



OPTAIN

Optimal Strategies to Retain Water and Nutrients

D6.3: Guidelines for optimal implementation of NSWRM and their combinations in the specific European biogeographical region of interest (Pannonian, Continental, Boreal) across various agroecosystems, terrain, soil, climatic conditions

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ABBREVIATIONS

AHP	Analytical Hierarchy Process
CAP	Common Agricultural Policy
COCOA	Contiguous Object COnnectivity Approach
CoMOLA	Constrained Multi-objective Optimisation of Land use Allocation
CS	Case Study
EC	European Commission
EEA	European Economic Area
EPI	Environmental Performance Indicator
EU	European Union
ET	Evapotranspiration
EBR	European Biogeographic Region
FADN	Farm Accountancy Data Network
GAEC	Good Agricultural and Environmental Conditions
LE	Learning Environment
LMM	Land Management Measures
MARG	Multi-Actor Reference Group
MOO	Multi-Objective Optimization
MS	Member State
N	Nitrogen
NWRM	Natural Water Retention Measures
NSWRM	Natural/Small Water Retention Measures
P	Phosphorus
PET	Potential Evapotranspiration
RBMP	River Basin Management Plan
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SAM	Structural Areal Measures
SLM	Structural Linear Measures
SPI	Socio-Economic Performance Indicator
SWAP	Soil-Water-Atmosphere-Plant model

SWAT+	Soil and Water Assessment Tool Plus model
ToC	Theory of Change
WFD	Water Framework Directive
WOCAT	World Overview of Conservation Approaches and Technologies
WP	Work Package

EXTENDED ABSTRACT

The purpose of the OPTAIN D6.3 was to explore, which NSWRM are the most efficient in the **Continental, Boreal and Pannonian biogeographical regions of Europe (EBR)**, focusing environmental, socio-economic and policy dimensions. To reach this, the OPTAIN researchers and CS leaders identified nearly 30 key research questions. Building on these inputs, the deliverable's shared goal was to determine whether the NSWRMs can be recommended for retaining water, sediment and nutrients in small agricultural catchments.

The **key methodological approach** used in the OPTAIN project was the multi-actor approach, adopted to ensure a harmonised process of stakeholder engagement and modelling across case studies and governance levels. To enable meaningful and efficient stakeholder involvement, multi-actor reference groups were established (WP1). Through a series of strategically designed workshops, these groups actively shared descriptions of good practices in a globally standardised way, using the WOCAT NSWRM catalogue (WP2).

The data collection and harmonisation for model-based assessment (WP3) laid the foundation for one of the project's most significant outcomes: a major breakthrough in creating the evidence base on the environmental and economic efficiency of measures implemented in selected case studies, achieved using the SWAT+ and SWAP models (WP4). This evidence supported the development of a shared understanding of optimised spatial combinations of measures using the COMOLA tool to explore the stakeholder-preferred outcomes (WP5).

Through a series of surveys, stakeholders on various levels shared their opinions on the efficiency and sufficiency of policies and approaches for promoting the NSWRM, as well as on issues and possible solutions for improving NSWRM uptake. The results capture perspectives of stakeholders ranging from supra national, through (international) river basin, and catchment, all down to local, field scale level, and provide a valuable and comprehensive policy overview to further guide NSWRM implementation (WP6). Finally, the OPTAIN findings were distilled and have been put forward to the OPTAIN Learning Environment (LE) platform where the evidence-base, presented through various carefully designed outputs, maintains accessible after the project to support multi-actor learning in real-life contexts (WP7).

The harmonised modelling in OPTAIN helps understand the efficiency of (i) land management measures (LMMs), (ii) structural linear measures (SLMs), and (iii) structural areal measures (SAMs) across the EBRs. **In the Continental EBR** multiple case studies report significant hydrological and agronomic benefits. LMMs reduced sediment and nutrient losses while increasing soil moisture; in some cases this came with slight grain yield reductions. SAM showed strong potential to mitigate high flows, improve low-flow conditions, reduce soil loss, and decrease nitrogen loads. SLMs reduced in-stream nitrogen loads; however, a trade-off was observed in some simulations with more days below low-flow thresholds, while crop-yield effects were minor.

In the Boreal EBR, the LMMs were the most effective in reducing nitrogen and phosphorus losses and increasing early-summer soil-water content. SLMs contributed to sizeable reductions in sediment loss and declines in nutrient loads. In areas prone to spring waterlogging, retention measures improved trafficability. The ability of LMMs to

enhance water retention while sharply lowering phosphorus losses suggests they can address both nutrient pollution and seasonal water-management challenges in this region.

In the Pannonian EBR, NSWRM implementation delivered substantial benefits for erosion control and water retention, with mixed effects on crop production. LMMs were the most effective for reducing sediment and phosphorus losses and for increasing soil-moisture storage; they also reduced nitrogen loss. Measures that remove arable land decreased total grain production, reflecting land-take. SLMs showed limited catchment-scale benefits. Yield responses varied: LMMs increased winter crop yields in some cases but had negligible effects on other crops.

Based on the findings explaining environmental and partially socioeconomic dimension to NSWRM relevance, the OPTAIN D6.3 provides indications for governance improvements that would likely lead to improved uptake and implementation of NSWRM in the respective EBRs. Policy and implementation surveys of WP6 show that the ambitions of the European Green Deal, Farm to Fork Strategy, and Water Framework Directive, policies must go beyond incremental improvements and actively support systemic change.

The most pressing changes show that future NSWRM policies need to improve coordination of governance across scales, ensure robust and sustained financial mechanisms, simplify administration, work more towards effective instead overwhelming knowledge transfer, and, most importantly, focus on improved stakeholder engagement. NSWRM are – here we put forward the synthesis of the available evidence – a strategic tool for advancing water quality and quantity goals, climate resilience, and sustainable agricultural production. However, their full potential will only be realised through integrated, well-designed, and adequately supported governance systems.

Why this work matters in terms of practical application, policy integration, and sustainability? D6.3 provides robust evidence that NSWRM can drive a shift from incremental improvements to systemic transformation in European agriculture, directly advancing the goals of the Green Deal, Farm to Fork Strategy, and Water Framework Directive. At the same time, it highlights gaps between the effectiveness of certain measures and the existing policy instruments supporting the uptake of NSWRM, clearly pointing to where governance improvements and targeted interventions are most needed. By building this evidence base, D6.3 lays the foundation for the co-creation of the next-generation of incentives – the focus of OPTAIN D6.4.

HIGHLIGHTS

- Local stakeholder involvement increases the relevance, accuracy, and legitimacy of NSWRM modelling.
- Standardised NSWRM documentation in WOCAT enhances knowledge sharing and cross-case comparison.
- Reliable NSWRM assessment is feasible in data-scarce catchments using open data and empirical models.
- Spatially targeted NSWRM combinations outperform single measures and mitigate climate impacts.
- Agricultural policy favours land and partly the structural linear measure, limiting transformative structural area and hydro morphological interventions.

1 INTRODUCTION

Effective management of landscapes and water is a key factor limiting crop production in Europe and is likely to become even more critical with climate change. Thus, effective adaptation strategies that focus on increasing water availability and improving water use efficiency are crucial for protecting agricultural production. To contribute to more sustainable and resilient agroecosystems, such strategies must consider more than just managing dry and wet periods and their biophysical benefits. They must also address the reuse of water and nutrients to improve water quality and quantity, and on providing environmental and socio-economic benefits.

This can be achieved either directly through better cultivation practices and water management, or indirectly through the cultivation of more productive crops (due to improved water and nutrient availability). Although there are many techniques for improving water retention at both the farm and catchment levels, and the associated benefits are well documented (e.g., European NWRM+ platform, 2025), we still lack a complete understanding of how different measures affect various regions, soil types, and farming systems under changing climate conditions (EC, 2014; Collentine and Futter, 2018; Garnier and Holman, 2019). To bridge this gap, it is essential to involve local actors such as farmers and advisors who understand the practical benefits and challenges of current systems. These individuals are directly involved in implementing measures and can assess their effectiveness.

Natural/Small Water Retention Measures (NSWRMs) are multifunctional measures that use natural means to manage water and nutrients in river catchments, including small-scale technical solutions to improve the efficiency of water use in agriculture. These measures have been increasingly studied for their impact on achieving a more balanced water quantity, as well as improving water quality and ecological status. The OPTAIN project aims to increase knowledge of the effectiveness of such measures (and their combinations), and to promote their implementation and optimal allocation. To support this task, the project focuses on 14 relatively small case studies – CSs (<250 km²) covering different soil types, climate zones, and agricultural systems (as shown in Figure 1). These case studies are spread across three **EBRs** – Boreal, Continental, and Pannonian, addressing challenges such as drought, flooding, water quality, climate change, and biodiversity restoration (Figure 1).

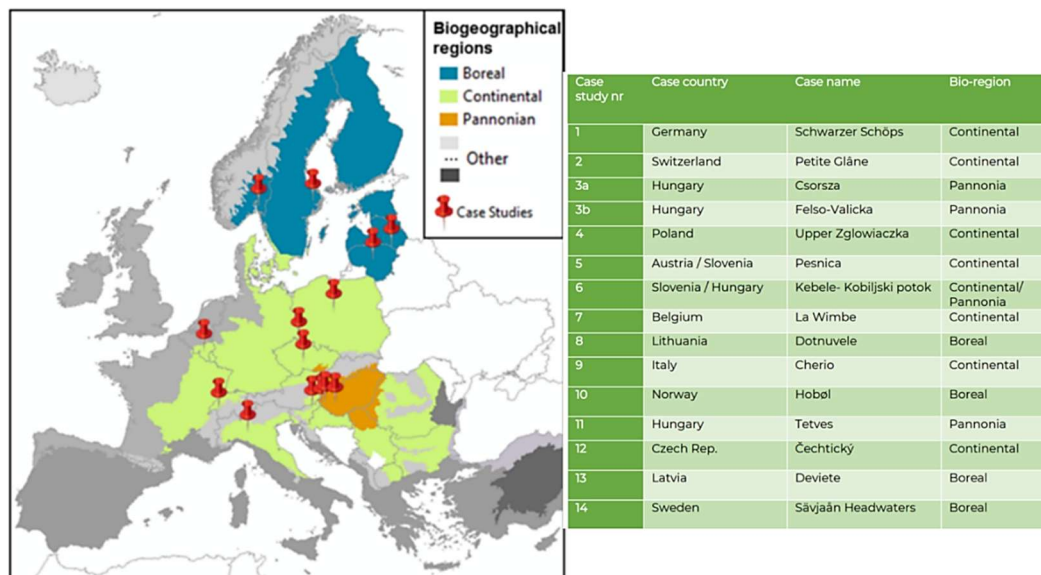


Figure 1: OPTAIN case studies

Cross-case evaluation of the effectiveness of NSWORMs is one of the key objectives of the project. In addition, the project aims to increase the acceptance and implementation of NSWORMs and their combinations by establishing guidelines for their optimal implementation in the specific EBRs of interest (Pannonian, Continental, Boreal). Within the project, specific regulatory challenges and gaps that hinder the accelerated implementation of NSWORMs have been identified. The regulatory challenges and gaps have been addressed in the NSWORM implementation guidelines under D6.3, and will also serve as a basis for developing the improved incentives in D6.4, aimed at motivating relevant stakeholders to put water, agriculture, environment, and climate policies into practice.

This deliverable D6.3 summarizes the results of the harmonized efforts across all OPTAIN CSs and aims to produce an integrated and accessible synthesis of the project findings and to formulate recommendations in language that is understandable to policymakers and farmers in the CSs.

