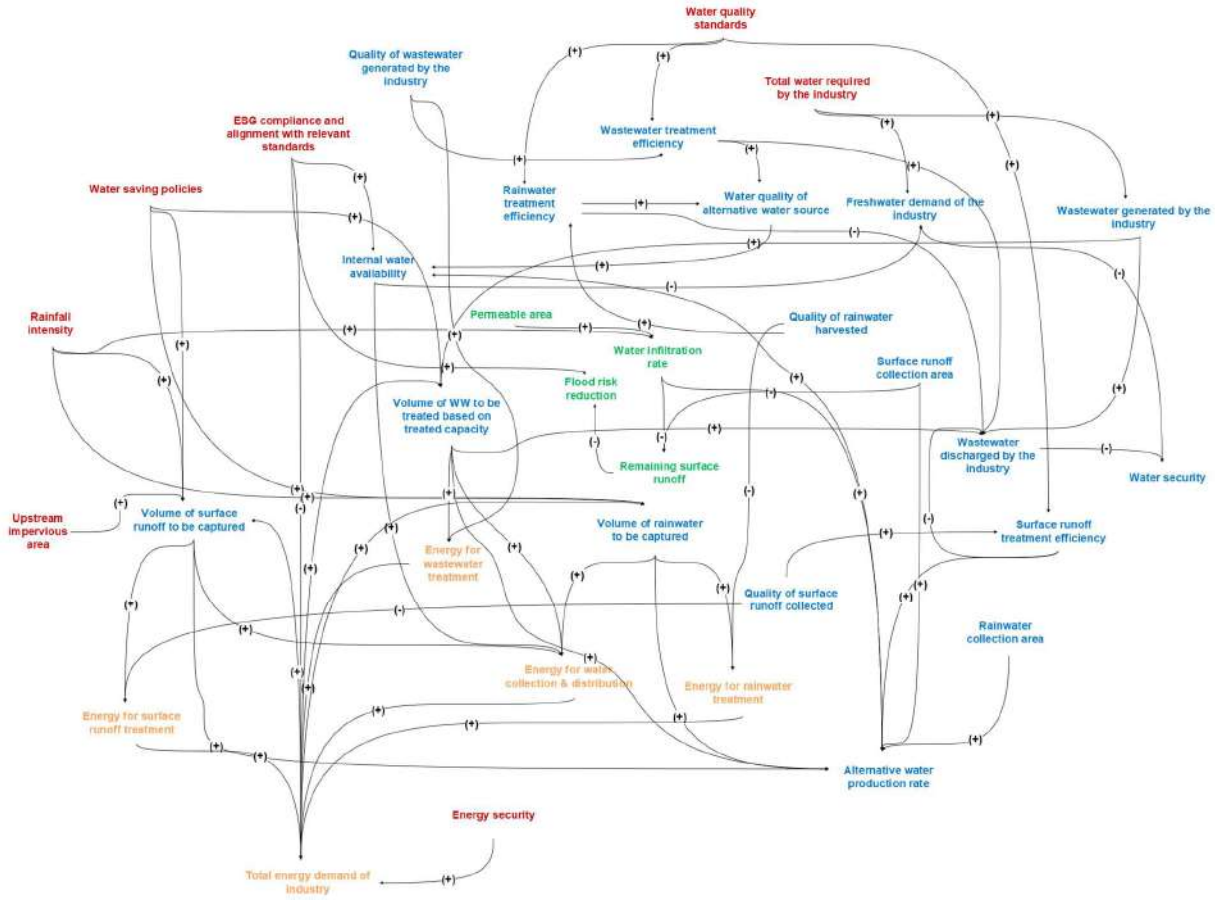

Figure 12. *CLD of DEMO 2*

Conversely, balancing loops regulate energy consumption and treatment capacity. Higher energy demand for treatment could impact energy security, requiring optimizations in efficiency and resource allocation. Additionally, compliance with water quality standards ensures that only properly treated water is reused, maintaining industrial sustainability while preventing environmental degradation.

The implementation of NBS for industrial water reuse in DEMO 2 highlights the potential of nature-based and circular solutions in industrial water management. By reducing external water dependence and enhancing

treatment efficiency, this DEMO contributes to sustainable water resource use, energy efficiency, and regulatory compliance in peri-urban industrial settings.

Scenario Development for DEMO 2

The scenario development for DEMO 2 focuses on the impact of smart water management, industrial water demand, climate variability, and evolving regulatory frameworks on water security and industrial sustainability. The baseline scenario assesses current water consumption patterns, while future scenarios analyse the effects of climate change, stricter regulations, and the polluter pays principle on the long-term resilience of the system.

The **baseline scenario** development process evaluates existing industrial water use, treatment efficiency, and regulatory compliance. It examines rainwater harvesting potential, wastewater treatment performance, and the capacity of bioswales to manage surface runoff. Additionally, it assesses the energy consumption associated with water treatment and its implications for overall industrial energy security. The current regulatory landscape and ESG compliance requirements shape industrial water management practices, influencing the extent to which alternative water sources are integrated.

Future scenarios explore the effects of climate change on water availability, considering variations in rainfall intensity, surface runoff generation, and seasonal water demand fluctuations. These scenarios analyse how prolonged droughts or increased storm events may affect water treatment efficiency and alternative water supply reliability. Reduced rainfall and longer dry periods may intensify industrial water stress, while extreme precipitation events may challenge runoff management and flood control measures.

Additionally, stricter environmental regulations and the polluter pays principle could alter the economic and operational feasibility of industrial water use. **Future scenarios** consider how tighter discharge limits and economic penalties for wastewater pollution may drive industries to increase internal water reuse, adopt alternative water sources, and invest in water-efficient practices. These regulatory pressures could reinforce the role of NBS and decentralized water treatment solutions in ensuring long-term compliance and cost-effectiveness.

By integrating these considerations, the scenario analysis for DEMO 2 assesses how climate variability and regulatory shifts influence water security, energy efficiency, and long-term industrial sustainability. The findings will provide critical insights into how NBS can enhance adaptive capacity while ensuring that industrial operations remain resilient, compliant, and environmentally responsible.

Data Needs Summary of DEMO 2

CLD illustrates a dynamic system involving interconnected variables primarily across water management and energy consumption, and to a lesser extent ecosystem services. To effectively monitor and model this system, comprehensive data collection is necessary to capture the interactions and feedback loops.

Key water-related data should include measurements of rainwater collection, encompassing the surface runoff collection area, the volume of runoff captured, and the quality of surface runoff. Water treatment processes require data on treatment capacities, the quality of untreated and treated water, and the efficiency of various treatment systems, such as those for freshwater, rainwater, and wastewater. Additionally, metrics on water reuse, discharge volumes, and water infiltration rates, alongside the characteristics of permeable surface areas, are essential for understanding aquifer recharge and overall system performance. Water-related data will also allow for the assessment of the only ecosystem-related service, i.e., flood risk reduction. Overall, understanding the ability of the system to enhance water security is vital for assessing its long-term sustainability.

Energy-related data should focus on the energy demands associated with rainwater, wastewater, and freshwater treatment processes. This includes measuring energy consumption, treatment energy efficiency, and energy intensity per unit of water treated.

System feedback and policy-related influences should be addressed by monitoring the impact of water-saving policies, regulatory compliance, and external factors such as upstream impervious areas and rainfall intensity. These elements shape the dynamics of water flow, treatment demands, and resource availability.

To ensure accurate representation of the behaviour of the data, in-situ data collection is essential. For variables that are difficult to measure directly, proxy indicators or simulations may be utilised. A combination of high temporal resolution data and modelling will capture its dynamic interactions and feedback mechanisms effectively.

Despite being a data-thirsty system, the current monitoring plan (Deliverable 2.2) has described in detail all the abovementioned water and energy aspects. As outlined in Deliverable 4.1, the data are of sufficient temporal resolution to capture the intrinsically dynamic behaviour of the system.

5.2.2 DEMO 3 in Alghero (Sardinia, Italy)

Nexus Interlinkages and Causal Loop Diagram for DEMO 3

The CLD in **Figure 13** highlights the WEFE nexus interlinkages within DEMO 3, which integrates sustainable agriculture, water reuse, renewable energy, and ecosystem restoration in a peri-urban farming system. This DEMO focuses on reducing water consumption, improving soil health, and protecting surface waters while ensuring sustainable crop production and energy self-sufficiency.

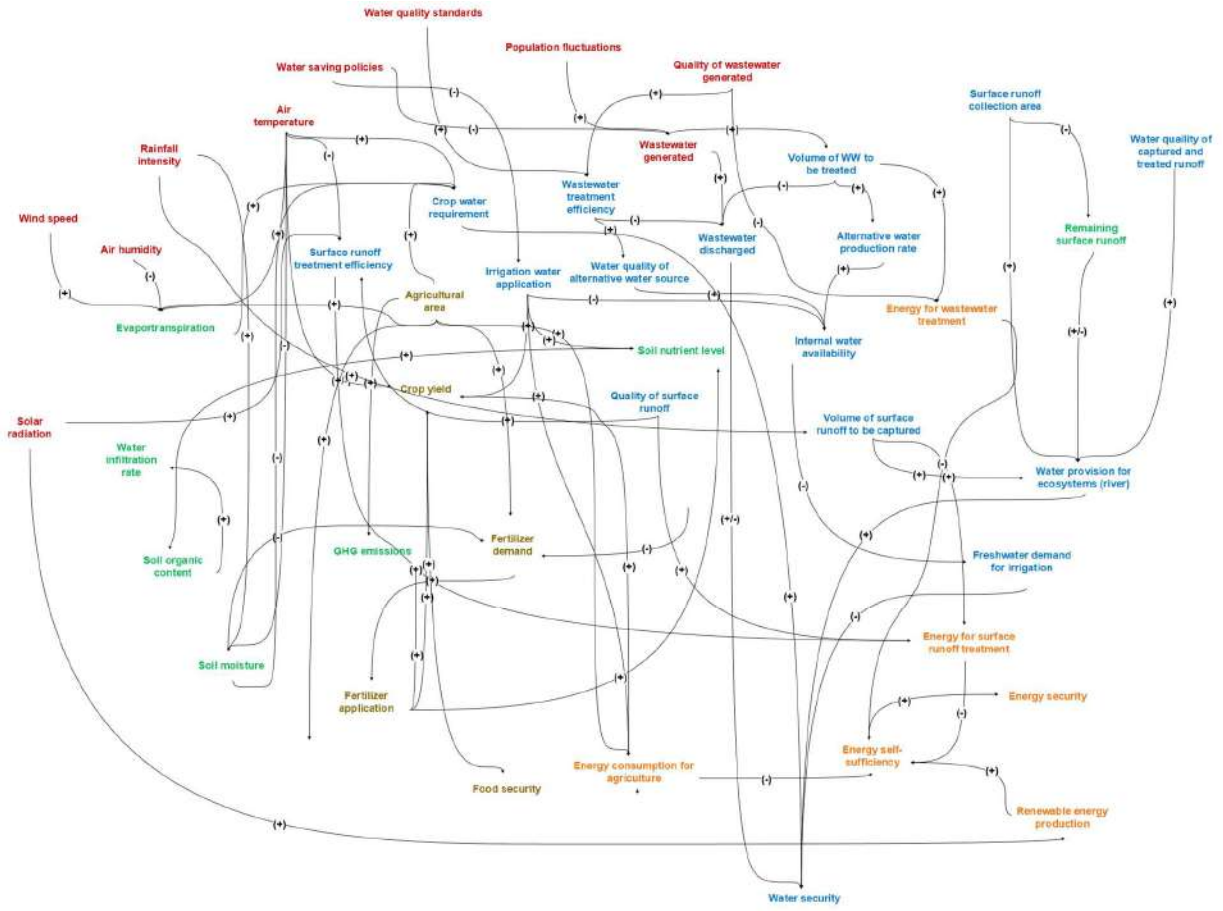

Figure 13. *CLD of DEMO 3*

The water component is essential to this DEMO, as irrigation depends on treated wastewater from the San Marco WWTP, ensuring compliance with EU Class A water quality standards. Alternative water production

from treated wastewater reduces reliance on freshwater resources, enhancing water security. Additionally, surface runoff management through wetlands and riparian buffers improves water quality before discharge into nearby rivers, contributing to water provision for ecosystems. The quality of treated wastewater and irrigation efficiency influence the crop water requirement and overall water availability, forming a reinforcing feedback loop between water reuse and sustainable agriculture.

The energy component is integrated through solar panels, which power both irrigation and wastewater treatment systems, supporting renewable energy production and energy self-sufficiency. The use of solar energy reduces dependency on external energy sources, contributing to energy security. However, energy is still required for wastewater treatment and surface runoff processing, balancing the sustainability gains from renewable energy with operational energy demands.