The synthesis of OPTAINs results compares and evaluates the NSWORMs identified in the catalogue of measures (WP2) by drawing on the results from integrated modelling (WP4) and multi-objective optimization (WP5). It considers the physical, environmental, and economic effectiveness of different individual NSWORMs. Additionally, it examines the effects of their combination and allocation across various spatial conditions in different EBRs, agricultural systems, and ecosystems of interest.

Based on the project results, region-specific guidelines for the optimal implementation and combination of NSWORMs are developed, integrated into the OPTAIN Learning Environment (LE), and made available to a wider audience. The guidelines provide a structured description of the entire implementation process (including the identification of management issues, related policy regulations, impacts on agricultural production and ecosystems, economic sustainability, technical design, and practical implementation) within the analyzed EBRs and have the potential for broad application.

In cooperation with Task 5.4, stakeholders (legislators, managers, advisers) and target groups (farmers, landowners) have been consulted on the applicability of the identified measures and their combinations, as well as additional barriers and solutions for their

implementation. This ensures that the measures considered in the guidelines are as attractive as possible, to be mainstreamed from economic, time management, and policy perspectives, and can be put into practice by target groups. It also serves as input into Task 6.4 and WP7.

This deliverable is structured as follows: Chapter 2 presents the EBRs context of the OPTAIN project, which is used for project synthesis and the preparation of regional guidelines. Chapter 3 introduces the methods adopted for performing both tasks. In Chapter 4, we present the most significant results, while Chapter 5 discusses the project's outcomes in more detail. We conclude the deliverable in Chapter 6, which also gives some directions for future work.

2 BIOGEOGRAPHICAL CONTEXT

The implementation of NSWORMs is influenced not only by local environmental and socio-political conditions, but also by general regional characteristics. A key challenge of the OPTAIN project is to synthesize knowledge from 14 different CSs across Europe and translate it into coherent, applicable guidelines for the EBRs. To achieve this effectively, a structured framework for comparing, grouping, and interpreting the results is essential.

Cross-case study evaluation and harmonization can follow a natural science perspective, namely common natural characteristics across the CSs (e.g., important biogeographical factors). However, it can also be argued that anthropogenic factors, such as socio-political characteristics and administrative and governance patterns, can play a decisive role in the implementation of NSWORMs. In other words, environmental characteristics alone do not explain implementation success. Social, economic, and governance factors - such as land tenure patterns, policy support, or the decentralization of decision-making - also play a decisive role. Therefore, a **dual perspective** is proposed, which **combines** insights from the **ecosystem perspective** (biogeographical and ecoregional classification) with those from a **social system perspective** (land use, participation in the Common Agricultural Policy (CAP), governance structures, etc.). This integrated approach allows us to examine both natural and anthropogenic motives for the introduction of NSWORMs.

Figure 2 illustrates the connection between the perspectives of the social system and the ecosystem, together with the selected anthropogenic and biogeographical factors that are relevant for the implementation of NSWORMs. Governance research, which is primarily rooted in the social system, also has a significant connection to the ecosystem, as was previously showcased by Albert et al., 2019.

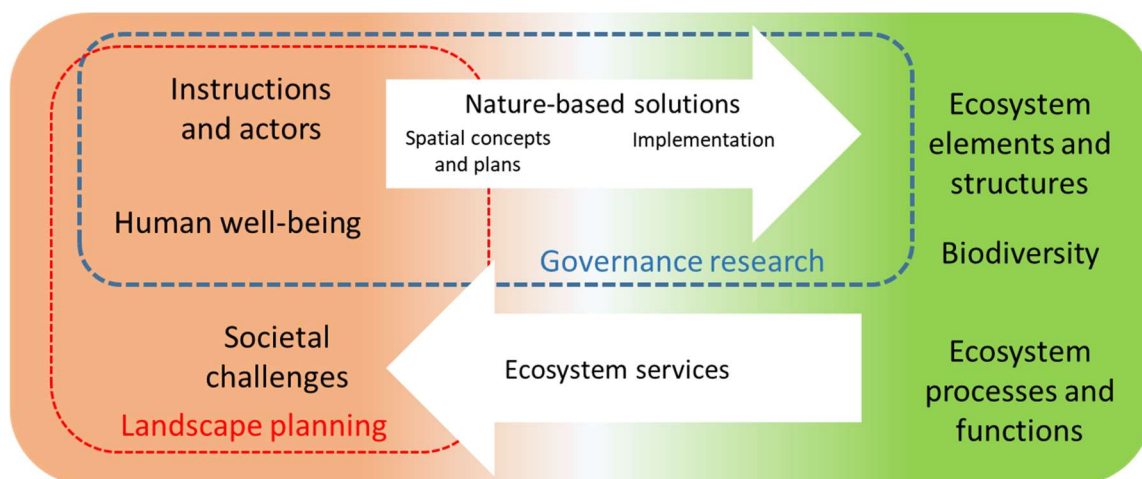


Figure 2: Conceptual Framework (own elaboration modified from Albert et al., 2019)

To synthesize the modelling and optimization results, the OPTAIN project aims to use the concept of EBRs, providing a scientifically grounded way to classify territories based on shared natural features — such as climate, soil, vegetation, and biodiversity patterns — that shape the ecological dynamics of land and water systems. Since NSWORMs are closely linked to these physical and biological systems, understanding their performance and suitability from a biogeographical perspective improves the relevance and scalability of the proposed measures. Grouping OPTAIN CSs by EBRs — specifically the

Boreal, Continental, and Pannonian regions — enables a comparative assessment of problems, policy contexts, and responses, and provides an effective platform for understanding commonalities, anticipating challenges to transferability, and tailoring region-specific recommendations in the guidelines.

It is a conceptual challenge to combine the EBRs perspective with other relevant ecosystem perspectives (e.g., the perspective of the Water Framework Directive (WFD) on Ecoregions) and social perspectives (e.g., anthropogenic factors from politics and governance, including land tenure issues, farmland composition, and centralization issues). However, this is important to summarize knowledge from the project and present the results to a broad audience.

This chapter first introduces the ecosystem perspective by discussing EBRs and the concept of the Ecoregions. It then introduces the social system perspective, namely factors related to land issues, policy, and governance that can play a major role in the design, introduction, and successful implementation of NSWRM.

2.1 Ecosystem Perspective

The ecosystem perspective is relevant for diagnosing similar problems and patterns based on the characteristics of the natural environment. Below, we present two natural scientific concepts: EBRs and Ecoregions.

The European Environment Agency defines EBRs as “areas of similar character in terms of the biota (fauna & flora)”, sharing “evolutionary history”, with boundaries “determined by changes in climate and movement of continents” (EEA Glossary, 1998). According to the map published by the European Environment Agency map (EEA, 2017), Europe is divided into 11 EBRs (Figure 3).

EBRs are useful reference units for describing habitat types and species that live under similar conditions in different countries, and are widely used in the technical literature (EEA, 2002). They are also used as official boundaries in the Habitats and Birds Directives (Cervellini et al., 2020).

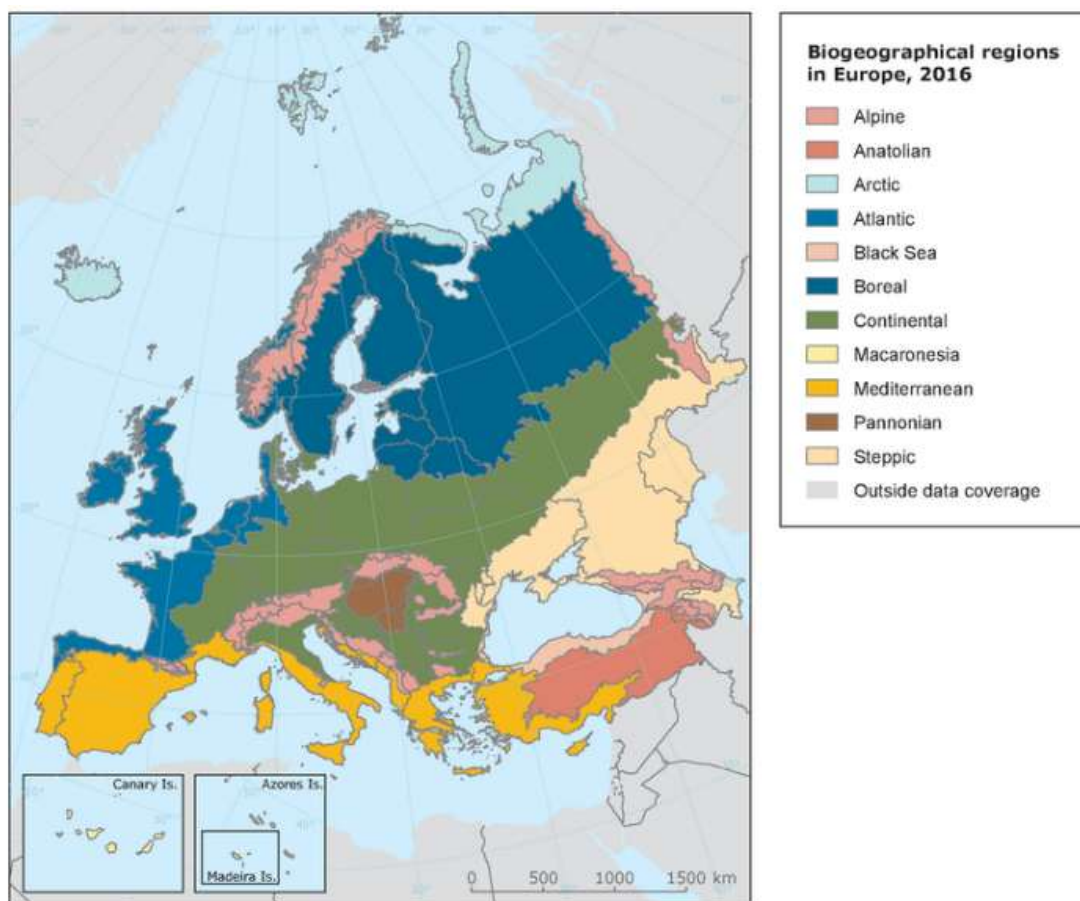


Figure 3: Biogeographic regions in Europe (EEA, 2017)

As a concept, EBRs are commonly used in ecology, evolution, and conservation biology (Vilhena & Antonelli, 2015). Biogeographical models are relevant for understanding patterns of biodiversity (Rangel & Diniz-Filho, 2013). Many studies focus on species origins and evolution, but are also very important for current conservation efforts and future scenarios, especially those concerning resilience to climate change (Vilhena & Antonelli, 2015).

Biogeographical classification can also improve the effectiveness of environmental regulations, international legal instruments, and policymaking, and create important fora for research (Rice et al., 2011). A delineation of ecologically meaningful regions and units is beneficial, as patterns of biodiversity, climate, and soil conditions can be better understood better. Therefore, as stated above, the governance perspective should not only build on social system factors alone, but should also consider the ecosystem characteristics as shown in Figure 2.

On the other hand, the WFD directive is based on an ecoregional map “*primarily to facilitate a standardized surface water typology for ecological assessment and a reporting scheme for all European inland waters*” (Zogaris et al., 2009). The WFD’s ecoregion map (Figure 4) builds on Illies’ 1967/1978 original and “*divides the continent into 25 regions. It is based on an integration of distribution limits and prevailing endemism of numerous freshwater-dependent organisms, particularly aquatic invertebrates*” (Zogaris et al., 2009).