The food and farming component is represented by crop cultivation over a five-year rotation cycle, including wheat, maize, and alfalfa. This system supports food security while maintaining soil fertility through organic fertilizers and crop residues. Soil organic content and soil moisture retention are improved by sustainable agricultural practices, positively influencing crop yield and reducing irrigation needs. Additionally, fertilizer application and nutrient cycling are optimized through organic inputs, reducing synthetic fertilizer demand and minimizing environmental impacts.

The ecosystem component is embedded in agricultural runoff and drainage management, where a free water surface wetland and riparian buffer filter nutrients and contaminants before reaching water bodies. These NBS enhance soil infiltration rates, improve water retention, and reduce surface runoff, contributing to flood risk reduction and water security. Vegetation within the riparian buffer further supports carbon sequestration, biodiversity, and overall ecosystem resilience.

The CLD in **Figure 13** illustrates multiple reinforcing feedback loops. Higher soil organic content improves water retention, reducing the need for irrigation, which in turn decreases reliance on external freshwater sources, reinforcing water security. Similarly, solar-powered wastewater treatment creates a circular system where renewable energy supports sustainable water reuse, which in turn sustains agriculture. However, balancing feedback loops regulate energy consumption for water treatment and the efficiency of runoff management, ensuring that resource use remains sustainable.

Overall, DEMO 3 demonstrates how integrated NBS can enhance agricultural sustainability by linking water reuse, renewable energy, and ecosystem-based solutions, ensuring resource efficiency and environmental resilience in peri-urban farming systems.

Scenario Development for DEMO 3

The scenario development for DEMO 3 focuses on evaluating the resilience of sustainable agriculture under climate change and energy constraints. The baseline scenario assesses current agricultural water use, energy consumption, and soil management practices, while future scenarios explore the impacts of climate variability on water availability and the sustainability of wastewater reuse for irrigation.

The **baseline scenario** development process evaluates irrigation efficiency, treated wastewater availability, crop water requirements, and nutrient management strategies. The role of solar energy in maintaining irrigation and wastewater treatment operations is also assessed, along with the effectiveness of wetlands and riparian buffers in improving water quality. This scenario establishes a reference for analysing how different stressors may alter system performance.

Future scenarios explore the effects of climate change on water availability, considering variations in rainfall intensity, evapotranspiration rates, and seasonal crop water demand. These scenarios analyse how prolonged droughts or extreme precipitation events may impact irrigation efficiency, soil moisture retention, and alternative water production from treated wastewater. Reduced precipitation could increase irrigation reliance on treated wastewater, while intensified rainfall may challenge surface runoff management and wetland filtration capacity.

By integrating these considerations, the scenario analysis for DEMO 3 will assess how climate variability and energy sustainability influence agricultural water security, crop productivity, and ecosystem resilience. These findings will provide critical insights into the role of NBS in maintaining sustainable agriculture, ensuring that water, energy, and nutrient management practices remain adaptive and efficient in a changing climate.

Data Needs Summary of DEMO 3

The provided CLD illustrates the dynamic interactions encompassing water, energy, agriculture, and ecosystem services (biodiversity support and water purification in particular). Accurate monitoring and modelling of this system necessitate a comprehensive set of data across multiple domains.

Water-related data requirements include the volume and quality of water generated, treated, and utilised. Parameters such as surface runoff collection, water infiltration rates, and irrigation efficiency are vital for assessing water management. Data on groundwater recharge, water quality standards compliance, and the water footprint of agricultural production should also be collected to evaluate resource sustainability.

Agricultural data must include metrics on crop yield. The quality of treated water used in irrigation, soil organic content, soil moisture, and nutrient levels should be monitored to ensure the productivity and health of the agricultural system. Additionally, data on fertiliser application and its impact on soil fertility are essential to understand the agricultural-environmental dynamics.

Energy-related data requirements include energy consumption for water treatment, irrigation, and agricultural operations, as well as the efficiency of energy use in these systems. Information on renewable energy integration and its contribution to reducing energy insecurity and carbon emissions should also be monitored. Energy outflows and demand for treatment and pumping activities need to be tracked to evaluate the overall energy footprint of the NBS.

Hydrometeorological data should capture changes in air temperature, humidity, wind speed, and solar radiation, which influence the resilience of the system.

As outlined in Deliverable 2.2, the abovementioned requirements will be met through the monitoring plans. Water will be monitored in both its volumetric and qualitative aspects. Soil quality will be likewise considered. In addition, soil biodiversity will be routinely monitored to complement the ecosystem dimension of the nexus. Lastly, the energy dimension of the nexus is adequately discussed in the monitoring plan, covering both the consumption of the treatment processes and the introduction of renewable energy.

As with any dynamic system, in-situ data collection is critical to ensure accurate representation of system behaviours. As indicated in Deliverable 4.1, available and future datasets are of sufficient spatiotemporal resolutions. For variables that are difficult to measure directly (e.g., irrigation demands), simulation models or proxy indicators should be employed.

Overall, these datasets collectively support the assessment of the performance of the NBS in addressing water, energy, food, and environmental challenges within an integrated nexus framework.

5.3 Rural Areas: Findings for all relevant DEMOs

5.3.1 DEMO 1.1 in Antissa (Lesvos, Greece)

Nexus Interlinkages and Causal Loop Diagram for DEMO 1.1

The CLD in **Figure 14** illustrates the WEFE nexus interactions within DEMO 1.1, which integrates wastewater treatment, agricultural water reuse, bioenergy production, and soil management in a rural setting. This DEMO emphasizes circular resource flows by recovering water, nutrients, and energy from municipal wastewater, reducing dependency on external inputs while promoting sustainability.

The water component is central to DEMO 1.1, where municipal wastewater undergoes anaerobic treatment in UASB reactors, followed by constructed wetlands, filtration, and disinfection. The reclaimed water is used for irrigation in multicultural cropland, reducing the demand for freshwater withdrawals and enhancing water

security. The efficiency of wastewater treatment directly influences water quality and availability, affecting crop productivity and soil health. Additionally, water infiltration and runoff processes impact groundwater recharge and surface water pollution, reinforcing the connection between water and ecosystem components.

The energy component is integrated through biogas generation from anaerobic digestion, which is upgraded to bio-methane and contributes to energy self-sufficiency. This reduces reliance on external energy sources, supporting energy security. However, energy is still required for wastewater treatment, water distribution, and agricultural operations, forming balancing feedback loops between energy production, consumption, and sustainability.

The food and farming component is driven by irrigated multicultural cropland, where fertigation water supports crop growth. The system maintains soil organic content and nutrient levels, improving agricultural output resilience. Fertilizer demand is reduced due to the availability of reclaimed water, which contains essential nutrients, forming a reinforcing feedback loop between water reuse and soil fertility. Additionally, crop water requirements and evapotranspiration rates influence irrigation needs, highlighting the interdependence between climate variables, water use, and crop productivity.

The ecosystem component benefits from the multicultural cropland, which supports biodiversity and provides ecosystem services such as carbon sequestration and habitat support. The CLD in **Figure 14** showcases how soil infiltration, surface runoff, and evapotranspiration interact with vegetation, climate, and water flows, shaping local microclimate conditions and reducing environmental impacts.

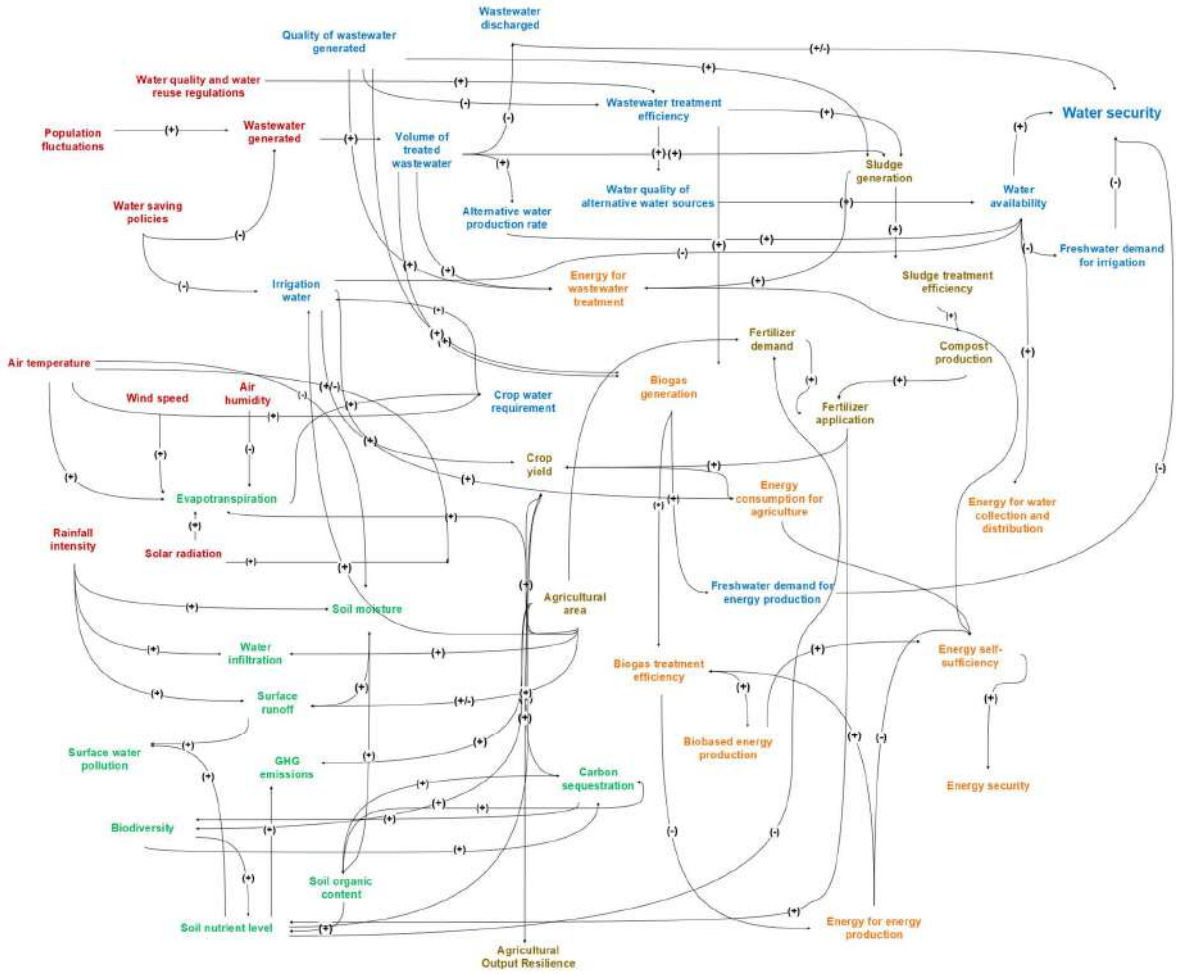

Figure 14. *CLD of DEMO 1.1*

Overall, DEMO 1.1 demonstrates a highly integrated approach where wastewater treatment, bioenergy recovery, and multicultural cropland interact to enhance sustainability, reduce external dependencies, and strengthen climate resilience in rural areas.

Scenario Development for DEMO 1.1

The scenario development for DEMO 1.1 focuses on assessing the resilience of wastewater reuse, energy recovery, and multicultural cropland under climate variability and resource constraints. The baseline scenario evaluates the current performance of the wastewater treatment system, bio-methane production, and fertigation efficiency, while future scenarios explore climate-induced water stress and its impacts on agricultural productivity and energy sustainability.

The **baseline scenario** development process assesses wastewater inflow variability, treatment efficiency, fertigation benefits, and bioenergy yields, establishing a reference for evaluating system resilience. Additionally, the role of reclaimed water in sustaining multicultural cropland and reducing groundwater withdrawals is examined, ensuring that water reuse strategies contribute to long-term agricultural sustainability.

Future scenarios explore the effects of climate change on water availability, considering variations in rainfall intensity, evapotranspiration rates, and irrigation demand. These scenarios assess how extreme droughts or shifting precipitation patterns may affect wastewater treatment efficiency, reclaimed water availability, and crop water requirements. Reduced rainfall could increase the importance of wastewater reuse, while prolonged droughts may affect water infiltration, soil moisture retention, and crop resilience.

The energy-water-agriculture interactions are also examined under future stressors. If water availability decreases, there may be increased energy demand for water treatment and distribution, affecting the system's energy balance and bio-methane utilization. Additionally, higher temperatures and increased evapotranspiration could modify crop water needs, influencing the effectiveness of fertigation strategies.