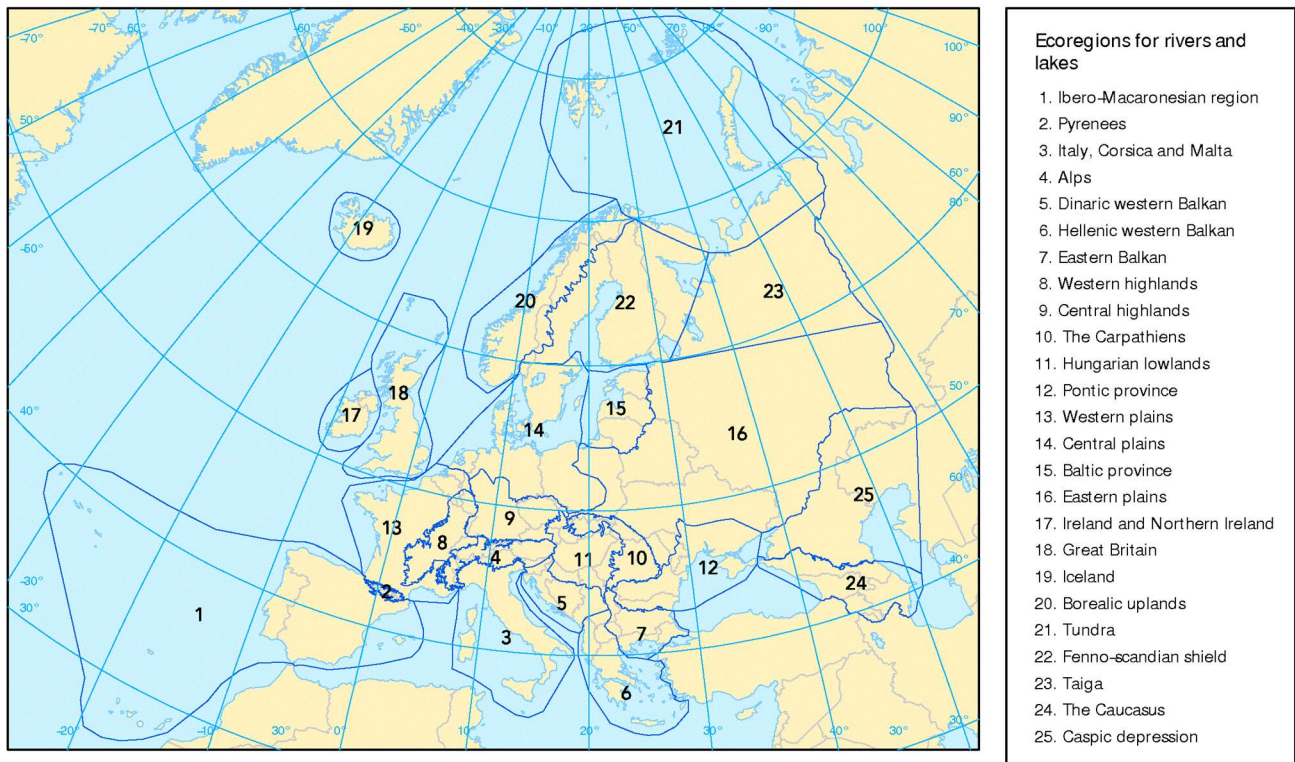


Figure 4: Ecoregion delineation in Europe (EEA, 2009)

The EBRs (Figure 3) and ecoregions (Figure 4) often overlap geographically, but serve different ecological and environmental purposes. EBRs are based on general ecological and climatic conditions, predominant vegetation types and habitats, and the distribution of terrestrial flora and fauna, while ecoregions are based on freshwater ecosystems, the hydrology of river basins, lake systems, the distribution of aquatic species, and ecological processes. Their overlap can be important for integrated biodiversity conservation planning to ensure that both terrestrial and aquatic ecosystems are taken into account.

There are more than twice as many ecoregions as EBRs in Europe (25 to 11), and they do not correspond to each other fully. However, some ecoregions correspond to state boundaries and do not divide states into as many regions. The ecosystem perspective can be seen as a gentler bridge to social factors, but it would bring many new entities to the OPTAIN CSs. This would mean, for example, that our four CSs from the Boreal EBR would be divided into three ecoregions (boreal uplands, central plains, and Baltic provinces). Many cases would be simple examples from their regions, lacking opportunities for generalization. We therefore use the EBRs as a starting point but enrich the perspective with relevant governance factors that are of great importance for the NSWRM implementation.

2.2 Social System Perspective

The ecosystem perspective has a limited importance in replicating the measures, as many other factors also play a crucial role in transferring best practices into real-life settings. To increase the adoption of measures, this needs to be accompanied by a social system perspective, linking the NSWRM implementation with various governance aspects, relevant actors, institutions, and land ownership issues that need to be equally considered in policy development and that do not necessarily follow the ecosystem perspective.

Below are some key examples illustrating alternative groupings of the CSs. The list is not exhaustive, but highlights some important aspects that need to be considered for better implementation of NSWRM. Governance patterns do not necessarily follow ecosystem patterns (biogeography) but should be given equal consideration when implementing NSWRM. We further focus on:

- land rent and land ownership,
- share of arable land and further varieties in farmland composition,
- average farm size,
- establishment of joint agricultural investments and management plans,
- differences or similarities in water governance systems, and
- the level of decentralization.

An important aspect influencing farmers' decision-making and the implementation of NSWRM is linked to the land tenancy vs. land ownership situation. Previous studies have shown that tenant farmers tend to maximize their short-term economic gains, leading to overuse of the soil. On the other hand, soil conservation efficiency is better performed by farmers who are landowners (Eder et al., 2021). Therefore, it could also be hypothesized that landowners who require more investment and pursue a long-term perspective show greater interest in implementing NSWRM (Prokopy et al., 2019).

The World Bank data on arable land shows that the average share of arable land in the EU-27 was 24.5%. However, the share of arable land is very unevenly distributed across countries and regions. The Implementation of NSWRM in areas of intensive agriculture will face different challenges than in areas where other forms of land use (forestry, pasture, etc.) predominate.

Another important factor influencing farmers' decision-making and implementation of NSWRM is related to the composition of farmland. Farms consist mainly of arable land but may also include other forms of land use such as forests and pastures. According to Eurostat data, the average composition of farmland in Europe varies considerably from country to country.

Another relevant factor in the implementation of NSWRM could be the size of the farm. Farmers who cultivate larger areas may have more land “available” for alternative management schemes. On the other hand, farmers with smaller farms may have a closer connection to their land and are willing to manage it more sustainably. Evidence shows regardless of the size, all farms are under specific circumstances willing to uptake alternative management schemes and that farm-size effect isn't straightforward; drivers and costs/benefits differ by size class (Wuepper et al., 2020; Cannesa et al, 2024)

Another key factor in the implementation of NSWRM is the influence of the CAP. The new CAP supports the implementation of NSWRM as part of its environmental and climate objectives. NSWRM are seen as an important tool for improving the resilience and sustainability of the EU's agricultural sector. The CAP encourages farmers to adopt sustainable practices that increase the water retention capacity of their soils and landscapes. The CAP offers farmers various instruments and incentives for implementing NSWRM, such as cross-compliance rules, green direct payments, rural development programs, or the new green infrastructure with eco-schemes (EC, 2021, 2024a, 2024b, 2024c). For the CSs located in the EU, NSWRM contribute to the priorities of the European Green Deal, the CAP, the Floods Directive, and the WFD.

Compared to voluntary measures, NSWORMs that are obliged by law obviously have a different status. Research has shown that the added value of voluntary practices is considerable for creating shared ambitions but limited in terms of actual water quality improvement (Wuijts et al., 2025). The challenge of choosing the optimal combination of voluntary and mandatory approaches to reach the desired environmental and economic outcomes remains. Even within the same EU agricultural policy, member states differ considerably in terms of voluntary measures and the choice of approaches used to motivate farmers to implement the NSWORMs through the policies.

In Europe, multi-level water governance is very diverse (Rowbottom et al., 2022). The same European directives are implemented differently in national contexts depending on existing institutions and responsibilities. Rowbottom et al. (2022) show that European water governance - illustrated by WFD implementation in selected member states - varies widely. It differs both in the degree of centralization/decentralization (national, regional, river basin, catchment, sub-catchment, and farm legislation) and in the policy instruments used (legal, non-legal, and codes of practice/guidance). An important dimension of multi-level governance is the competence and power of authorities at different levels, which depends on the level of decentralization of the political system.

The NSWORM implementation could be influenced by the degree of decentralization and the fact that different EU member states have different actors with decision-making power over the NSWORM implementation. To compare the degree of decentralization between the EU member states, a Decentralization Index was (European Committee of the Regions, 2024) that takes into account three dimensions of decentralization (political, administrative, and fiscal).

3 METHODS

3.1 Theory of change framework

The biogeographical context was used to synthesize the project results and develop regional guidelines based on the **Theory of Change (ToC)** methodology (Figure 5). ToC is a structured framework that guides the design, implementation, and evaluation of interventions or projects by showing the causal links between activities, outputs, and outcomes while also clarifying the underlying assumptions (Janzen et al., 2017). It provides a framework for working towards achieving the desired results. By this it helps stakeholders understand the dynamics of change and how specific interventions lead to targeted goals (Clark, 2024).

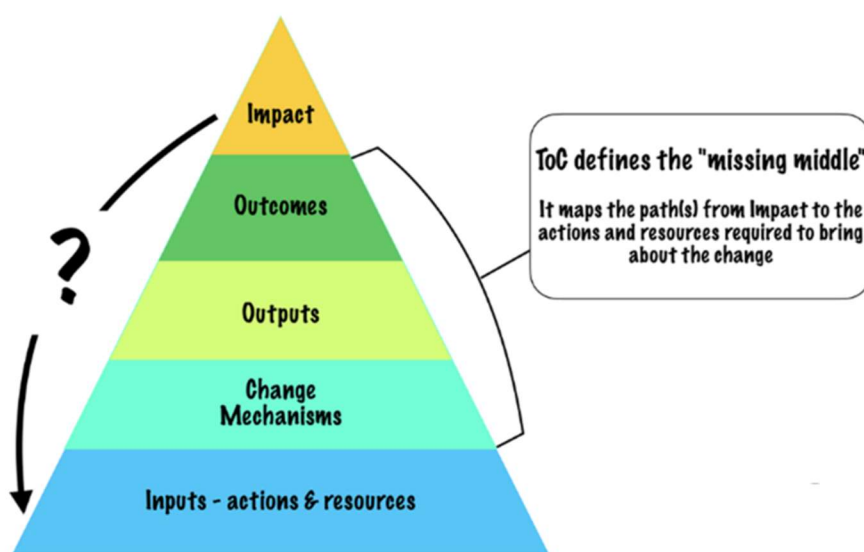


Figure 5: Idea of the Theory of Change (adopted from Jurevicius, 2024)

A similar framework, Change Management, focuses on implementing change within organizations (Phillips & Klein, 2022). Change Management is about managing the process of change within an organization, while ToC is a framework used to plan and articulate how an initiative will achieve its long-term goals. Given the ToC flexibility, it can provide many possible hypotheses on how an intervention will contribute to a change process, which is essential for effective project planning and implementation (Simeone et al., 2023).

The challenge is to develop a ToC that is flexible enough to adapt to each individual research project, while also offering common implementation features that facilitate research planning and management across projects (Janzen et al., 2007). For example, each research project has its own inputs (resources and service capacities generated by the project) and outputs (immediate results of project's activities), which should be clearly identified and tracked.