By integrating these elements, the scenario analysis for DEMO 1.1 will provide critical insights into the sustainability of wastewater reuse, bioenergy production, and multicultural cropland under changing climatic conditions, ensuring that the system remains adaptive and resilient to future environmental challenges.

Data Needs Summary of DEMO 1.1

The CLD outlines a dynamic system where water management, energy production, agriculture, and ecosystem services interact to achieve integrated sustainability outcomes.

Water-related data requirements include the quantity and quality of wastewater treated, the efficiency of wastewater treatment processes, and the volumes of treated water reused. Monitoring alternative water production rates, water retention, infiltration, and runoff are vital for understanding water availability and security within the system. Surface water quality, agricultural water use, and irrigation efficiency must also be tracked to evaluate the NBS's impact on local water cycles and agricultural productivity.

In the agricultural domain, data should cover both soil health and crop yields produced by the system. Soil health parameters, such as soil organic content, soil moisture, and nutrient levels, are critical for assessing the sustainability of agricultural practices. Metrics on soil biodiversity and carbon sequestration further reflect the contribution of the system to ecosystem health and climate resilience.

Metrics on sludge generation, compost production, and fertiliser application are required to link wastewater treatment processes to agricultural productivity and soil health. Monitoring the efficiency of sludge treatment and the use of fertilisers derived from compost will enhance the understanding of resource recovery in the system.

The energy component requires detailed monitoring of energy consumption for water treatment, irrigation, and agricultural operations, as well as biogas production and utilisation efficiency. Data on energy production and overall energy self-sufficiency will indicate the NBS ability to contribute to energy security. Energy demand

for water distribution and treatment should also be assessed to understand the energy footprint of the system.

The monitoring plan, as described in Deliverable 2.1, balances water, energy and soil monitoring, addressing most of the aspects of the abovementioned data needs. The water monitoring plan is detailed, emphasizing both the quantitative and qualitative considerations of water security in the DEMO. Soil data collection also supports the link between wastewater treatment, compost production and agricultural productivity, thereby enabling a clear understanding of the resource recovery processes. Similarly, energy monitoring effectively disaggregates consumption pathways (e.g., wastewater treatment and agricultural operations) and accounts for energy production dynamics, offering a nuanced view of energy flows in the system. While the monitoring plan provides valuable insights into various aspects of NBS operation, additional data on fertilization practices and compost application would further strengthen the assessment of its impacts on soil fertility and agricultural productivity. Capturing these elements more comprehensively would help establish the feedback loop between NBS processes, nutrient cycling, and crop yield outcomes. Where direct measurements are unavailable, modeling and proxy indicators – such as soil organic matter, nutrient levels, and plant biomass – can help fill in the gaps, ensuring a more robust evaluation of the NBS contribution to sustainable agriculture and soil health.

By collecting high-resolution temporal and spatial data for these variables, as indicated in Deliverable 4.1, the dynamic behaviour of the system can be accurately captured by our nexus approach, offering insights into its performance across the water-energy-farming-ecosystem nexus.

5.3.2 DEMO 1.2A in Ano Mera (Mykonos, Greece)

Nexus Interlinkages and Causal Loop Diagram for DEMO 1.2A

The CLD in **Figure 15** illustrates the interactions between the water, energy, food, and ecosystem components of DEMO 1.2A, which integrates a sub-surface rainwater collection and smart irrigation system to support climate-resilient agriculture in a region affected by water scarcity and seasonal tourism-driven water demand fluctuations.

The water component plays a central role, as rainwater is collected, stored, and reused for irrigating an oregano field, reducing reliance on groundwater and conventional water sources. The availability of alternative water sources alleviates water scarcity and mitigates competition between agricultural and domestic water demands. The efficiency of the system depends on rainfall intensity, surface runoff, and water infiltration rates, which influence rainwater storage capacity and irrigation supply stability.

The energy component is linked to water pumping, storage, and irrigation processes, where the energy demand for water management depends on the efficiency of smart irrigation. This creates a balancing feedback loop, where optimized irrigation reduces energy consumption, improving overall resource efficiency and energy security.

The farming component is impacted by water availability, as sufficient and timely irrigation ensures oregano yield and agricultural output resilience. Smart irrigation contributes to water efficiency, preventing overuse while maintaining soil moisture levels. Additionally, soil organic content, nutrient levels, and evapotranspiration rates influence crop water requirements, forming feedback loops that regulate fertilizer demand and soil health.

The ecosystem component is reflected in the sustainable management of agricultural land, contributing to soil health, biodiversity, and carbon sequestration. Reduced groundwater abstraction limits environmental degradation, while improved water infiltration and reduced surface runoff enhance soil moisture retention and climate resilience. Seasonal variations in tourism-driven water demand interact with water-saving policies, influencing long-term water security in the region.

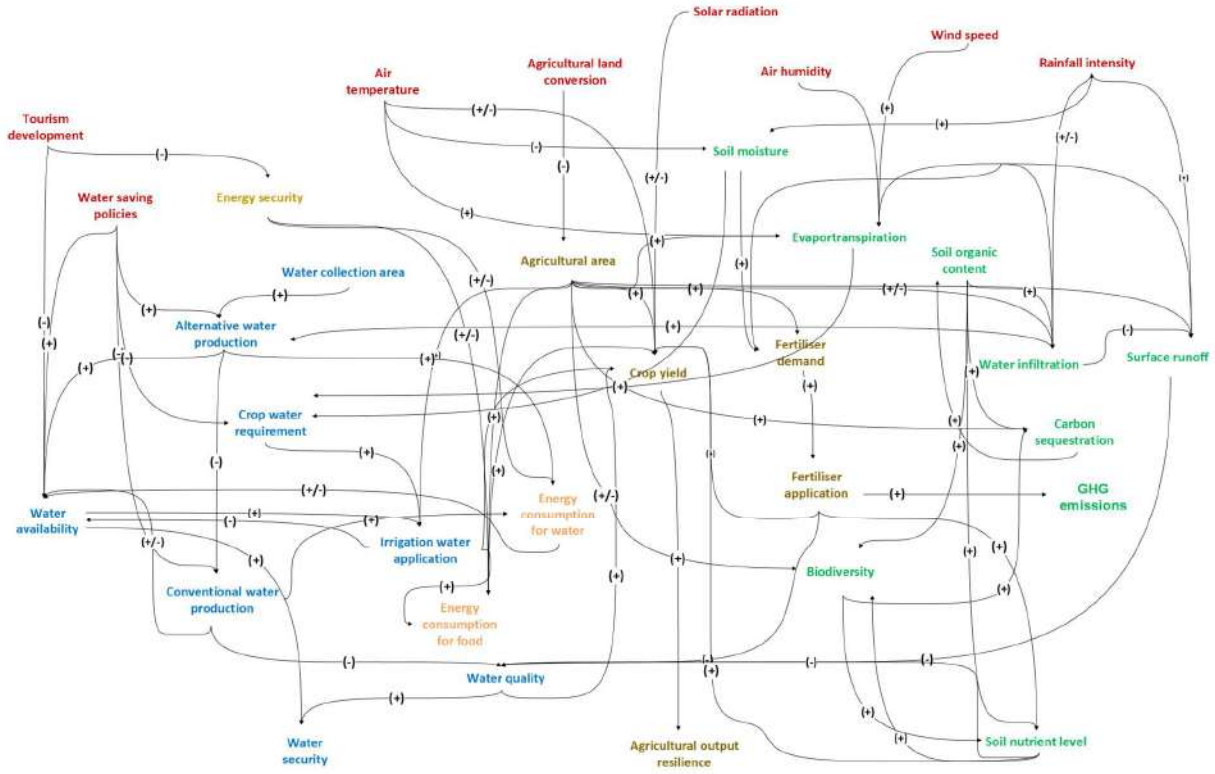

Figure 15. *CLD of DEMO 1.2A*

Through these interconnected elements, DEMO 1.2A demonstrates how integrating NBS with smart irrigation and rainwater harvesting improves agricultural resilience while mitigating resource conflicts between agriculture and tourism in a water-stressed environment.

Scenario Development for DEMO 1.2A

The scenario development for DEMO 1.2A focuses on analysing the performance of the rainwater harvesting and irrigation system under different climate and resource availability conditions, ensuring that it remains resilient to climate variability and seasonal water demand fluctuations.

The **baseline scenario** assesses the effectiveness of rainwater collection and storage, the efficiency of smart irrigation, and the system's ability to maintain stable oregano production while reducing reliance on groundwater. It also examines the influence of seasonal tourism on water availability, ensuring that agriculture and domestic use can coexist without exacerbating local water scarcity.

Future scenarios explore the effects of climate change on water availability, considering variations in rainfall intensity, evapotranspiration rates, and irrigation demand. These scenarios analyze how prolonged droughts or shifts in precipitation patterns may affect rainwater harvesting efficiency, potentially reducing water storage reliability and increasing dependence on conventional water sources.

Additionally, **future scenarios** assess the long-term impact of water-saving policies and shifting land use patterns on the sustainability of the system. Increased tourism development or changes in agricultural land use could modify water demand dynamics, influencing resource allocation strategies and the effectiveness of the implemented NBS.

By examining these variables, scenario analysis for DEMO 1.2A provides insights into how rainwater harvesting and smart irrigation can support climate-resilient agriculture while ensuring long-term water security in a tourism-influenced, water-scarce environment.

Data Needs Summary of DEMO 1.2A

As in the previous DEMO, The CLD illustrates a dynamic system focusing on the interactions between water, energy, agriculture, and ecosystem services. To effectively monitor and model this system, data requirements must address key internal variables and feedback loops.

This complex causal diagram requires comprehensive water-related data monitoring to address water scarcity and optimise the sub-surface rainwater collection system. Continuous rainfall data is crucial for evaluating the volume of rainwater captured, while data on runoff collection efficiency, surface permeability, and infiltration rates ensure the performance of the system in harvesting water. Post-capture water quality metrics, such as turbidity, pH, nutrient content, and microbial contamination, are essential to guarantee suitability for irrigation. Storage performance data for detention vaults and tanks will determine their ability to provide sufficient water during dry periods, while smart irrigation system data, including distribution rates and soil moisture levels, will optimise water use for the oregano field. A water use balance, incorporating withdrawals for agricultural irrigation and domestic needs versus storage replenishment, is critical for assessing sustainability. Additionally, the temporal extent of the data needs to be sufficient to capture the resilience of the system to climatic and seasonal variations, particularly during peak tourism months.

Data on crop yield must be collected to link water management with productivity. Soil health data, including soil moisture, organic content, and nutrient levels, are vital to understanding the connection between soil fertility, carbon sequestration, and greenhouse gas emissions. Additionally, data on fertiliser application and demand are necessary to assess nutrient cycling and its impact on agricultural output.

Energy-related data should encompass energy consumption for water and food production, highlighting energy efficiency and its role in enhancing energy security. Biodiversity indicators further reflect the ecosystem-related benefits from the application of the system.

The monitoring plan (see Deliverable 2.2) has carefully considered a thorough water monitoring campaign, covering adequately all aspects of the rainwater harvesting system (quantity of harvested water, and post-harvesting quality features). Soil monitoring is primarily covering fertility and its water holding capacity. Therefore, this aspect could be augmented through the inclusion of soil organic content and soil biodiversity. Lastly, energy-related monitoring efforts are sufficiently covering the estimation of the energy footprint of agricultural productivity.

The data collection process should incorporate in-situ monitoring to effectively capture dynamic interactions at an appropriate local scale. High-resolution temporal and spatial data are essential for elucidating the feedback mechanisms that drive the complex network of cause-and-effect relationships within the nexus. As outlined in Deliverable 4.1, the current data sources are aligned with the required spatial scale for accurately representing system dynamics. In terms of temporal resolution, the majority of datasets are collected at intervals of one month or less, enabling the effective monitoring of seasonal variations within the system. However, certain longer-term dynamics will inherently be captured through datasets with lower collection frequencies, which complement the high-resolution data by providing broader temporal trends.

5.3.3 DEMO 1.2B in Ano Mera (Mykonos, Greece)

Nexus Interlinkages and Causal Loop Diagram for DEMO 1.2B

The CLD in **Figure 16** illustrates the interactions between the water, energy, food, and ecosystem components of DEMO 1.2B, which integrates a rainwater harvesting system, bioswale, and smart irrigation to enhance water security and climate resilience in a region characterized by seasonal water scarcity and tourism-driven demand fluctuations.

The water component is central, as the system captures, stores, and reuses rainwater and stormwater runoff from rooftops and yards, supplying non-potable domestic water and irrigation for a lavender field. This reduces dependence on groundwater and conventional water supplies, mitigating water scarcity risks. Bioswales facilitate aquifer recharge, ensuring long-term groundwater stability, particularly during dry seasons when water availability is limited. Stormwater collection and infiltration processes help manage surface runoff, reducing flood risks while improving soil moisture retention and water infiltration rates.

The energy component is linked to water collection, storage, and distribution for domestic and agricultural applications. Smart irrigation optimizes water use efficiency, thereby reducing energy demand for water pumping. The system contributes to energy security by minimizing the need for high-energy water extraction and transport, particularly in peak tourism seasons when resource demand surges.

The farming component benefits from enhanced irrigation reliability, ensuring stable lavender production while reducing agricultural pressure on groundwater resources. Efficient water use enhances crop yield, while improved soil moisture and infiltration support long-term agricultural sustainability. The relationship between fertilizer demand, soil nutrient levels, and crop productivity establishes feedback loops that regulate resource use and environmental impact.

The ecosystem component plays a role in aquifer recharge, soil health, and flood risk reduction. The bioswale enhances biodiversity by supporting vegetation growth and natural water filtration processes. Surface runoff management mitigates pollution risks, preventing contaminants from entering natural water bodies. By improving water infiltration and soil organic content, the system supports ecosystem services that contribute to long-term climate resilience.

These interactions demonstrate how DEMO 1.2B leverages NBS to enhance water security, agricultural sustainability, and ecosystem health, while addressing water-energy challenges in a tourism-affected region.

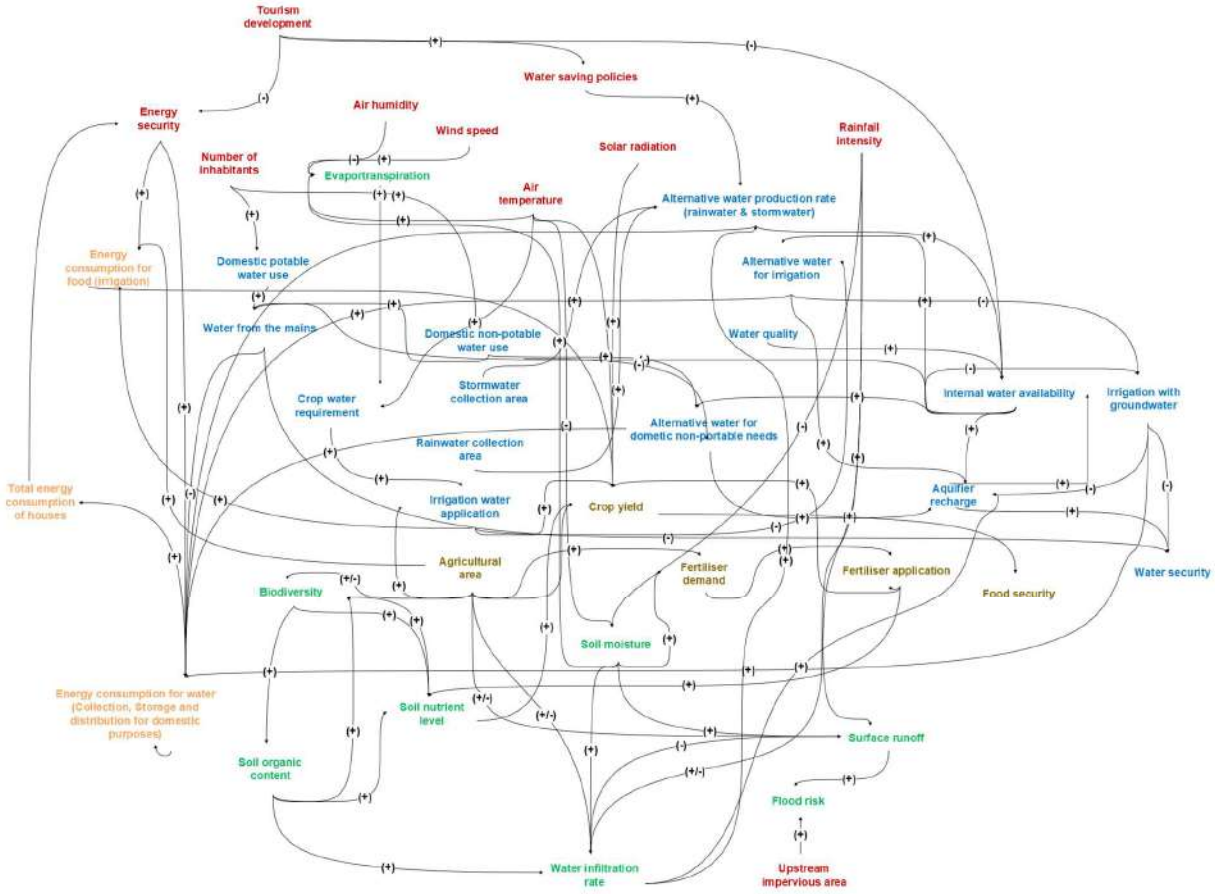

Figure 16. *CLD of DEMO 1.2B*

Scenario Development for DEMO 1.2B

The scenario development for DEMO 1.2B focuses on evaluating the system's capacity to sustain water availability under changing climate conditions and fluctuating tourism-driven water demand.

The **baseline scenario** assesses rainwater harvesting efficiency, stormwater infiltration, and aquifer recharge rates, while analysing the system's ability to provide alternative water for non-potable domestic uses and irrigation. The impact of seasonal tourism on water demand is examined to ensure that the system effectively mitigates competition for water resources between domestic and agricultural users.

Future scenarios explore the effects of climate change on water availability, considering variations in rainfall intensity, stormwater runoff, and extended drought periods. These scenarios assess how shifts in precipitation patterns may impact the system's reliability, particularly during low-rainfall seasons, and evaluate whether the aquifer recharge function remains effective under extreme weather events.

Additionally, scenarios analyse the long-term sustainability of stormwater harvesting policies, considering potential increases in tourism-driven water demand and how stricter water-saving policies might enhance overall system efficiency. By integrating these insights, DEMO 1.2B's scenario development provides a comprehensive understanding of how rainwater harvesting and bioswale-based recharge can support climate-resilient water management in a region where tourism and agriculture compete for scarce water resources.

Data Needs Summary of DEMO 1.2B

Like in the previous DEMO, the CLD focuses on water security, energy consumption, agricultural productivity, and to a lesser extent on ecosystem services. Effective data collection is essential to capture the dynamics of this interconnected system and inform sustainable resource management.

Water-related data must include metrics on the availability and quality of alternative (harvested rainwater) and conventional water sources, the volume of water collected and distributed, and irrigation water application efficiency. Data on rainwater and stormwater collection areas, as well as groundwater recharge and withdrawals, are essential to evaluate water security and sustainability. Monitoring domestic potable and non-potable water use, alongside crop water requirements, is critical for balancing competing demands. Lastly, water-related data will allow further estimation of surface runoff and, thereby, flood risk mitigation from the operation of the NBS.

For agriculture, data collection should encompass crop yield, and fertiliser application rates, alongside soil health indicators such as soil moisture levels, organic content, and nutrient availability. Biodiversity metrics are also necessary to understand the ecological impacts of agricultural practices and their role in maintaining ecosystem resilience.

Energy data should focus on energy consumption for water collection, treatment, and distribution, as well as energy use for agricultural operations. Monitoring energy requirements linked to domestic and irrigation water demands provides insights into resource efficiency and energy security.

The monitoring plan outlined in Deliverable 2.2 provides comprehensive coverage of water aspect of the rainwater harvesting system. Soil monitoring focuses again on fertility but could benefit from the addition of data on soil organic content and biodiversity to strengthen the analysis. Energy monitoring effectively captures the energy footprint associated with agricultural productivity. In-situ monitoring is critical to capturing the local-scale dynamics and interactions of the system. High-resolution spatial and temporal data are vital for understanding the feedback mechanisms within the nexus. Deliverable 4.1 confirms that the spatial scale of the data is well-suited to represent system dynamics, while temporal resolutions of one month or less effectively capture seasonal variations. Longer-term trends, although less frequently collected, provide necessary context and complement the high-resolution datasets, ensuring a balanced and comprehensive approach to monitoring.

5.3.4 DEMO 1.3 in Kamares basin (Sifnos, Greece)

Nexus Interlinkages and Causal Loop Diagram for DEMO 1.3

The CLD in **Figure 17** illustrates the water and ecosystem interactions in DEMO 1.3, where traditional dry-stone dams and water storage ponds are implemented to enhance water retention, flood mitigation, and biodiversity conservation in the Kamares Basin of Sifnos.

The water component is central to this DEMO, as the dry-stone dams and ponds increase water infiltration, reduce surface runoff, and improve aquifer recharge, directly enhancing water availability and security. These interventions mitigate flood risks by slowing water flow and promoting controlled infiltration into the soil, reducing the impact of extreme rainfall events. Additionally, water stored in ponds serves as a buffer during dry periods, ensuring a more stable water supply. However, evaporation losses, influenced by air temperature, humidity, and wind speed, can reduce stored water availability.

Although the food/farming component is not an integral part of this DEMO, the increased water availability aims to support local agricultural activity by providing water for irrigation. However, agricultural production and management remain external to the scope of this DEMO.

The ecosystem component is enhanced through biodiversity conservation, as the dry-stone dams and ponds create habitats for native species. Improved soil moisture and water retention foster vegetation growth, which in turn supports wildlife populations, including birds, amphibians, and aquatic plants. By reducing soil erosion, the system also contributes to long-term land stability, preventing degradation and ensuring continued ecosystem services.

Overall, DEMO 1.3 demonstrates how traditional water management techniques can enhance water security, mitigate flood risks, and sustain biodiversity in a climate-sensitive environment.

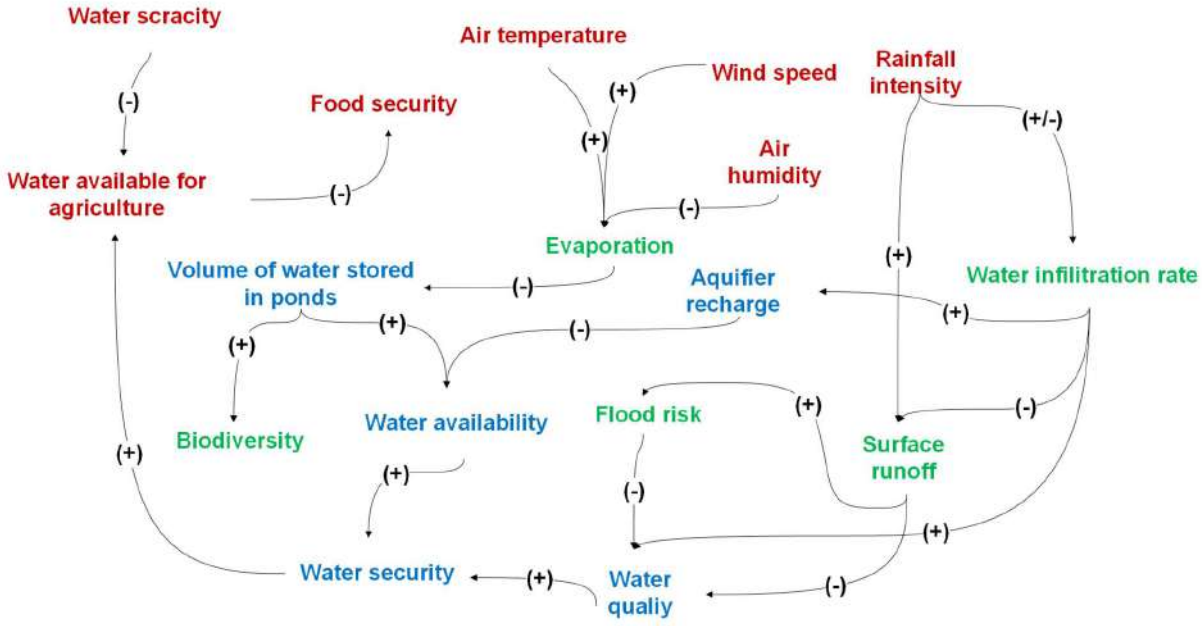

Figure 17. *CLD of DEMO 1.3*

Scenario Development for DEMO 1.3

The scenario development for DEMO 1.3 explores how climate variability and extreme weather events may impact the effectiveness of dry-stone dams and water storage ponds in sustaining water retention, flood mitigation, and biodiversity conservation.

The **baseline scenario** evaluates the system's ability to increase water infiltration, store water for ecosystem and irrigation support, and regulate surface runoff, while considering seasonal variations in rainfall, evaporation, and water demand. It also assesses biodiversity trends in response to improved soil moisture and habitat availability.