The process of developing the ToC comprises six steps (

Figure 6), which involve the project partners, define the objectives, and clarify the roles of the stakeholders involved. This structured process promotes consensus and collaboration. Additionally, it ensures that all key stakeholders contribute effectively to the project's objectives and approach.

When comparing the ToC steps with the key steps of the OPTAIN project (Figure 6) many similarities in the workflow can be identified. The results of Deliverable 6.3 are therefore structured in accordance with the ToC framework, explicitly indicating the ToC step to which each OPTAIN result contributes. All six ToC steps are briefly presented below.

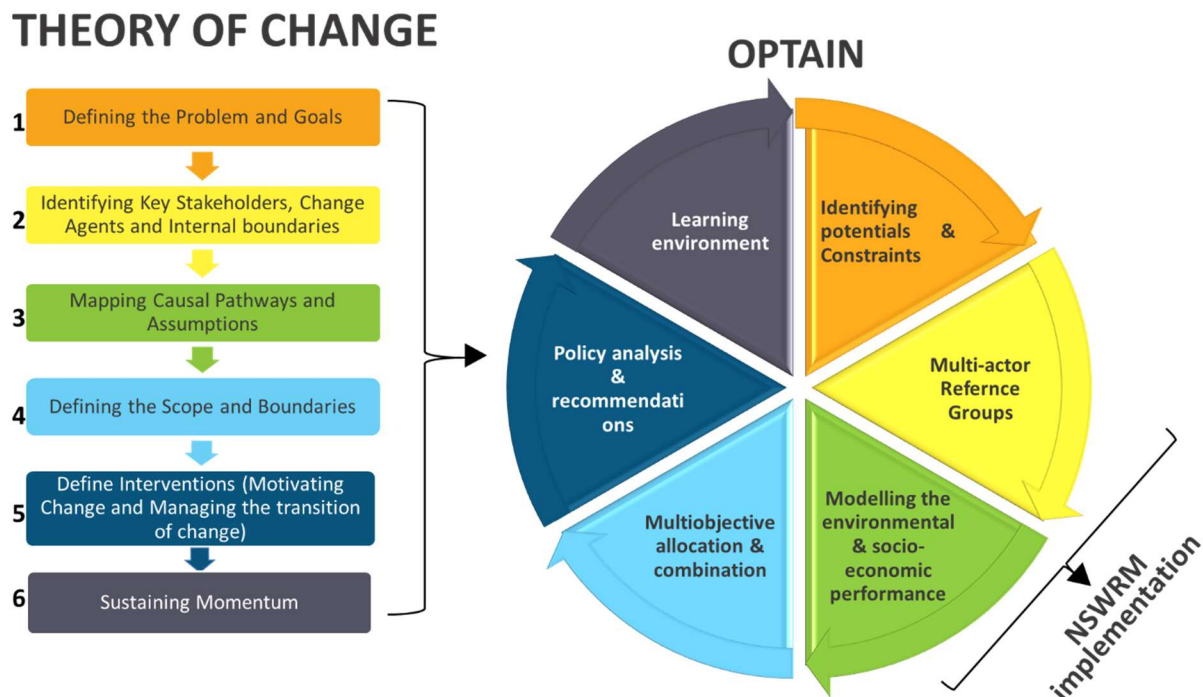


Figure 6: The six steps of the Theory of Change methodology and its connection to the OPTAIN project

STEP 1: Defining the Problem and Goals

The first step in developing a ToC is to define the problem and understand the goals clearly. This requires a thorough analysis of the context, including the causes of the problem and the desired outcomes.

STEP 2: Identifying Key Stakeholders, Change Agents and Internal boundaries

Stakeholder engagement is a critical component of the ToC development. Identifying key stakeholders ensures that their perspectives and roles are taken into consideration throughout the project. Engaging stakeholders early on ensures that their insights and expertise inform the ToC, leading to a more robust and contextually relevant framework. Stakeholders should be involved in all stages of the process, from defining the problem to mapping the causal pathway and identifying assumptions. This ensures that the ToC is grounded in the local context and is feasible to implement (Wu et al., 2024).

Furthermore, these processes bring together different perspectives and aim to maximize the benefits and minimize the losses for all parties involved. Enhanced meaningful participation is characterized by reciprocity when researchers and other community members jointly take the lead in guiding and executing the research

agenda, including research design, implementation, and dissemination (Douthwaite et al., 2020).

Stakeholders can be identified using a top-down approach, with experts determining the categories of stakeholders (Figure 7). Some stakeholders can be categorized as "key players" who have both a high interest and a high influence, while others can be classified as "subjects" having a high interest but only a low influence.

To propose legislative recommendations, developing political support is essential. In this context, change agents are the key players making the change happen. Their presence and competence can have the same impact (if not greater) as any intervention plan (de Caluwé & Vermaak, 2003). Within the OPTAIN project framework, a change agent is a person or organization that drives, initiates, and promotes the implementation of NSWORMs and their integration into water policy and CAP. Possible change agents in countries participating in the project were identified in a World Café session, held as part of the OPTAIN General Assembly in Iseo, Italy, in September 2023.

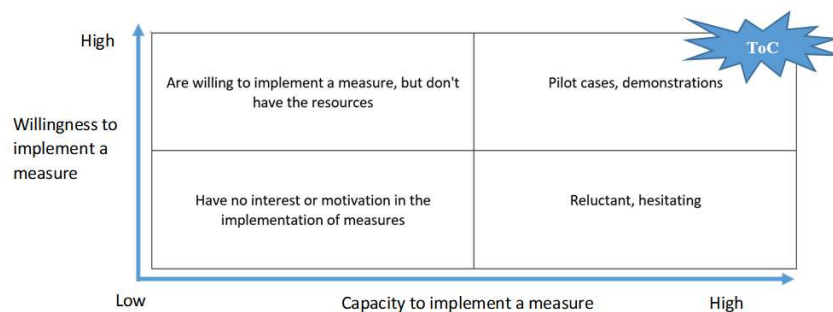


Figure 7: The categorization of stakeholders

STEP 3: Mapping Causal Pathways and Assumptions

The next step involves mapping out the causal pathways that link the intervention activities to the desired outcomes, underlying the assumptions. The pathways can be based on evidence from previous research and stakeholder engagement (Wu et al., 2024). They are used to divide the research process into stages, e.g., preparation, implementation, and sustainability (Hiltensperger et al., 2024).

Within the OPTAIN project, complex cross-WP and cross-task interactions were analyzed in detail using the IDEF0 diagram (Čerkasova et al., 2021). This representation of the project's internal structure and information streams helped WPs and task leads to identify the disagreements between the project processes. These were then addressed internally, resulting in a common understanding of the technical and functional background of the data, information, and knowledge produced within the project. Despite the differences between the CS sites, each process related to the activities in these sites was carried out in a harmonized way based on defined and agreed-upon protocols, producing inter-comparable data and information.

STEP 4: Defining the Scope and Boundaries

This step is essential to ensure that the intervention remains focused and goals are achievable. It involves identifying the scope of the intervention and its specific external boundaries, which are prerequisites for the identification of the governing processes. These processes define the necessary change from the existing to the objective situation

in a dynamic world (Jalagat, 2016), considering expected future scenarios (e.g., future climate). In other words, external boundaries define the interaction between the project and the outside world.

The project's scope was well defined. It identified all the advantages and shortcomings of the existing system, with a clear definition of the objectives that should be achieved while implementing a change. Additionally, their direct and indirect effects were anticipated and modelled, with foreseeable effects and consequences focusing environmental, socio-economic and policy dimensions.

STEP 5: Define Interventions and guidelines for change

The change should be initiated with a strong and clear necessity for a change, taking into account that the future is discounted and that there will always be resistance (opposition) to change (Fairhurst & Putnam, 2018). This is also related to the necessary risk and uncertainty management (see ISO 31.000 family), as the common perception is that the future benefits of any change are more uncertain than the risks (uncertainties) related to its implementation.

Within the ToC, forces for change must be identified, for example, climate and biodiversity change, a healthy environment, resilience to floods and droughts, or human well-being. The change can also be motivated through finance, economy, or politics. Thus, the key purpose of ToC is a) to recognize the motivation that will support the shift from the current to the objective state, b) to achieve positive expectations, c) to understand restraining and driving forces and to manage them well, and d) to lead the change.

Regulations can motivate the introduction of various incentives. The incentives can be understood as the motivation to implement measures by bearing direct and indirect costs (extrinsic motivation) or promoting motivation through increasing awareness, knowledge, and competence (intrinsic motivation).

STEP 6: Sustaining Momentum

Sustainability and scaling are critical considerations in this final phase of the ToC development. From initiating the change to managing the transition, it is important to sustain the momentum. The ToC must be refined iteratively based on stakeholders' feedback and the results of ongoing monitoring and evaluation. This iterative approach ensures that the ToC remains relevant and effective throughout the intervention lifecycle (Wu et al., 2024). Once change is initiated, it must be continuously supported to stay on course until the desired results are achieved. However, knowledge often fails to diffuse beyond academia into the contexts where it could drive large-scale change. Addressing complex environmental, socio-economic, and policy challenges instead requires collaborative efforts that actively include diverse perspectives and skills.

3.2 Synthesis of OPTAIN project findings

3.2.1 The narrative approach

The narrative approach is a qualitative, flexible method for research synthesis, which allows for the inclusion of nuances, contradictions, and contextual details that might be lost in more rigid forms of analysis. The narrative can also incorporate CSs, direct quotes, and stakeholder perspectives, enriching the synthesis and making it more engaging and accessible to a wide range of audiences.

The narrative approach has been widely used in the social sciences, education, and health research, as it values personal stories and experiences as a means to make sense of complex issues and relationships (McLeod, 2024). When applied to data science and research synthesis, the narrative approach helps translate complex information into compelling and relatable stories, enhancing comprehension and making findings more memorable and actionable. However, to avoid oversimplification of complex information, it is important to balance narrative engagement and accuracy (Dove & Jones, 2012).

Within the OPTAIN project, the narrative approach was used to synthesize and present the results of multiple work packages (WPs) in a coherent and meaningful way. The project consortium provided the key inputs in defined the structure to showcase the most important outcomes. These insights were then integrated into a structured narrative that clarifies how each component contributes to the project's overarching objectives.

The aim of the D6.3 was to investigate which NSWRM are most efficient under certain EBRs, with a focus on environmental, socio-economic and policy dimensions. To reach this, the researchers and CS leaders in OPTAIN project were asked to identify the key questions that should guide the synthesis. Nearly 30 key questions were collected. Building on these inputs, and on previous research (Sowińska-Świerkosz & García, 2021), the deliverable's shared goal was distilled as follows: To determine whether the NSWORMs can be recommended for retaining water, sediment and nutrients in small agricultural catchments.

The research questions were grouped to address six aspects of NSWORM implementation and impact:

- Stakeholder acceptance: which NSWORMs are likely to be accepted by different stakeholder groups?
- Policy adequacy: is the existing policy framework sufficient to implement and manage particular NSWORMs?
- Resource efficiency: are specific NSWORMs resource-efficient?
- Synergies vs. trade-offs: do NSWORMs generate more synergies than trade-offs, and how can trade-offs be minimized?
- Contextual fit: Is the choice of NSWORMs (including their natural components) appropriate for local environmental conditions?
- Temporal effectiveness: how does the effectiveness of NSWORMs change over time?

To guide further discussion and research, five hypotheses were developed. These reflect thematic priorities across OPTAIN and capture critical assumptions about the role, implementation, and impacts of NSWORMs.