Future scenarios explore the effects of climate change on water availability, considering variations in rainfall intensity, runoff generation, and seasonal water demand fluctuations. These scenarios analyse how prolonged droughts or increased storm events may affect water storage, aquifer recharge, and flood control efficiency.

In cases of higher evaporation rates due to rising temperatures, the scenarios assess potential reductions in stored water volumes and impacts on ecological resilience.

Additionally, **future scenarios** consider how land-use changes and tourism-driven water demand might affect water security and whether additional conservation strategies may be necessary to preserve biodiversity and maintain stable water availability in the region. By integrating these aspects, scenario development provides a comprehensive understanding of how NBS can sustain water resources, mitigate flood risks, and support local ecosystems under changing environmental conditions.

Data Needs Summary of DEMO 1.3

As outlined in the previous subsection, the quantification of the nexus necessitates a data monitoring strategy to assess its impact on water retention, flood mitigation, and biodiversity conservation. Given the regional challenges of water scarcity, irregular rainfall, and seasonal tourism-driven demand, the following data categories are critical for evaluating the effectiveness of the NBS.

Water-related data must include metrics on rainfall intensity, distribution, and seasonal variability to assess water availability and infiltration potential. The volume of water stored in ponds, aquifer recharge rates, and infiltration efficiency are essential to measure the efficacy of the system in augmenting local water supplies. Surface runoff data, alongside evaporation and soil moisture levels, will help evaluate water retention capacity and the reduction of water loss. Water quality metrics should also be monitored to ensure stored and infiltrated water meets agricultural and ecological standards.

Flood mitigation data should focus on surface runoff volumes, flood occurrence frequency, and flood risk reduction following the implementation of stone dams. Additionally, erosion rates and sediment transport data are necessary to understand the role of the NBS in controlling soil degradation.

Biodiversity data must include indicators of habitat creation and species diversity. Monitoring changes in biodiversity provides insights into the ecological benefits of the stone dams and ponds.

The current monitoring plan, as outlined in Deliverable 2.2, provides a solid foundation for assessing water-ecosystem interlinkages. While certain parameters, such as water quality metrics (e.g., turbidity, pH, and nutrient content) and surface runoff dynamics, are not explicitly measured, these aspects will be partially addressed through simulated datasets. Similarly, soil health indicators, including soil organic content, moisture levels, and erosion rates, will be assessed using proxies derived from existing open data sources. This approach ensures a comprehensive evaluation of the NBS's contribution to soil stability and hydrological performance without requiring an expansion of the current monitoring plan.

Lastly, while biodiversity is partially addressed through marsh frog abundance and the area of temporary ponds, broader biodiversity metrics, such as bird diversity or vegetation health, would provide a more comprehensive view of habitat enhancement and ecological resilience.

5.4 Natural Areas: Findings for all relevant DEMOs

5.4.1 DEMO 6.1 near Alcañiz (Aragon, Spain)

Nexus Interlinkages and Causal Loop Diagram for DEMO 6.1

The CLD in **Figure** 18 illustrates the interactions within DEMO 6.1, which focuses on forest health and biodiversity conservation through the control of invasive mistletoe in pine forests. Unlike other DEMOs, this intervention does not directly target the WEFE nexus, as it primarily addresses forest management and biodiversity restoration.

The core objective of DEMO 6.1 is to control invasive mistletoe through pruning and thinning, which improves forest health and enhances carbon sequestration by maintaining healthy tree cover. The removal of invasive species contributes to biodiversity restoration, reinforcing the positive impact of conservation laws. The

extent of the intervention area determines the scale of benefits, as a larger intervention area can result in greater biodiversity gains and enhanced carbon storage.

Extreme weather events pose a threat to forest health, potentially weakening trees and making them more susceptible to biotic stressors like mistletoe. By improving tree vitality, this DEMO enhances forest resilience against climate variability.

Additionally, this DEMO considers the potential commercial utilization of harvested biomass from mistletoe removal, supporting local economic development. However, this introduces energy consumption for biomass harvesting, which could create additional resource demands that need to be balanced with the overall environmental benefits.

Although DEMO 6.1 contributes to climate mitigation through carbon sequestration, it does not directly integrate the water, energy, or food components of the WEFE nexus. Instead, it remains a biodiversity-focused intervention with indirect ecosystem service benefits.

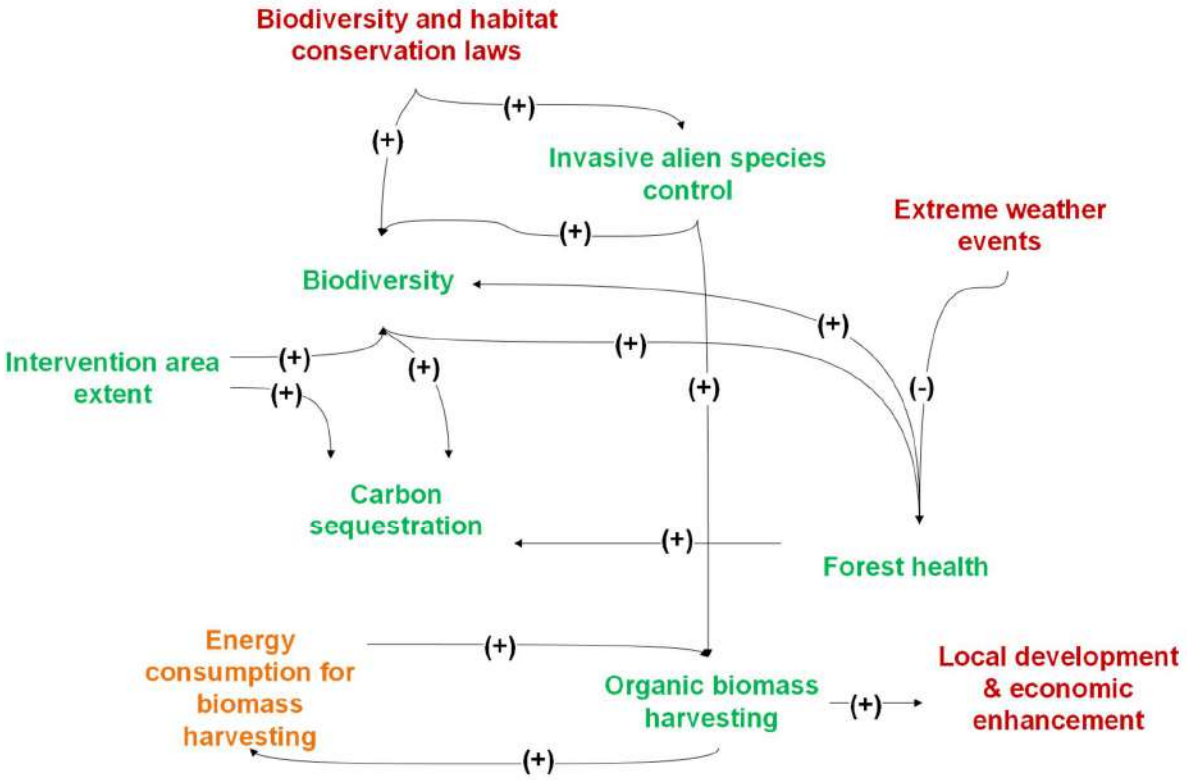

***Figure** 18. CLD of DEMO 6.1*

Scenario Development for DEMO 6.1

The **baseline scenario** evaluates the impact of mistletoe control measures on forest health, biodiversity restoration, and carbon sequestration. It assesses how pruning and thinning efforts influence tree recovery, mistletoe regrowth, and habitat restoration, considering natural regeneration rates and seasonal variations.

Future scenarios remain open-ended, as the specific aspects that can be investigated will depend on available data and monitoring outcomes. Potential areas of exploration include the long-term resilience of the forest under climate change, considering the influence of extreme weather events on tree vitality and mistletoe regrowth. Additionally, scenarios could examine the broader ecological impacts of invasive species control, the potential benefits of adaptive forest management strategies, or the economic feasibility of biomass

utilization. By keeping the future scenario exploration flexible, DEMO 6.1 can adapt its research focus based on emerging insights and project developments.

Data Needs Summary of DEMO 6.1

As highlighted by the CLD, the nexus approach for the present DEMO requires a data collection framework to evaluate its effectiveness in restoring forest health, controlling invasive mistletoe, and promoting biodiversity. Given the climate-related challenges of increasing temperatures, and prolonged droughts, monitoring the interplay between ecological and socioeconomic variables is critical.

Data on invasive mistletoe infestation levels is central to this project. Metrics should include density, spatial distribution, and progression of mistletoe infestations over time. Forest health indicators, such as tree canopy density, growth rates, and resistance to extreme weather events, are also essential to assess ecosystem resilience and recovery. Biodiversity metrics should encompass species richness, habitat diversity, and the effectiveness of conservation measures, including the control of invasive species. Carbon sequestration data, including biomass estimates and soil carbon content, is necessary to quantify the contribution of the NBS to climate mitigation. Economic data is equally important. Monitoring the volume and quality of harvested biomass and its associated energy consumption will provide insights into the economic viability of biomass utilization.

The monitoring plan in Deliverable 2.2 indicated that there already exists a foundation for assessing biodiversity and energy-related impacts. Key elements, such as invasive mistletoe monitoring, are well-covered through indicators like the percentage of affected trees by infestation level and the number of parasitized trees, which provide essential data for targeted control efforts. Additionally, metrics on tree removal, aboveground carbon storage, and carbon removal illuminate the contributions of the NBS to carbon sequestration and overall forest management. Indicators for tree regeneration and mortality rate further enhance the ability to evaluate forest health and resilience over time. Energy-related monitoring, including the energy footprint per kilogram of food and operational energy consumption, is also sufficiently detailed, reflecting the emphasis on energy efficiency and sustainability in biomass utilization. Some aspects remain unaddressed in the current monitoring framework, such as broader biodiversity metrics (species richness, habitat diversity) and soil health indicators (organic content, erosion rates, nutrient levels). These could help assess the effects of mistletoe control and forest restoration on soil stability and fertility. Where direct measurements are lacking, proxy indicators like vegetation cover, soil moisture, and remote sensing data can help fill the gaps, ensuring a more comprehensive evaluation of the NBS impacts.

5.4.2 DEMO 7 in Central Alentejo – streams (7.1) and montado (7.2) ecosystems (Portugal)

Nexus Interlinkages and Causal Loop Diagram for DEMOs 7.1 and 7.2

DEMO 7.1 focuses on the restoration and conservation of riparian woodlands and Mediterranean water stream vegetation through the implementation of NBS. The CLD in **Figure** 19 illustrates the key interactions within this system. The primary intervention involves invasive alien species control and the restoration of native vegetation, which directly enhances biodiversity support and improves water quality in streams. The establishment of riparian buffer areas further strengthens these effects by stabilizing soil and reducing erosion. Soil organic content increases due to improved vegetation cover, which in turn supports water infiltration and reduces surface runoff. Enhanced infiltration contributes to aquifer recharge and increases water availability, ultimately supporting water security. The system also exhibits a feedback loop where improved water availability sustains vegetation cover in riparian zones, further reinforcing biodiversity and ecosystem resilience. Climate variables such as rainfall intensity and air temperature influence water infiltration and vegetation growth, affecting the overall effectiveness of the interventions.

DEMO 7.2 targets the restoration of degraded Mediterranean ecosystems, particularly through the revival of agroforestry practices and native vegetation restoration. The CLD in **Figure** 20 highlights the key dynamics of this intervention. Invasive species removal promotes biodiversity, which in turn enhances soil organic content

and carbon sequestration. The restoration of native vegetation improves soil nutrient levels, supporting vegetation health and increasing agricultural yield while minimizing water and energy inputs. A critical feedback loop exists where enhanced soil conditions further support biodiversity, leading to long-term ecosystem resilience. Additionally, by improving vegetation health, the system can mitigate the impacts of extreme weather events, reducing vulnerability to environmental stressors while enhancing sustainable land use.