Hypothesis 1:

Local stakeholders improve the relevance, accuracy, and legitimacy of NSWRM modelling by contributing local knowledge, validating assumptions, and co-owning the process.

Hypothesis 2:

Standardized NSWRM documentation in WOCAT supports knowledge sharing, cross-case comparison, and integration into learning platforms.

Hypothesis 3:

In data-scarce catchments, reliable NSWRM assessment is possible using open data, empirical methods, and predictive models, if key environmental and management data are approximated with sufficient resolution.

Hypothesis 4:

Spatially targeted NSWRM combinations outperform single measures in retaining water and nutrients and can partly offset climate change impacts, even though field-level and catchment-scale effects may differ.

Hypothesis 5:

Agricultural policy promotes NSWRLMs but mainly supports soil and landscape measures, favoring large farms and preserving the status quo over broader, transformative hydro-morphological interventions.

Each hypothesis addressed a distinct dimension of the OPTAIN project - from stakeholder engagement and data availability to policy influence and spatial effectiveness. Together, they provided a structured foundation for testing, refinement, and synthesis as the project approached its final stage.

3.2.2 The database approach

When analyzing data, the database approach refers to the process of using a structured database system to manage and analyze gathered information. This involves storing data in an organized format, for example, in tables or a relational database, and using query languages (e.g., SQL) to retrieve and manipulate this data. The aim is to analyze the data by applying filters, aggregations, and calculations to uncover patterns, trends, or anomalies. This method ensures that the data is handled efficiently, especially when dealing with large amounts of collected information, and enables consistent, reproducible analysis. Overall, it provides a systematic and scalable data analysis, often used in research.

SQL databases allow complex data aggregation, summarizing the collected data into a format suitable for graphical visualization. Horizontal aggregation, as discussed by Bodhe and Mankar (2012), is particularly useful as it transforms data into a horizontal tabular layout, making it easier to interpret and visualize.

To be able to cluster, compare, and synthesize catchment and field scale modelling results obtained within the OPTAIN project – specifically those from the Soil Water and Assessment Tool Plus (SWAT+) and Soil-Water-Atmosphere-Plant (SWAP) modelling – and systematically evaluate NSWMR effectiveness across different EBRs, a harmonized database was created consisting of the following tables (Figure 8):

- *optainCaseStudies* containing the basic characteristics of each CS,
- *optainIndicators* summarizing the basic information of all the hydrological and water quality indicators used,
- *optainIndicatorInfo* describing modelled and calibrated indicators tailored to the data availability and specific objectives of each CS to ensure robustness and reliability of the simulated results and
- *optainMeasureIndicatorsValues* presenting the percentage changes in indicator values relative to the status quo for each implemented measure in each CS, providing a quantitative basis for assessing the relative effectiveness of different NSWMRs and emphasizing both the potential benefits and the variability of responses across the CSs.

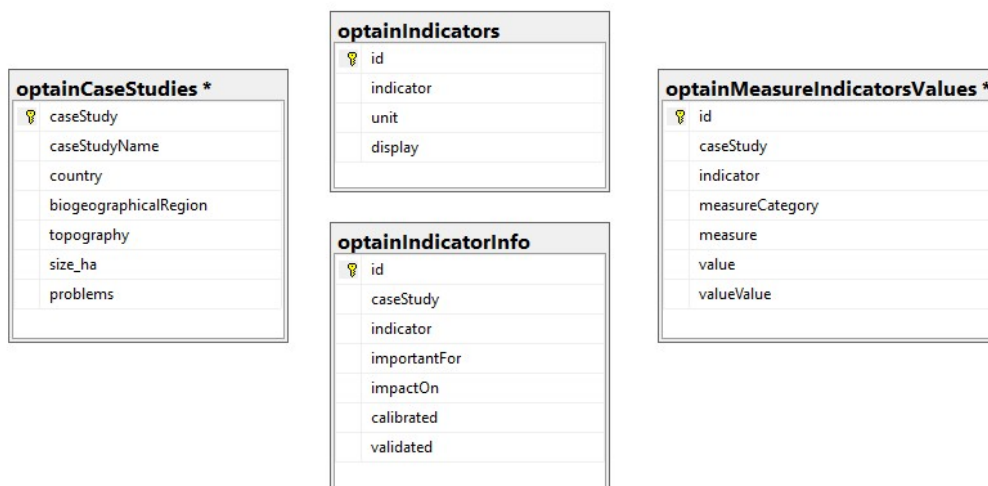


Figure 8: A diagram of the OPTAIN MS SQL Database

Due to the large number of indicators used in OPTAIN (see Chapter 4.1.2.3), the SWAT+ modelers selected the most informative ones, separately for catchment and field-scale analysis. It was agreed that the focus of the project synthesis is nutrient and sediment loads and minimal/maximal discharges at the catchment level, as well as on nutrient/sediment loss and soil water content at the field scale. This common exercise resulted in the selection of nine indicators, presented in Table 1.

Additionally, three SWAP indicators were selected (runoff, soil water storage and drainage/percolation) that are in line with the topics of interest (Table 1).

Table 1: Selected SWAT+ and SWAP indicators

Model	Indicator	Description	Scale
SWAT+	Nload [kg/yr]	Nitrogen load in the river channel	Catchment
	Pload [kg/yr]	Phosphorus load in the river channel	Catchment
	Q_max_aa [m ³ /s]	Annual average maximal flow - Flood management	Catchment
	Q_min_aa [m ³ /s]	Annual average minimal flow - Drought management	Catchment
	Sedload [tons/yr]	Sediment load in the river channel	Catchment
	N_loss [kg N/ha, yr]	Nitrogen loss from cropland	Field
	P_loss [kg P/ha, yr]	Phosphorus loss from cropland	Field
	Sed_loss [tons/ha, yr]	Sediment loss from cropland	Field
	sw_vp* [mm]	sw_4_5_6_7_8_9	Soil water content in vegetation period
sw_4_5_6_7_8_9_10		Soil water content in vegetation period	Field
sw_5_6_7_8_9		Soil water content in vegetation period	Field
SWAP	Runoff [mm]	Annual average surface runoff	Field
	soil_wat_storage [mm]	Annual average soil water storage	Field
	drainage/percolation [mm]	Annual average percolation through soil profile	Field

* As vegetation periods in CSs are different, the sw_vp (soil water vegetation period) indicator is used to summarize all available indicators for soil water content. Where the numbers represent the consecutive months of the year.

* Cropland includes both arable land (land under temporary crops, temporary meadows, and fallow land (less than 5 years)) and land under permanent crops (orchards, vineyards, etc.).

Statistical analysis of the selected indicators

The graphical visualization of the selected indicators listed in Table 1 was created using box plots, a tool commonly used in exploratory data analysis to summarize the distribution of a dataset. Box plots effectively display key statistical measures such as the median, quartiles, and potential outliers, providing insights into the data's location, spread, and skewness. The design of a box plot allows for a compact visualization of data, making it a popular choice for comparing multiple datasets (Ramsay & Diaz-Rodriguez, 2024).

The figures in the sub-chapters 4.1.3.6.1 and 4.1.3.6.2 are divided into different box plot graphs marked with letters A-D (see also equations below):

- **Graph A** presents the average percentage change of an individual indicator (PC; in %) between the results of the NSWRM measure scenario (MMI) and the status quo model (SQM) results.
- **Graph B** shows the weighted percentage change (WPC), i.e. the PC weighted by the ratio between the implemented NSWRM area (MSA) and the total catchment area (TCA).
- **Graph C** presents weighted percentage change (WPCR), i.e. the PC weighted by the ratio between the implemented NSWRM measure (MSA) and the total cropland area (TCR).
- **Graph D** exhibits the annual change of the selected indicator in units per hectare (CPH) of NSWRM implemented. Annual change for runoff, soil water storage and drainage/percolation is presented in mm.

$$PC = (MMI \times 100) / SQM \quad (A)$$

$$WPC = PC \times ((MSA / TCA)) / 100 \quad (B)$$

$$WPCR = PC \times ((MSA / TCR)) / 100 \quad (C)$$

$$CPH = (SQM - MMI) / MSA \quad (D)$$

where:

PC	... percentage change between NSWRM (MMI) and status quo modelling results (SQM) [%]
MMI	... model measures (NSWRM) results for individual indicator [kg; ton; m ³ /s; mm]
SQM	... status quo model results for individual indicator [kg; ton; m ³ /s; mm]
WPC	... PC weighted by the ratio between the implemented NSWRM area (MSA) and the total catchment area (TCA).
WPCR	... PC weighted by the ratio between the implemented NSWRM measure (MSA) and the total cropland area (TCR).
MSA	... implementation area for individual measures (NSWRM) scenarios specific area [ha]
TCA	... total catchment area [ha]
TCR	... total cropland area [ha]
CPH	... annual change of the selected indicator in units per hectare of NSWRM implementation [kg/ha/year; m ³ /s; mm/ha/year]

3.3 Regions' guidelines for optimized implementation of NSWRM

To support the development of implementation guidelines at the level of EBRs, a survey on the cross-catchment transferability of NSWRM was conducted as part of the OPTAIN General Assembly 2023 (held in Iseo, Italy). A World Café (Löhr et al., 2020) session was organized to support the development of region-specific and context-sensitive recommendations. The objective of the cross-catchment survey was to assess the transferability, suitability, and feasibility of NSWRM under diverse local conditions, and to identify key barriers and enablers for their implementation. The analysis was structured according to the Theory of Change (ToC) Framework (see Chapter 3.1), which

provided a systematic approach to mapping causal pathways and assumptions. The results of this survey are presented in Chapter 4.2.

To complement the survey, visualizations of governance structures used, following the results of deliverable D6.2 and the approach of Rowbottom et al. (2022), resulting in NSWRM implementation maps. These tools provide an overview of how different institutional layers, policy frameworks, and stakeholder groups influence the adoption of NSWRMs. They also highlight opportunities for alignment, coordination, and scaling across regions, while making the contextual differences that shape practical implementation explicit.

To inform the region-specific guidelines further, farmers and land managers view of implementing NSWRMs, they were invited to participate in an online survey investigating their views on implementing NSWRMs and their perspectives on the sufficiency or insufficiency of incentives.

The questions addressed:

- The sufficiency of funds for implementing and for maintaining the measure, i.e. if access to / lack of funds represented a barrier or a motivation.
- The sufficiency of administrative support for applying for funds and for providing information on the technical implementation of the measures.
- The situation regarding access to machinery and instruments.

The survey (anonymous) was first developed and tested in CSs 5 and 6 and was then developed further to be applied in the national languages by the local research teams. The teams selected the measures to be addressed. The selected measures align well with the modelling work that ran in parallel.

The results present farmer's and land owner's perspectives on the available support – as motivating or demotivating the adoption of agri-environmental measures. In the results, we shed light on the adoption of measures from practitioners' perspectives, by asking:

- Do available subsidies motivate for implementation of measures, or do they present a barrier?
- Does available administrative support motivate for implementation of measures, or is insufficient information a barrier?
- Do you have access to the machinery and equipment needed for implementing the measure?

In total, 129 respondents from, Belgium, Czech Republic, Germany, Lithuania, Poland, and Slovenia filled in the survey. The research is ongoing and the results are preliminary as more data are being received.

4 RESULTS

4.1 Synthesis of OPTAIN project findings

This chapter summarizes the key project findings, clustered according to the ToC framework described in Chapter 3.1, and specifies which ToC step each OPTAIN result contributes to. The synthesis begins with the narrative approach (see Chapter 3.2.1) and is followed by the database approach for modelling results (see Chapter 3.2.2).