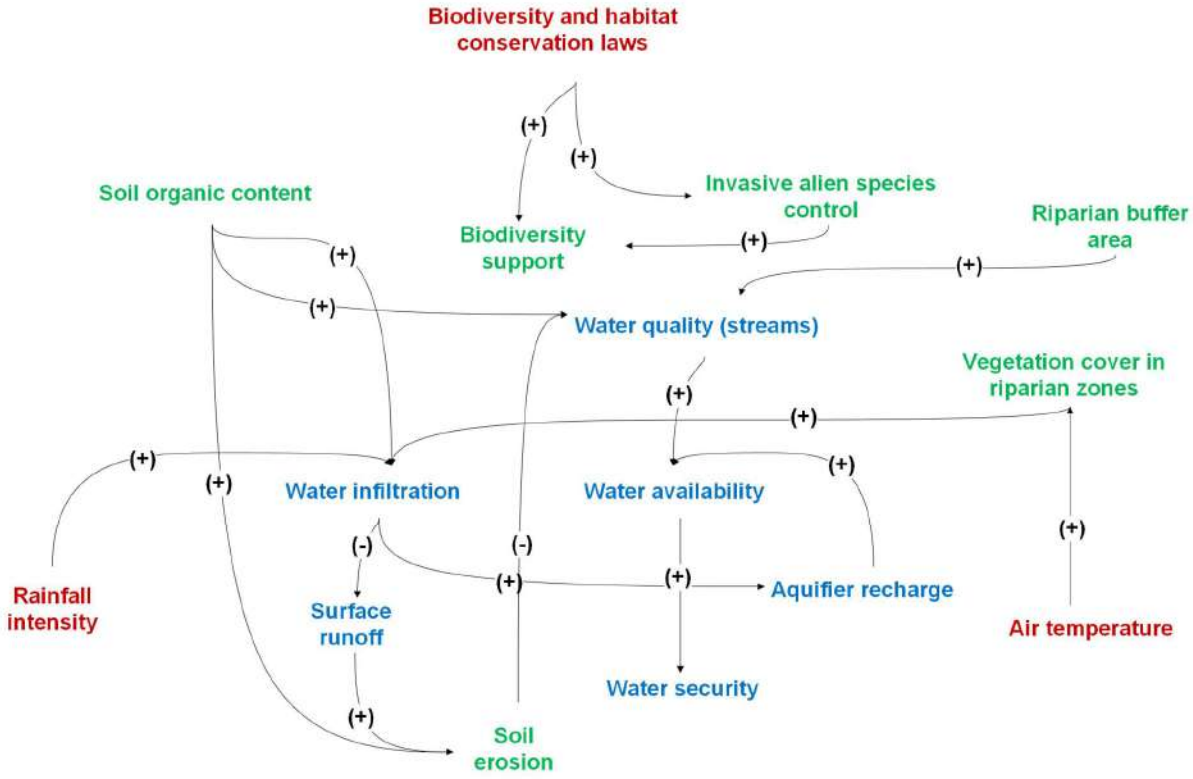

***Figure** 19. CLD of DEMO 7.1*

The interlinkage between DEMO 7.1 and DEMO 7.2 is evident in their complementary roles in ecosystem restoration. DEMO 7.1 focuses on riparian areas, ensuring water quality and availability, which indirectly supports the broader landscape targeted in DEMO 7.2. Conversely, DEMO 7.2 enhances terrestrial biodiversity and soil conditions, which contribute to improved water retention and infiltration, benefiting riparian ecosystems. Together, these DEMOs foster habitat and landscape connectivity, improving ecosystem stability and reinforcing ecological processes across the region. This connectivity is essential for maintaining biodiversity corridors, mitigating habitat fragmentation, and ensuring long-term climate adaptation.

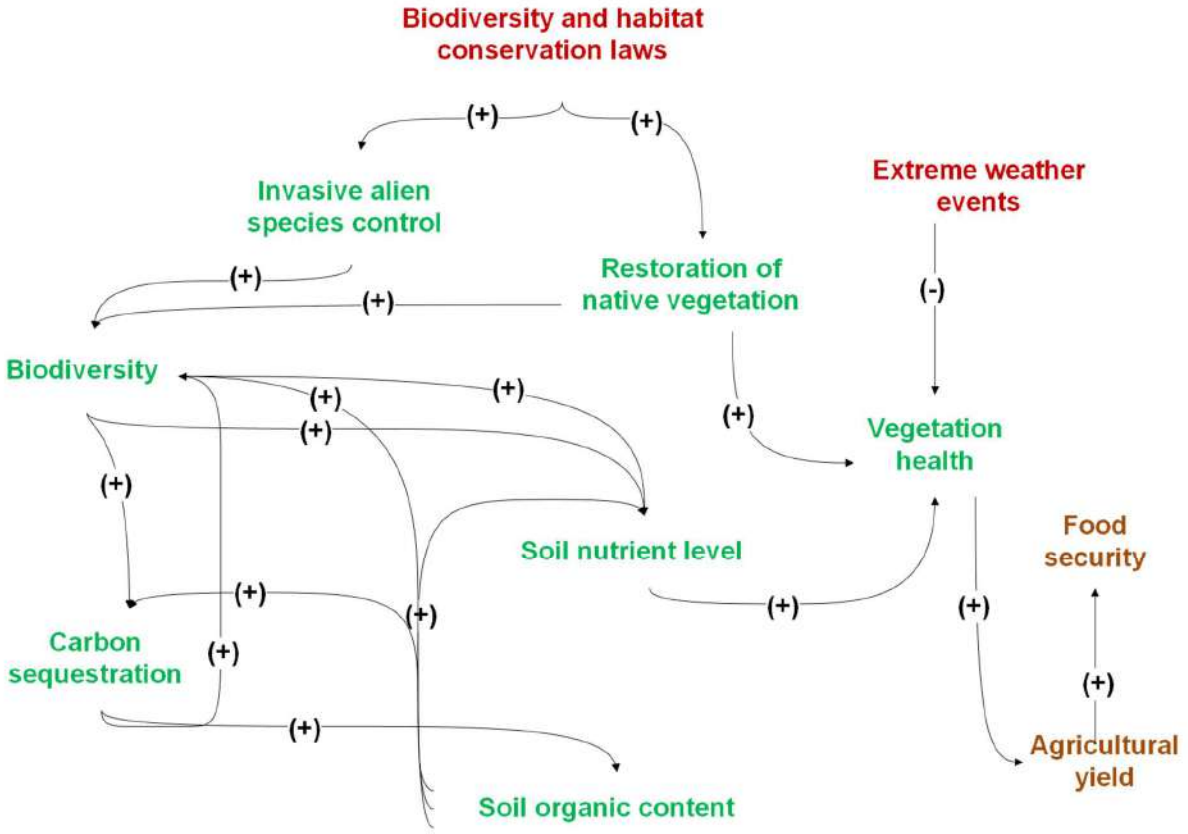

***Figure** 20. CLD of DEMO 7.2*

Scenario Development for DEMOs 7.1 and 7.2

Both DEMOs contribute significantly to biodiversity conservation by enhancing landscape structure for connectivity. The restoration of riparian vegetation in DEMO 7.1 improves water availability and ecological conditions in aquatic and semi-aquatic habitats, while the interventions in DEMO 7.2 focus on ecosystem restoration and the revival of agroforestry, supporting biodiversity in terrestrial environments. Together, these DEMOs play a key role in mitigating habitat fragmentation and strengthening ecological corridors, which are essential for species dispersal and climate adaptation.

To assess the long-term impact of these NBS interventions, CREAF is conducting a landscape connectivity model based on the mobility of target species. This modelling approach evaluates ex-ante and ex-post scenarios, comparing habitat connectivity before and after the implementation of NBS. The results will provide insights into the effectiveness of riparian and agroforestry restoration in facilitating species movement, improving ecological resilience, and reinforcing biodiversity networks at the landscape scale.

Future scenario analyses may further explore the influence of climate variability on habitat connectivity, assessing how extreme weather events, temperature fluctuations, and changes in precipitation patterns affect the success of ecosystem restoration. Additionally, scenarios may consider the role of land-use changes and conservation policies in maintaining and expanding biodiversity corridors over time. These evaluations will inform adaptive management strategies to maximize the ecological benefits of DEMO 7.1 and DEMO 7.2.

Data Needs Summary of DEMOs 7.1 and 7.2

The transition to a quantified expression of the WEFE nexus for DEMO 7.1 requires a broad spectrum of data. For water-related aspects, it is essential to measure stream water quality, focusing on parameters such as

turbidity, nutrient concentrations, and pollutants, which should be complemented by baseline water quality data. Regional hydrology data, including seasonal water flows in riparian zones and rainfall patterns, are crucial for understanding water availability. Groundwater levels or recharge rates, soil permeability, and infiltration rates are vital for assessing aquifer recharge and water infiltration. Additionally, runoff coefficients and soil moisture data are necessary to evaluate surface runoff dynamics. Soil organic content data, including organic matter levels pre- and post-restoration, as well as carbon sequestration rates in riparian soils, are essential. Data on soil erosion rates and sediment yields in streams pre- and post-restoration are also needed. To monitor ecosystem services, biodiversity metrics such as habitat quality indices, biodiversity indices, and monitoring of biodiversity support before and after intervention must be included. Metrics for riparian buffer size, continuity, vegetation cover, and health are critical for evaluating their effectiveness. Climate data requirements focus on rainfall intensity and patterns, including historical and real-time data, as well as variability and trends over time. Data on extreme weather events, such as floods and droughts impacting restored ecosystems, should also be considered to assess climate variability impacts.

The monitoring plan, detailed in Deliverable 2.2, primarily focuses on soil and biodiversity, aligning well with key requirements such as soil organic carbon, bulk density, water holding capacity, and habitat conservation status; this is critical for assessing ecosystem restoration and biodiversity support. Metrics like tree regeneration and planted species survival rates directly address biodiversity-related goals within the WEFE nexus. However, direct water-related metrics are missing, limiting the assessment of hydrological impacts. To bridge this gap, modeling and proxy indicators will ensure a more integrated evaluation of water-related feedback loops and synergies within the nexus.

For DEMO 7.2, the CLD highlights that data requirements for quantifying the depicted linkages include measurements of soil nutrient levels, organic content, and carbon sequestration rates, as well as biodiversity metrics such as habitat connectivity, species richness, and invasive species control. Hydrological data on water retention is also important, given the reliance on rainwater to sustain forest ecosystem services. The monitoring plan addresses these needs effectively by including soil-related indicators such as organic carbon content, bulk density, and water holding capacity, along with biodiversity metrics such as habitat conservation status, invasive species coverage, and tree regeneration. These align well with the focus of the demo on soil quality and biodiversity restoration. While water-related metrics could further enhance the ability to comprehensively address hydrological and climatic dimensions of the WEFE nexus, such data can be retrieved from open sources, eliminating the need to expand the current monitoring plan. The same applies for the absence of agroforestry-specific indicators, such as agricultural yield.

Conclusively, the current monitoring plan effectively captures critical aspects of soil quality and biodiversity restoration. Yet, both DEMO 7.1 and DEMO 7.2 would benefit from expanded metrics to address water-related impacts and agroforestry outcomes comprehensively. These additions would enable a more robust evaluation of the contributions of both interventions to the WEFE nexus. Nonetheless, the plan provides a solid foundation, and supplementary data from external sources can bridge most of the identified gaps without major revisions.

5.4.3 Demo 8 in Izmir delta ecosystem (Turkey)

Nexus Interlinkages and Causal Loop Diagram for DEMO 8

DEMO 8 primarily focuses on the interaction between the water and ecosystem components of the WEFE nexus, with a strong emphasis on ecosystem restoration and the role of wastewater reuse in improving downstream environmental conditions. Unlike other DEMOs that target strong cross-sectoral linkages (e.g., agriculture, energy), this DEMO emphasizes how wastewater reclamation influences ecosystem health through aquifer recharge, salinity reduction, and habitat improvement.

As shown in **Figure 21**, the alternative water production rate (treated wastewater) serves as a key driver, contributing to groundwater recharge and reducing aquifer salinity, which in turn enhances surface and groundwater quality. Improved water availability supports vegetation health, leading to increased soil nutrient

levels and carbon sequestration, which further enhance biodiversity. These improvements create favorable conditions for communal grazing, indirectly linking water management to food security in the area.

On the other hand, climatic factors, such as air temperature and rainfall intensity, may influence surface runoff and salinity levels, potentially affecting the efficiency of ecosystem restoration efforts. The legal and regulatory framework plays a critical role, particularly through biodiversity and habitat conservation laws and water quality standards, which help ensure that ecosystem restoration efforts align with environmental protection objectives.

While wastewater treatment is not directly linked to other nexus components (e.g., food and energy), its downstream ecological impacts demonstrate a key water-ecosystem connection. By restoring biodiversity and improving soil conditions, DEMO 8 contributes to long-term ecological stability, offering indirect benefits to grazing-based food production and carbon storage.