4.1.1 Defining the problem and goals

Step 1 of the ToC identifies problems and goals of a particular project. One of the main problem addressed by the OPTAIN project is how to maintain or improve water and nutrient retention in the landscape despite the increasing number of extreme events that we face in many European regions, which exacerbates the conflicts between different water users.

Climate projections indicate that a change towards longer and more severe droughts and heavy rainfall can be expected, which will pose additional challenges in agricultural catchments as water scarcity, excess water, and nutrient and sediment runoff increase. The project aims to improve implementation and understanding of the benefits of NSWRM, which can support the retention and management of water and nutrients through natural means and processes, contributing to more resilient agriculture and society. The NSWRMs used in the OPTAIN (Figure 9) follow the concept of Natural Water Retention Measures – NWRM (<https://www.nwrn.eu/measures-catalogue>).

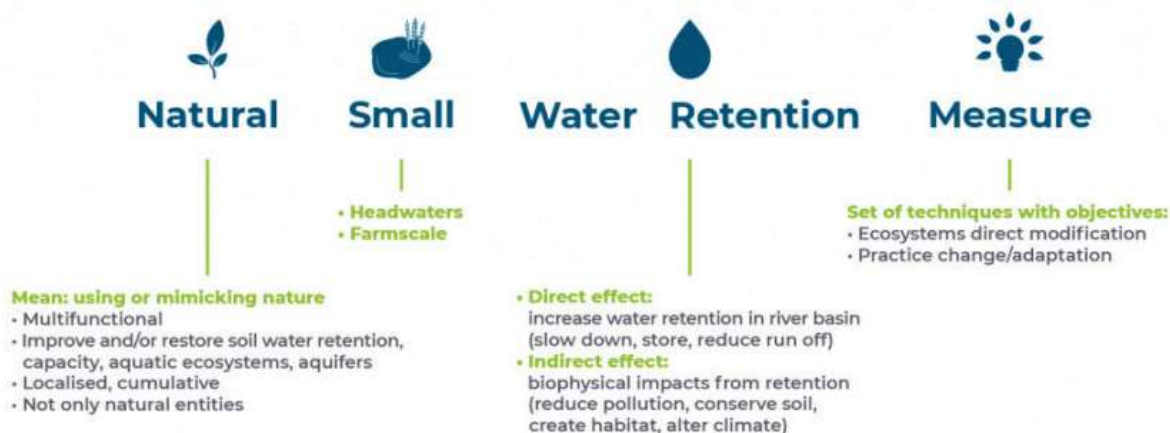


Figure 9: Natural Small Water Retention Measures (NSWRMs)

More specifically, OPTAIN aims to increase the acceptance and implementation of NSWRM by investigating under which climate conditions, where (at which location within the catchment), and using which NSWRM combinations we can achieve the best performance, considering environmental and socio-economic indicators, to meet the specific conditions and management needs of each catchment.

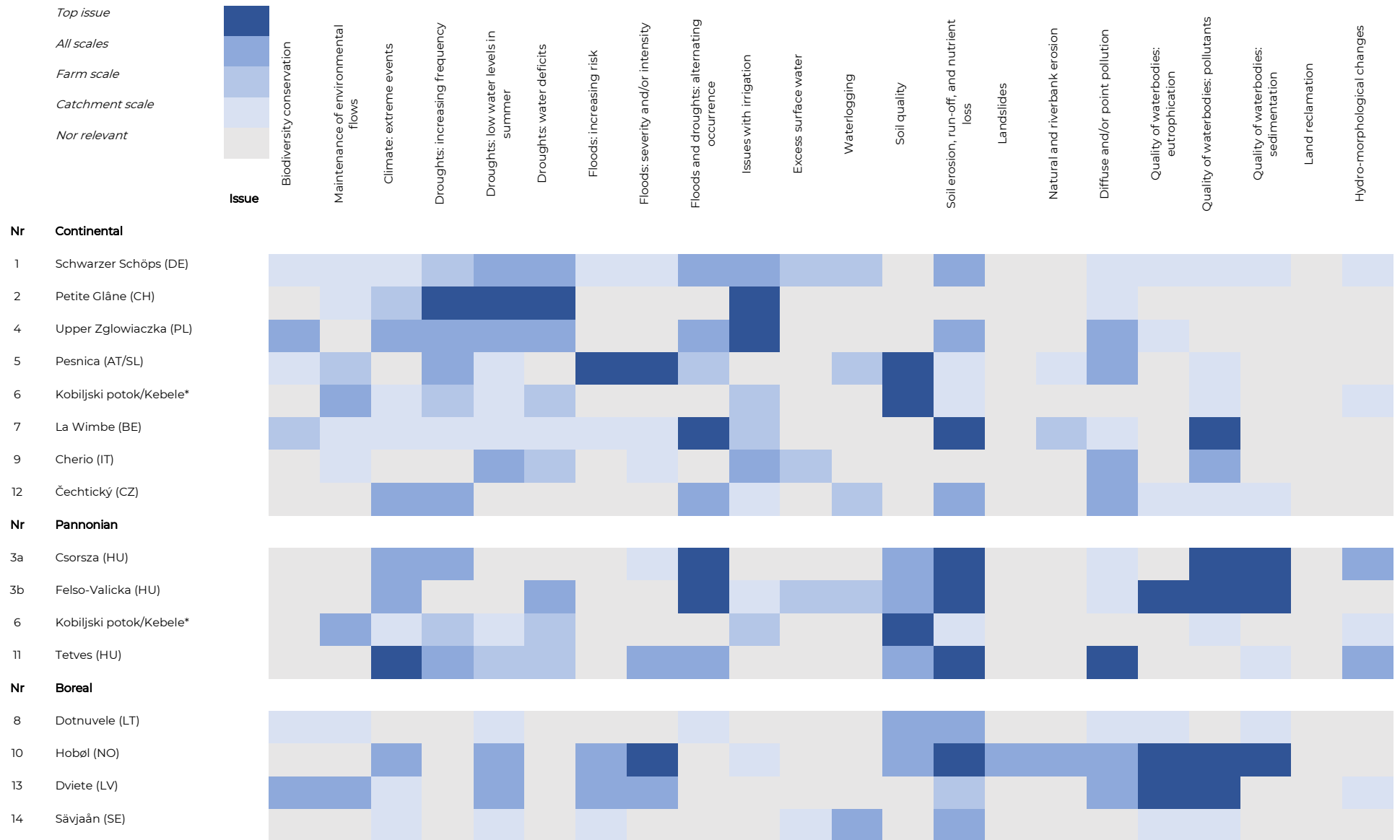
Regions tend to experience similar problems, although some local, site-specific problems can also be present. Table 2 identifies issues in all the OPTAIN CSs and their cumulative importance across the EBRs (adapted from Čerkasova & Idzelytė, 2021). Please note that the Kobiljski potok/Kebele case represents both the Continental and Pannonian regions and is listed in both categories.

Table 2 shows that problems related to the droughts (increasing frequency, low water levels in summer, water deficits) are a common problem for many continental EBR CSs. The alternating occurrence of floods and droughts was also identified as a critical problem in the cases. In addition, soil erosion, run-off, nutrient loss, and diffuse and/or point pollution have been identified as common problems.

In the Pannonian EBR, soil quality, soil erosion, run-off, and nutrient loss seem to be the most critical issues. Climate extreme events, droughts connected to water deficits, alternating occurrence of floods and droughts, and water quality issues are also among the most critical challenges.

For the Boreal region, the emphasis has been put on soil erosion, run-off, and nutrient loss, followed by the water quality issues, droughts (more specifically, low water levels in summer), and increasing risk of floods.

Table 2: Issues identified within the OPTAIN case studies



Site-specific problems (defined by stakeholders)

As an alternative, local stakeholders participating in OPTAIN Multi-Actor Reference Groups (MARGs) workshops were asked to identify and rank the most relevant problems within their CSs by filling in questionnaires. These workshops took place in 14 different case studies in 13 countries in Europe. Altogether, 294 stakeholders contributed their insights to the questionnaire. The results (Table 3) show that the key problem identification was ranked similarly to Table 2 for the Continental and Boreal biogeographical region, but differently for the Pannonian one.

- Continental and boreal: droughts > nutrient runoff > erosion > floods
- Pannonia: floods and droughts > erosion > nutrient runoff

Table 3: OPTAIN Case studies with dominant project-related issues

CS nr	Case country	Case name	EBR	Size km ²	Problems with:			
					P losses	N losses	Floods	Droughts
1	Germany	Schwarzer Schöps	Continental	136	x		x	x
2	Switzerland	Petite Glâne	Continental	101	x			x
3a	Hungary	Csorsza	Pannonia	21	x		x	
3b	Hungary	Felso-Valicka	Pannonia	21	x		x	
4	Poland	Upper Zglowiaczka	Continental	78	x	x	x	x
5	Austria / Slovenia	Pesnica	Continental	137			x	x
6	Slovenia / Hungary	Kebele-Kobiljski potok	Continental / Pannonia	247	x	x	x	x
7	Belgium	La Wimbe	Continental	128			x	x
8	Lithuania	Dotnuvele	Boreal	176	x	x		
9	Italy	Cherio	Continental	153		x	x	x
10	Norway	Hobøl	Boreal	56	x	x	x	
11	Hungary	Tetves	Pannonia	117	x		x	
12	Czech Rep.	Čechtický	Continental	72	x	x	x	
13	Latvia	Deviete	Boreal	254	x	x	x	
14	Sweden	Sävjaån Headwaters	Boreal	125	x		x	x

MARG members from the Continental and Boreal regions identified droughts as the most relevant problem, while for the Pannonian region, droughts and floods were identified as equally important problems. A pairwise comparison of the importance of water retention measures and reduced run-off was similar for the Continental and Boreal regions, with water retention measures being slightly more important than reduced run-off. On the contrary, for the Pannonian region, they were ranked equally important.

Problem identification is important because it can guide the selection of measures and interventions within a particular region.

Water quantity problems

Due to the changing climate, floods and droughts are becoming increasingly problematic, affecting different sectors (e.g., agriculture, environment, etc.). Within the OPTAIN project, 9 out of 14 CSs indicated that they are facing more frequent droughts, while 6 CSs reported on alternating occurrences of floods and droughts. The modelling and analysis of these trends largely depend on the appropriate definition of the physical setting and on data availability.

When defining the flood risk and flood hazard areas, we follow the Floods Directive (2007/60/EC) (EC, 2007). According to the Directive, five CS sites (CH, BE, IT, HU, LV) are in a flood risk area, and four (DE, CH, BE, IT) are in a flood hazard area (Čerkasova Idzelytė, 2021).

Agricultural droughts are defined as a lack of sufficient moisture in the topsoil to support crop growth. On the other hand, hydrological droughts are connected with low water levels in the hydrological system, i.e., abnormally low streamflow in rivers, lakes, reservoirs, and groundwater. The OPTAIN CSs provided information on the changes in the severity, duration, and frequency of both types of droughts. Most CSs (10) experience an increase in the severity and frequency of hydrological droughts, while eight CSs experience more agricultural droughts. Only in two CSs, agricultural droughts are not a relevant issue (CS8 and CS12).