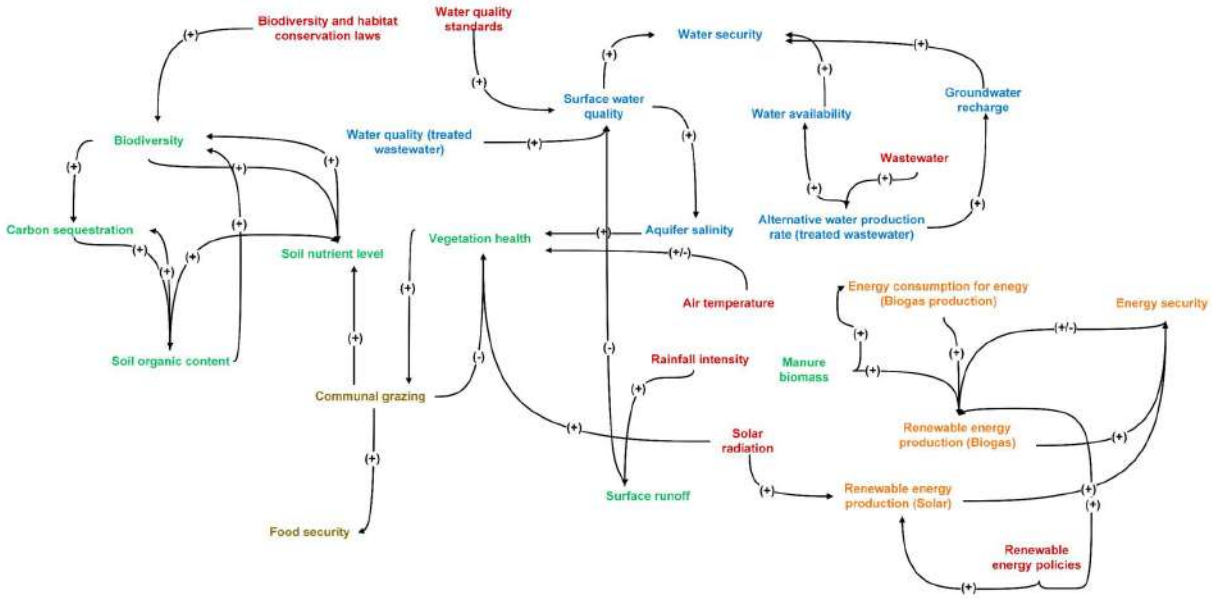

Figure 21. *CLD of Demo 8*

Scenario Development for DEMO 8

The **baseline scenario** examines the immediate effects of wastewater injection into the aquifer, focusing on its role in reducing salinity, improving water availability, and enhancing habitat conditions. Key aspects include the response of vegetation to improved soil quality, the extent of aquifer recharge, and the effectiveness of groundwater upwelling in sustaining lagoon areas. The impact on biodiversity, particularly migratory species and native flora, is also assessed.

Future scenarios remain open-ended to allow for adaptive management based on initial observations. Potential areas of investigation include:

- The long-term sustainability of aquifer recharge and soil salinity reduction, considering seasonal and climatic variations.
- The resilience of newly created habitats to external pressures such as climate change, extreme weather events, and water availability fluctuations.
- The extent to which improved water and soil conditions can support communal grazing and food security, particularly under varying environmental and socio-economic conditions.
- The role of policy and governance frameworks in maintaining ecosystem services, including potential regulatory shifts affecting water reuse, biodiversity conservation, and land-use practices.

Data Needs Summary of DEMO 8

The most prominent data requirements for the WEFE nexus modeling approach, based on the mapping illustrated in the CLD, comprise critical elements across water, ecosystem, food, and climate domains.

Water-related data should include water availability metrics to measure resource accessibility, as well as detailed water quality parameters for both surface water (in the open channels) and treated wastewater; parameters such as nutrient levels, turbidity, contaminants, and pH would be sufficient for the scope of our analysis. These metrics are essential for evaluating the suitability of water for aquifer recharge, which is of primary concern in this demo. Additionally, groundwater recharge rates and aquifer quality (salinity in particular) need to be monitored to assess the sustainability of water resources under current and future conditions. Surface water data, including volumes, rates, and seasonal variations, are crucial for evaluating water infiltration capacity, while rainfall intensity and patterns must be continuously monitored to account for the effects of climatic conditions on water resources. Ecosystem-related data is equally important and should include vegetation health indicators such as canopy cover, species diversity, and regeneration rates to measure ecosystem recovery and biodiversity enhancements from the intervention. Soil organic content and nutrient levels must also be monitored to assess soil fertility, carbon sequestration potential, and the impacts of land management practices. Biodiversity metrics, such as species richness, habitat connectivity, and the abundance of key species, are necessary to measure ecological health and resilience. Food and agricultural data are critical, with a particular focus on how grazing impacts soil quality, vegetation health, and biodiversity. Grazing should be monitored directly (e.g., assessing stocking rates over a given time to assess grazing pressure) to understand the interconnected effects of land use practices. Conclusively, these data streams will eventually enable the modeling of the dynamic feedback loops within the WEFE nexus.

The current monitoring plan (the reader is advised to refer to Deliverable 2.2) provides comprehensive coverage of key aspects related to soil health, water resources, biodiversity, and energy security, aligning well with many of the requirements for a robust WEFE nexus modeling approach. However, there are some minor mismatches and gaps that, if addressed, would allow for a more holistic assessment.

In terms of soil health, the plan includes essential metrics such as soil physical and chemical fertility, organic carbon content, bulk density, and water holding capacity. These indicators are critical for assessing soil fertility, carbon sequestration potential, and resilience to erosion. Additionally, the inclusion of soil pollution by arsenic and arsenic concentration in pastures highlights the focus on contamination risks and their implications for agriculture and ecosystem health. However, the monitoring plan could benefit from accounting for the broader soil biodiversity or microbiome health, which are important for understanding ecological interactions within the soil system.

Water-related metrics are also well-represented, with indicators for effective wastewater treatment, reclaimed water production, and water provision by ecosystems. The monitoring of groundwater recharge, infiltration rates, and aquifer surface ratios (with excessive arsenic and nitrate) addresses hydrological sustainability and contamination risks. However, more comprehensive monitoring of water quality parameters, such as nutrient levels, turbidity, or microbial content, in reclaimed or surface water, are missing. These would be beneficial for evaluating the suitability of water for irrigation or ecological purposes.

Biodiversity metrics focus on habitat restoration, focal species, and tree biomass removal, which align with conservation goals. While these indicators provide valuable insights into habitat health and restoration efforts, broader biodiversity metrics such as species richness, faunal abundance, or functional diversity are absent, limiting the ability to evaluate ecosystem-wide impacts.

Energy-related indicators, such as biogas generation from wastewater treatment and PV electricity generation are well-addressed.

Overall, the current monitoring plan addresses critical aspects of the WEFE nexus. The inclusion of additional water quality metrics, soil biodiversity indicators, and broader biodiversity assessments would strengthen its comprehensiveness.

6 Integration of Nexus Quantification, Circularity and Sustainability Assessment, and Decision Support in CARDIMED

The CARDIMED project adopts an integrated approach that combines nexus quantification with circularity, sustainability assessments, and digital decision support. This methodology ensures a comprehensive evaluation of the implemented NBS across DEMOs, providing critical insights into resource flows, environmental impacts, and system-wide dynamics. The nexus-based approach is fundamental for capturing interdependencies across WEFE, highlighting both synergies and trade-offs. Without this perspective, sustainability assessments may fail to account for indirect benefits and potential unintended consequences.

The nexus quantification generates essential outputs that directly contribute to circularity and environmental sustainability assessments. By analysing water, energy, and material flows within DEMOs, this quantification supports the identification of resource efficiencies, dependencies, and sectoral interactions. For example, quantifying alternative water production rates, such as treated wastewater reuse or harvested rainwater, provides crucial input for assessing water circularity performance. Similarly, energy consumption metrics for water treatment, irrigation, or urban cooling contribute to life cycle assessments by pinpointing high-energy demand areas and identifying optimization opportunities. In agricultural DEMOs, indicators such as crop yield, soil nutrient levels, and fertilizer use are critical for evaluating environmental sustainability, ensuring that resource use efficiency and ecosystem impacts are properly accounted for.

Beyond environmental and circularity performance, nexus quantification also facilitates economic and social impact assessments. While the modelling of resource flows captures systemic efficiencies, additional data is required to complete a holistic evaluation. The economic assessment necessitates detailed information on investment costs, operational expenditures, and financial returns from recovered water, energy, or biomass. Meanwhile, the social dimension involves aspects such as stakeholder acceptance, well-being, public participation, and job creation, which require targeted surveys, engagement activities, and policy analysis. By linking nexus quantification with sustainability and circularity assessments, CARDIMED ensures a robust evaluation framework that captures the full range of NBS impacts. This integration allows for the identification of high-priority interlinkages, ensuring that critical trade-offs and synergies are incorporated into decision-making.

In addition to supporting sustainability assessments, the CARDIMED WEFE nexus model is closely linked to the development of a DSS. The stepwise approach presented in Section 4 culminates in a quantitative description of WEFE system dynamics through an equation-free approach, representing a significant advancement in systems-based decision-making. Traditional models often rely on predefined equations to capture system behaviours, but these may not fully account for emergent properties, nonlinear interactions, and feedback loops within the WEFE nexus. The flexibility of this equation-free approach is crucial for assessing diverse NBS implementations, where the complexity of system interactions requires adaptable methodologies.

To leverage this flexibility, the equation-free modelling approach is embedded within a digital solution that enables users to explore various "what-if" scenarios. This functionality allows stakeholders to evaluate how different external forcings – such as climate-related drivers including precipitation changes, temperature fluctuations, or extreme weather events – affect water, energy, food/farming, and ecosystem components over medium- to long-term time horizons. The system dynamically processes these inputs, simulates responses, and compares outcomes against a defined baseline, offering a robust comparative analysis of different intervention strategies. By eliminating the need for rigid governing equations, the model remains adaptable to new data and emerging insights, providing policymakers, urban planners, and other stakeholders with a responsive tool for evaluating the resilience and sustainability of NBS interventions.

This scenario-based testing functionality is a key intersection between the nexus model and WP4, which focuses on the development and deployment of the DSS. While the equation-free approach enhances the analytical capabilities of the digital tool, the DSS encompasses a broader range of functionalities beyond

scenario testing. The integration of nexus modelling with the DSS ensures that decision-makers have access to a comprehensive platform for evaluating trade-offs, synergies, and long-term sustainability under different future conditions. By bridging nexus quantification, circularity and sustainability assessments, and digital decision support, CARDIMED provides an advanced, science-based framework for guiding the implementation of NBS and maximizing their long-term benefits.

7 Challenges and Limitations

The development and application of the WEFE Nexus framework within CARDIMED have provided a robust methodological foundation for assessing the complex interactions between water, energy, food, and ecosystems across diverse demonstration sites. However, several challenges and limitations arise from both the methodological approach and its practical implementation in the CARDIMED DEMOs, which must be acknowledged when interpreting the results.

One of the key challenges stems from data availability, quality, and harmonization. The WEFE Nexus framework relies on a combination of qualitative expert knowledge and quantitative data from monitoring efforts. While extensive data collection strategies have been established, variations in data availability across the different DEMOs present a limitation. Some DEMOs have access to long-term environmental datasets, while others, particularly newly implemented NBS interventions, lack historical records. The integration of heterogeneous datasets – ranging from sensor-based real-time measurements to socio-economic indicators – poses additional difficulties in ensuring data consistency and comparability across different case studies. In some cases, missing data or data collected at different temporal and spatial resolutions can impact the reliability of causal inference and modelling.

Another limitation arises from the complexity of causal inference using CCM. While CCM enables the identification of causal relationships in dynamic systems, it requires time series with sufficient temporal extent data to produce robust results. Many of the CARDIMED DEMOs are in the early stages of implementation, meaning that the available monitoring periods may not be sufficient to establish strong causal dependencies.

Acknowledging these challenges, the first mitigation measure is to augment existing data. Synthetic data generation is not a viable augmentation approach here, exactly due to the limited amount of data that would significantly distort the distribution of actual data. Therefore, we will initially look into the option of integration of diverse data sources (e.g., remote sensing data or simulated data) or proxies. If still data is scarce, structured expert elicitation will estimate missing parameters. This involves consulting domain experts using structured interviews to derive best estimates for uncertain variables. Expert elicitation introduces the second mitigation measure. This measure suggests a shift from dynamic systems captured with empirical data to Bayesian Networks (BNs), which are graphical probabilistic models that represent relationships between variables using conditional probabilities. They are particularly useful when empirical data is limited, as they can integrate expert knowledge with available data to estimate uncertain system behaviours. By incorporating expert-elicited probability distributions where data is missing, BNs allow for uncertainty quantification, scenario analysis, and decision support. The graphical nature of BNs is in line with the CLD structure, allowing a smooth transition to different quantification approach.

The spatial and temporal scale variability across CARDIMED DEMOs presents another methodological challenge. The framework has been applied to DEMOs situated in urban, peri-urban, rural, and wilderness areas, each with distinct environmental conditions, governance structures, and implementation scales. This diversity enhances the framework's applicability but complicates direct comparisons between case studies. While urban DEMOs often have well-defined boundaries and measurable impacts, large-scale ecological restoration projects in rural and wilderness areas (e.g., DEMOs focused on ecosystem recovery) exhibit diffuse, long-term impacts that are more challenging to quantify within the project's timeframe. The ability to detect significant changes in system behaviour may thus be constrained for interventions whose benefits take years or even decades to materialize.

Furthermore, the participatory approach used in developing the CLDs presents inherent subjectivity. Although an iterative review process involving experts, WP5 leaders, and DEMO stakeholders was implemented to refine the diagrams, expert-driven causal structures can still reflect biases in knowledge and assumptions. While the integration of multiple perspectives improves the robustness of the framework, it remains a qualitative approximation of complex real-world interactions, requiring continuous validation through quantitative modelling and empirical data collection.

A critical limitation also lies in the predictive modelling of system behaviour. The WEFE Nexus framework aims to explore future scenarios of NBS performance under different environmental and climatic conditions, yet the accuracy of these projections is inherently limited by the uncertainties associated with climate change, land-use changes, and socio-economic drivers. Scenario-based modelling relies on assumptions regarding future trends, and while sensitivity analyses can help estimate uncertainties, the predictive results should be interpreted as explorative rather than deterministic. Additionally, feedback loops identified in CLDs may evolve over time due to unforeseen external influences, further complicating long-term predictions.

Finally, practical implementation constraints may influence the feasibility of applying the WEFE Nexus framework in decision-making processes. While the framework provides valuable insights for stakeholders, translating model outputs into actionable strategies requires clear communication of results and engagement with policy-makers, urban planners, and local communities. In some cases, the complexity of the framework may limit its accessibility for non-experts, necessitating additional efforts to develop user-friendly tools and visualization methods to support decision-making.

Despite these challenges, the methodological advancements made in this deliverable represent a significant step forward in integrating WEFE Nexus assessments into NBS planning. Addressing the identified limitations – through ongoing data collection, refinement of causal inference methods, and improved stakeholder engagement – will further enhance the applicability and robustness of the CARDIMED WEFE Nexus framework in supporting climate resilience strategies.

8 Conclusion

This deliverable establishes a structured WEFE Nexus framework to evaluate the impact of NBS implemented across CARDIMED DEMOs. The framework applies a stepwise methodology that integrates qualitative system mapping with quantitative assessment, ensuring a holistic evaluation of resource interdependencies and trade-offs. A key innovation is the participatory development of CLDs, which serve as initial representations of system behaviour and provide a foundation for data-driven nexus quantification. This approach enhances the applicability of the framework by incorporating local knowledge and operational constraints, ensuring that the analysis is relevant to site-specific conditions.

The transition from qualitative CLDs to a data-driven assessment enables the measurement of key nexus interactions, supporting a more robust evaluation of the sustainability and resilience of NBS. This quantification phase provides essential inputs for environmental, economic, and social impact assessments, ensuring that decision-makers have access to comprehensive insights into resource flows, efficiency gains, and potential risks. By integrating nexus modelling with circularity and sustainability evaluations, this deliverable reinforces the importance of systemic thinking in NBS design and implementation.

The connection between the WEFE Nexus framework and the CARDIMED DSS represents a significant advancement in decision support for NBS interventions. The equation-free approach embedded in the DSS enables scenario testing and policy analysis, allowing stakeholders to assess how different climate and socio-economic drivers influence WEFE interactions. By simulating future conditions, the DSS provides a flexible, adaptive tool that enhances evidence-based decision-making and facilitates the long-term planning of sustainable solutions.

While this framework marks a major step forward in WEFE Nexus analysis, several challenges remain. Data availability, methodological complexity, and the need for greater integration of socio-economic variables must be addressed to further refine the quantification process. Future efforts will focus on enhancing data collection methods, improving the DSS interface for user engagement, and strengthening the alignment of nexus modelling with sustainability indicators. By continuously improving these components, CARDIMED will ensure that NBS interventions are effectively evaluated and optimized for resilience, circularity, and long-term sustainability in the Mediterranean region.

References

Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The water-energy-food nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters, 13*(4), 043002. https://doi.org/10.1088/1748-9326/aaa9c6

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J., Haworth, B., Duce, S., & Imanari, Y. (2015). Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science & Policy, 54*, 389–397. https://doi.org/10.1016/j.envsci.2015.08.002

Carvalho, P. N., Finger, D. C., Masi, F., Cipolletta, G., Oral, H. V., Tóth, A., & Exposito, A. (2022). Nature-based solutions addressing the water-energy-food nexus: Review of theoretical concepts and urban case studies. *Journal of Cleaner Production, 338*, 130652. https://doi.org/10.1016/j.jclepro.2022.130652

Cenci, S., & Saavedra, S. (2019). Non-parametric estimation of the structural stability of nonlinear ecological systems. *Nature Ecology & Evolution, 3*(6), 912–918. https://doi.org/10.1038/s41559-019-0879-1

Chang, C. W., Ushio, M., & Hsieh, C. H. (2017). Empirical dynamic modeling for beginners. *Ecological Research*, 32(6), 785-796. http://doi.org/10.1007/s11284-017-1469-9

Clark, A. T., Ye, H., Isbell, F., Deyle, E. R., Cowles, J., Tilman, G. D., & Sugihara, G. (2015). Spatial convergent cross mapping to detect causal relationships from short time series. Ecology, 96(5), 1174-1181.

Coletta, V. R., Pagano, A., Pluchinotta, I., Zimmermann, N., Davies, M., & Butler, D. (2024). Participatory causal loop diagrams building for supporting decision-makers integrating flood risk management in an urban regeneration process. *Earth's Future, 12*(1), e2023EF003659. https://doi.org/10.1029/2023EF003659

Deyle, E. R., & Sugihara, G. (2011). Generalized theorems for nonlinear state space reconstruction. *PLoS ONE, 6*(3), e18295. https://doi.org/10.1371/journal.pone.0018295

Giordano, R., Osann, A., Henao, E., Llanos López, M., González Piqueras, J., Nikolaidis, N. P., Lilli, M., Coletta, V. R., & Pagano, A. (2025). Causal loop diagrams for bridging the gap between water-energy-food-ecosystem nexus thinking and nexus doing: Evidence from two case studies. *Journal of Hydrology, 650*, 132571. https://doi.org/10.1016/j.jhydrol.2024.132571

Gondhalekar, D., & Ramsauer, T. (2017). Nexus City: Operationalizing the urban water-energy-food nexus for climate change adaptation in Munich, Germany. *Urban Climate, 19*, 28-40. https://doi.org/10.1016/j.uclim.2016.11.004

Laspidou, C. S., Mellios, N. K., Spyropoulou, A. E., Kofinas, D. T., & Papadopoulou, M. P. (2020). Systems thinking on the resource nexus: Modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions. *Science of the Total Environment, 717*, 137264. https://doi.org/10.1016/j.scitotenv.2020.137264

Littlejohns, L. B., Hill, C., & Neudorf, C. (2021). Diverse approaches to creating and using causal loop diagrams in public health research: Recommendations from a scoping review. *Public Health Reviews, 42*, 1604352. https://doi.org/10.3389/phrs.2021.1604352

Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., ... & Zheng, C. (2017). Challenges in operationalizing the water–energy–food nexus. *Hydrological Sciences Journal, 62*(11), 1714-1720. https://doi.org/10.1080/02626667.2017.1353695

Maragkaki, A., Koukianaki, E. A., Lilli, M. A., Efstathiou, D., & Nikolaidis, N. P. (2024). Optimizing the water-ecosystem-food nexus using nature-based solutions at the basin scale. *Frontiers in Water, 6*, 1386925. https://doi.org/10.3389/frwa.2024.1386925

Munch, S. B., Brias, A., Sugihara, G., & Rogers, T. L. (2020). Frequently asked questions about nonlinear dynamics and empirical dynamic modelling. *ICES Journal of Marine Science, 77*(4), 1463–1479. https://doi.org/10.1093/icesjms/fsz209

Nair, S., George, B., Malano, H. M., Arora, M., & Nawarathna, B. (2014). Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources, Conservation and Recycling, 89*, 1–10. https://doi.org/10.1016/j.resconrec.2014.05.007

Nika, C. E., Vasilaki, V., Expósito, A., & Katsou, E. (2020). Water cycle and circular economy: Developing a circularity assessment framework for complex water systems. *Water Research, 187*, 116423. https://doi.org/10.1016/j.watres.2020.116423

Pahl-Wostl, C. (2019). Governance of the water-energy-food security nexus: A multi-level coordination challenge. *Environmental Science & Policy, 92*, 356-367. https://doi.org/10.1016/j.envsci.2017.07.017

Purwanto, A., Sušnik, J., Suryadi, F. X., & de Fraiture, C. (2019). Using group model building to develop a causal loop mapping of the water-energy-food security nexus in Karawang Regency, Indonesia. *Journal of Cleaner Production, 240*, 118170. https://doi.org/10.1016/j.jclepro.2019.118170

Restrepo, J. D., Bottaro, G., Barci, L., Beltrán, L. M., Londoño-Behaine, M., & Masiero, M. (2024). Assessing the impacts of nature-based solutions on ecosystem services: A water-energy-food-ecosystems nexus approach in the Nima River Sub-Basin (Colombia). *Forests, 15*(11), 1852. https://doi.org/10.3390/f15111852

Rozhkov, A. (2024). Applying graph theory to find key leverage points in the transition toward urban renewable energy systems. *Applied Energy, 361*, 122854. https://doi.org/10.1016/j.apenergy.2024.122854

Schlemm, A., Mulligan, M., Tang, T., Agramont, A., Namugize, J., Malambala, E., & van Griensven, A. (2024). Developing meaningful water-energy-food-environment (WEFE) nexus indicators with stakeholders: An Upper White Nile case study. *Science of the Total Environment, 931*, 172839. https://doi.org/10.1016/j.scitotenv.2024.172839

Seddon, N., Chausson, A., Berry, P., Girardin, C. A., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B, 375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Simpson, G. B., & Jewitt, G. P. (2019). The development of the water-energy-food nexus as a framework for achieving resource security: A review. *Frontiers in Environmental Science, 7*, 8. https://doi.org/10.3389/fenvs.2019.00008

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill/Irwin.

Sugihara, G., May, R., Ye, H., Hsieh, C. H., Deyle, E., Fogarty, M., & Munch, S. (2012). Detecting causality in complex ecosystems. *Science, 338*(6106), 496-500. https://doi.org/10.1126/science.1227079

Sun, B., Deng, J., Scheel, N., Zhu, D. C., Ren, J., Zhang, R., & Li, T. (2024). Causalized convergent cross mapping and its implementation in causality analysis. *Entropy, 26*(7), 539. https://doi.org/10.3390/e26070539

Takens, F. (1981). Detecting strange attractors in turbulence. In D. A. Rand & L.-S. Young (Eds.), *Dynamical systems and turbulence, Warwick 1980* (pp. 366-381). Springer. https://doi.org/10.1007/BFb0091924

Uleman, J. F., Luijten, M., Abdo, W. F., Vyrastekova, J., Gerhardus, A., Runge, J., ... & Verhagen, M. (2024). Triangulation for causal loop diagrams: Constructing biopsychosocial models using group model building, literature review, and causal discovery. *npj Complexity, 1*(1), 19. https://doi.org/10.1038/s44260-024-00017-9

Vanino, S., Baratella, V., Pirelli, T., Ferrari, D., Di Fonzo, A., Pucci, F., Nikolaidis, N. P., Lilli, M. A., Doğan, Z. A., Topdemir, T., & Awabdeh, S. (2024). Nature-based solutions for optimizing the water–ecosystem–food nexus in Mediterranean countries. *Sustainability, 16*(10), 4064. https://doi.org/10.3390/su16104064

Ye, H., Deyle, E. R., Gilarranz, L. J., & Sugihara, G. (2015). Distinguishing time-delayed causal interactions using convergent cross mapping. *Scientific Reports, 5*, 14750. https://doi.org/10.1038/srep14750

Zellner, M., Massey, D., Rozhkov, A., & Murphy, J. T. (2023). Exploring the barriers to and potential for sustainable transitions in urban–rural systems through participatory causal loop diagramming of the food–energy–water nexus. *Land, 12*(3), 551. https://doi.org/10.3390/land12030551