When information on droughts is unavailable, a detailed analysis must be performed to determine if the issue is relevant. However, without long-term hydrological and meteorological measurements, such an analysis is challenging. Long-term data series are unavailable for CSs in HU (3a, 3b, 11), CS7 (BE), CS9 (IT), CS13 (LV), and CS14 (SE). Hence, before the modelling task, we had to identify the nearest flow gauge with a long time series and verify its similarity to the CS catchment. These data served as a reasonable proxy, in cases where no data was available within the CS. Other techniques (i.e., remote sensing and machine learning algorithms) might also be used to determine the relevance of drought issues. However, such an analysis would require expertise beyond that available within the OPTAIN project. In cases of data unavailability, the modelling results used to assess the effectiveness of NSWORMs in addressing drought issues are to be considered highly uncertain (Čerkasova & Idzelytė, 2021).

Water quality problems

Within the OPTAIN project, an analysis of the current and desired status of the water bodies in the CS catchments was performed. All the relevant water bodies and their current states were identified, based on indicators defined by the 2nd River Basin Management Plan for the EU member states, or a similar policy for non-EU members. The target status was also indicated (Čerkasova & Idzelytė, 2021).

The screening resulted in the following conclusions (Figure 10):

- Most of the CSs reported the need to improve the water quality status of their water bodies.
- 21 water bodies need improvement by one step (i.e., from Bad to Moderate).

- Eight water bodies reported the need to improve by two steps (i.e., from Bad to Good),
- One water body needs improvement by three steps, from Bad to Very Good.
- 18 water bodies have moderate or better ecological/chemical status and therefore need only maintenance of the current state.

Based on the aggregated questionnaire results, the main issues are the exceedance of TP, TN, and phosphate (PO₄- P) concentrations in the rivers. These nutrients can be associated with agriculture and, in the case of P, with possible soil erosion and/or point source pollution. The target value for water quality improvement is Moderate or higher for all the CSs, while the majority of the water bodies aim for improvements to a Good status. One third of the CSs reported that water quality improvement is also needed in the downstream locations of the CS sites. As the selected CSs are located in the headwaters or tributaries of larger rivers, the possible solutions within the CSs could have an effect at the larger river-basin scale (Čerkasova & Idzelytė, 2021).

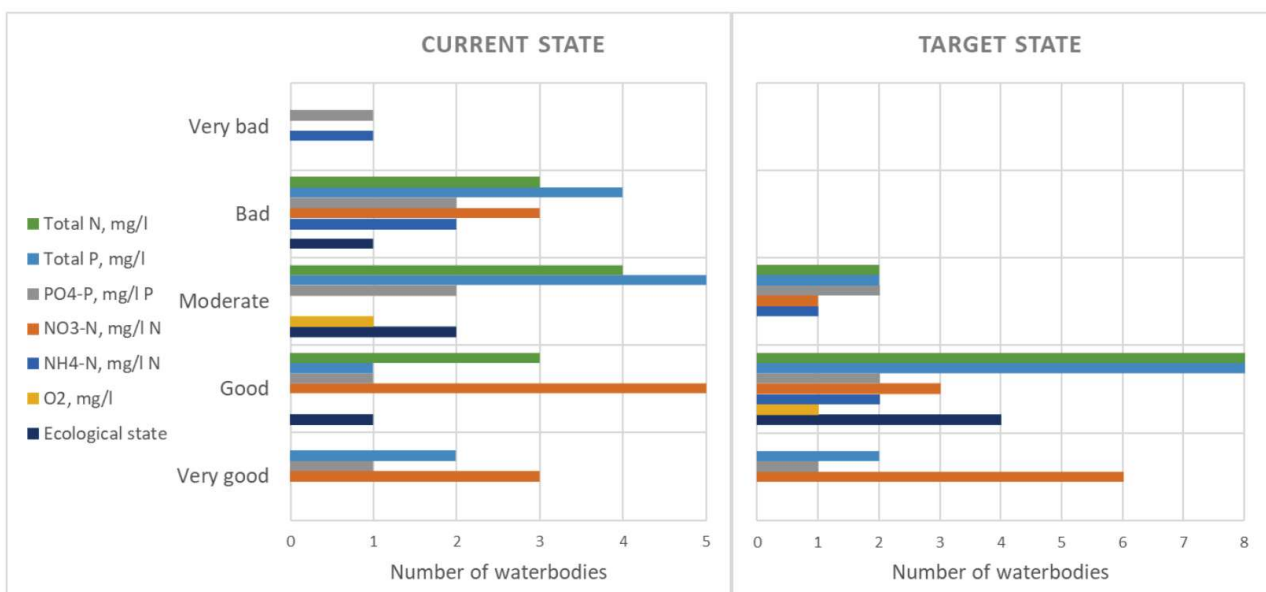


Figure 10: Current and target ecological/chemical status of the water bodies in the CS catchments according to the 2nd River Basin Management Plan (Čerkasova & Idzelytė, 2021)

Food production problems

In general, average yield gaps were available at the country level. These could also be derived from the Global Yield Gap Atlas (2020), which contains a ten-year-old dataset with a coarser resolution. The aggregated results of the yield gap show that, among the varying crop types grown in the CS areas, the largest yield gap in absolute terms (t/ha) is observed with potato and silage maize crops, both in the CS12 (CZ). For cases with available information on the long-term average total yields, we calculated the relative yield gaps, expressed as a percentage of the average yield. The results show that in the CS countries, the yield gap for barley, maize, potatoes, rapeseed, sugar beets, sunflower seeds, and wheat crops is 4% to 37% of the observed yields, on average. The highest relative yield gaps are observed in Latvia (barley and wheat), Hungary and Poland (maize), Lithuania and Slovenia (potatoes), Lithuania (rapeseed), Italy and Hungary (sugar beet), and Poland (sunflower). Germany, Sweden, and Switzerland report the smallest relative yield gaps (i.e., 0-5%) for most crops.

The yield gap percentage was calculated using average country statistics, because the total average yields for the CS areas were not available. Therefore, the percentage statistics do not fully represent the chosen CS areas.

Governance dimension

To better define the problems and goals within the OPTAIN CSs, the governance dimension must also be taken into account.

Table 4 summarizes some of the key differences in the selected governance factors among the countries participating in OPTAIN. There is a significant variation in the share of rented land, reflecting differing land tenure traditions and agricultural economies. For example, the Czech Republic, Belgium, and Germany rely heavily on renting, while Poland and Austria maintain more ownership-based farming structures.

The share of arable land and cropland varies significantly, indicating diverse agricultural capacities and land use priorities. High shares in Hungary and Germany signal intensive crop production, while low levels in Sweden and Slovenia reflect geographic or climatic limitations.

The average farm size differs reasonably across countries, shaped by historical patterns of land distribution and policy. The large average farm sizes in the Czech Republic and Germany support industrial-scale farming, whereas the smaller holdings in Slovenia and Poland point to more fragmented, often family-run operations.

Table 4: Key differences in the selected governance factors among the OPTAIN countries

Countries	Share of rented land (%)	Arable land (%)	Woodland and shrubland (%)	Grassland (%)	Average farm size (ha)	CAP (yes/no)	Decentralization Index (0-3)
Austria	31	16	48.5	24.2	19.4	yes	1.5
Belgium	74.1	28.6	27.8	28.2	34.6	yes	2.1
Czech Republic	87.9	32.1	39.3	20.1	133	yes	1.9
Germany	70.5	33.4	35.7	20.8	58.6	yes	2.5
Hungary	67.2	45.4	28.2	17.5	9.5	yes	1.4
Italy	38.8	24.3	41.2	16.4	12	yes	1.7
Latvia	44.6	21.9	56	20.9	23	yes	2.5
Lithuania	60.1	36.4	39.6	21.9	16.7	yes	1.5
Norway	48	2,2	37,8	2,25	26,1	no	n.a.
Poland	27.5	36.2	37.6	20.7	10.1	yes	1.9
Slovenia	31.8	9	65.8	17.8	6.7	yes	1.8
Sweden	53.4	6.2	68.5	5.5	45	yes	2.4
Switzerland	47	10	32.3	24.5	21.8	no	n.a.

Variation in average farm size and land ownership patterns suggests different potential for and reliance on joint agricultural investments and cooperative management, with larger-scale systems more likely to support formalized joint ventures. Differences in decentralization show indices of variation in water governance approaches. Highly decentralized countries such as Germany and Sweden likely allow for more regionally tailored water management. On the other hand, more centralized systems may enforce uniform governance across diverse landscapes.

Decentralization levels range from relatively centralized (e.g., Hungary, Austria) to highly decentralized (e.g., Germany, Sweden), affecting how agricultural and environmental policies are implemented and adapted locally. This has implications for responsiveness, efficiency, and regional equity in governance.

There is a huge variation in land ownership among farmers within the EU states participating in the OPTAIN project. A telling example is Farm Accountancy Data Network (FADN) statistics quoted by (Střeleček et al., 2011), presenting the share of rented land in the EU (Table 5).

Two neighboring countries, Poland and the Czech Republic, both representing CSs within the Continental EBR, hugely differ in terms of rented land share, with 27.5% in Poland and 87.9% in the Czech Republic. Based on previous research, it can be hypothesized that farmers who own the land will show more interest in NSWRMs, and that additional attention and incentives are needed to make the NSWRMs attractive, both for farmers renting the land and for the original landowners who do not manage their land (Sklenicka et al., 2015, Leonhardt et al., 2019).

Share of arable land shows the highest value for Hungary (45.4%) and the lowest value for Sweden (6.2%) (The Global Economy, 2021) - see Figure 11. This would be even lower for Norway, not covered in the dataset, where it is only around 3% (Dybdal, 2023). For Switzerland, also not covered in the EU statistics, it would be just a bit above the Slovenian value, i.e., around 10% (Macrotrends, 2021).

Table 5: Distribution of the EU states according to share of rented land in 2007 (adopted from Střeleček et al., 2011)

Share of rented land (%)	EU states and their shares
15-30	Ireland (16.5%), Poland (27.5%), Denmark (28.3%)
30-45	Austria (31%), Slovenia (31.8%), Portugal (31.8%), Spain (33.6%), Finland (34.8%), Italy (38.8%), Netherlands (40.3%), Romania (41.8%), Great Britain (42.6%), Greece (43%), Latvia (44.6%)
45-60	Luxembourg (50.7%), EU (52.5%), Sweden (53.4%), Estonia (59.8%)
60-75	Lithuania (60.1%), Cyprus (64%), Hungary (67.2%), Germany (70.5%), Belgium (74.1%)
75-90	Malta (82.2%), France (84.5%), Czech Republic (87.9%), Bulgaria (89%)
Above 90	Slovakia (96.3%)

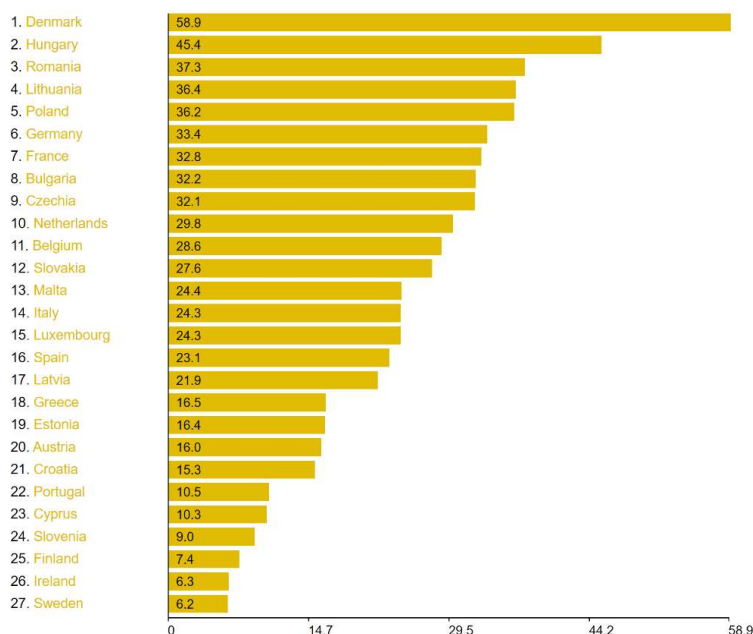


Figure 11: Arable land as % of the total land area

Most of the arable land consists of cropland (Figure 12). EU regions with high shares of cropland (e.g., Denmark and Hungary) have fertile lands and a long tradition of agriculture (Figure 13). In most Member States, a cropland share ranges from 15% to 35% of the total area, while in several countries this share is significantly lower (Eurostat, 2021).

Farmland composition reflects variations in the OPTAIN CSs. In Lithuania, land belonging to farms is hugely dominated by utilized agricultural areas, with a marginal share of wooded and other areas. By contrast, in Norway, most of the farmland is composed of other types of areas, followed by wooded land and utilized agricultural area

(Figure 13). It can therefore be easier to compromise NSWRM implementation on farms that have other types of land not dedicated to intensive agricultural production.

Share of total area by type and land cover (%), 2018

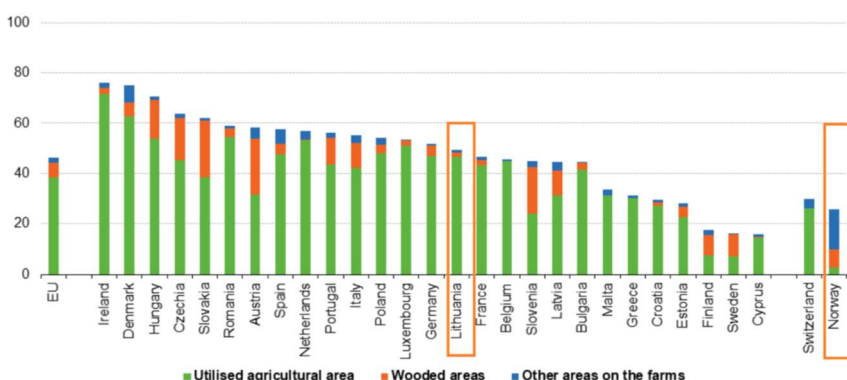
	Total area (km2)	Woodland and shrubland	Cropland	Grassland	Water areas and wetland; bareland	Artificial
EU	4 125 107	46.8	24.2	17.4	7.3	4.2
Belgium	30 666	27.8	29.1	28.2	3.3	11.7
Bulgaria	110 996	48.8	32.3	14.7	2.0	2.3
Czechia	78 871	39.3	33.7	20.1	2.4	4.4
Denmark	42 925	21.9	47.7	19.7	3.8	6.9
Germany	357 569	35.7	32.3	20.8	3.7	7.6
Estonia	45 336	58.7	12.9	16.2	10.5	1.7
Ireland	69 947	24.2	5.5	57.7	8.5	4.2
Greece	131 694	57.6	20.5	13.8	4.1	4.0
Spain	498 502	50.1	27.4	12.8	6.0	3.7
France	549 060	36.0	29.9	24.6	3.8	5.7
Croatia	56 594	59.2	16.6	17.4	3.7	3.2
Italy	302 072	41.2	31.7	16.4	4.2	6.6
Cyprus	9 253	46.5	30.4	10.9	6.0	6.2
Latvia	64 585	56.0	15.4	20.9	5.9	1.7
Lithuania	65 284	39.6	32.0	21.9	4.3	2.1
Luxembourg	2 595	36.9	21.8	32.9	1.1	7.4
Hungary	93 012	28.2	43.5	17.5	6.8	4.0
Malta	316	16.9	28.7	18.5	8.4	27.5
Netherlands	37 377	16.8	23.0	34.2	13.3	12.6
Austria	83 878	48.5	15.9	24.2	7.3	4.2
Poland	311 929	37.6	34.7	20.7	3.3	3.6
Portugal	89 103	56.2	16.3	15.8	5.3	6.4
Romania	238 398	37.0	32.6	22.9	4.7	2.8
Slovenia	20 273	65.8	11.0	17.8	1.2	4.3
Slovakia	49 035	49.5	27.5	17.6	2.0	3.4
Finland	338 411	69.6	5.3	5.7	17.6	1.7
Sweden	447 424	68.5	4.0	5.5	20.1	1.8

Source: Eurostat (online data code: lan_lcv_0vw)



Figure 12: Share of cropland (and other land uses) in the EU Member States

Land belonging to farms by type of land (% share of total land area, 2020)



Source: Eurostat (online data codes: ef_lus_main and reg_area3)



Figure 13: Farmland composition (Eurostat, 2022)

Another figure dedicated to agricultural land use shows the utilized agricultural area as composed of arable land, permanent grassland, and permanent crops, together with kitchen gardens. Again, noticeable differences can be observed, for example, showing huge differences in permanent grassland (very high in Slovenia and low in Sweden, Hungary, Lithuania, and Poland; Figure 14).

Another relevant factor in NSWRM implementation may be the farm size. Figure 15 shows that average farms are larger in Southern Sweden and Eastern Germany compared to farms in Poland, Italy, Hungary, Slovenia, and the Baltic states. More research is needed to understand the relationship between farm size and willingness to adopt NSWRMs.

OPTAIN research (Monaco et al., 2024) showed the implementation of some NSWORMs may require large investments that put a strain on the overall income of farms and/or households. Therefore, farms and households with higher financial means are likely be more willing to invest in technology (e.g. machinery needed for certain field operations) as well as structural and long-standing solutions. Policy recommendations and options influence farmers' ability to place and utilise NSWORMs (Dessart et al., 2019).

Targeted public financial support and other sources of funding can actually reduce investment costs for farmers, leading to a higher acceptance of NSWORMs especially among small farms: for example, it has been found that small farms with a low level of mechanisation are more willing to participate in Rural Development Policy (RDP) contracts that support the provision of environmental services in both Italy and Belgium (Pascucci et al., 2013; Vanslebrouck et al., 2002).

However, the decision to implement NSWORMs at farm level is motivated by a variety of complex factors that go far beyond potential financial compensation (Vik and McElwee, 2011; Veidal and Flaten, 2011; Alsos et al., 2003) and incentives through by public policies. These include the local environment, pedo-climatic constraints, structural characteristics of farms (e.g. farm size, access to technology) (Pagliacci et al., 2020), farm operation characteristics (e.g. intense use of production factors, availability of specific infrastructures) (Runick et al., 2021), the use of external information sources and the avail of professional associations or advisory services for consultation (Diederer et al., 2003). We also assume that previous experiences with climate-related and macroeconomic shocks will lead farmers to take certain NSWORMs to counteract adverse effects (on crop yield, farmers' profit, input use and efficiency, capital use, production risks) and limit the negative effects in the short term so that they do not suffer from the same shock in the future (Monaco et al., 2024).

Most of the OPTAIN CSs are in the EU, except for the Norwegian and Swiss cases. The European Economic Area (EEA) Agreement does not cover agricultural policy. Thus, Norway and Switzerland developed their national agricultural policies. However, CAP reforms may still influence both countries in terms of agricultural policy and farmers' situation.

Type of agricultural land use
 (% share of utilised agricultural area, EU countries, 2020)

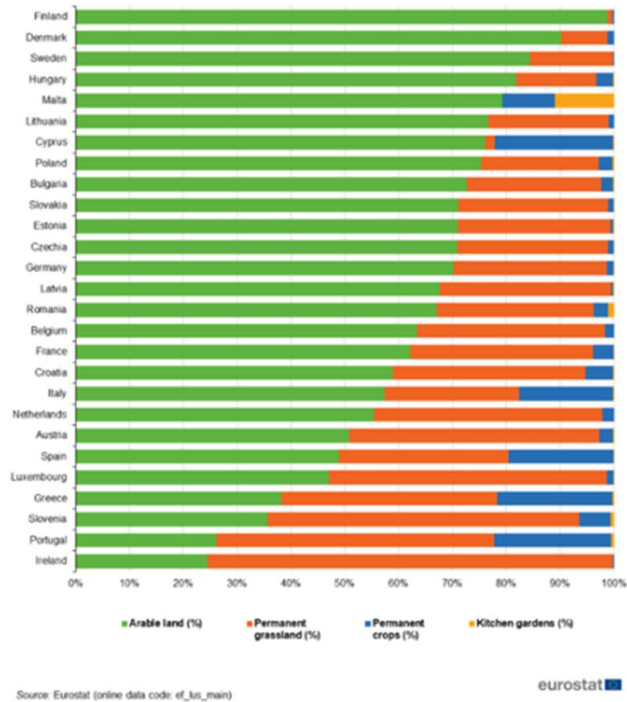


Figure 14: Type of agricultural land use (Eurostat, 2020)

Average farm size by region

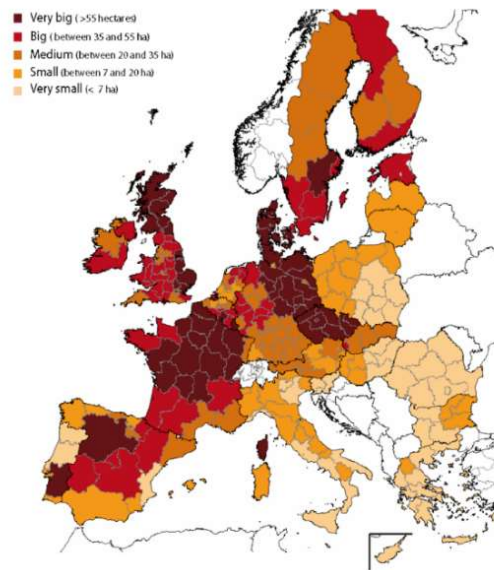


Figure 15: Average farm size (European Parliamentary Research Service, 2007)

From the OPTAIN CS countries, Germany ranks first (1/27) in the Decentralization Index, followed by Latvia (2/27), Sweden (4/27), Belgium (7/27), Poland (8/10), Czech Republic (9/27), Slovenia (10/27), Italy (13/27), Lithuania (17/27), Austria (18/27) and Hungary (21/27) (Figure 16).

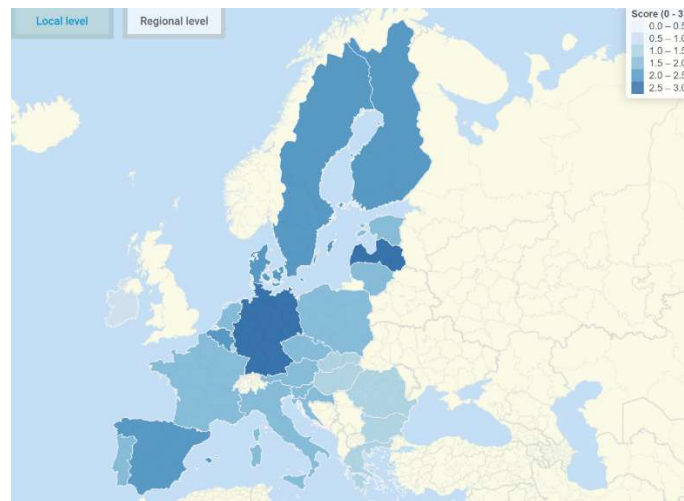


Figure 16: Degree of decentralization among the EU members

Several Member States have legislative powers at the sub-national level (i.e., Austria, Belgium, Finland, Germany, Italy, Portugal, and Spain).

It can be expected that there is a significant difference in the involvement of different scale actors between the most decentralized CS (in Germany) and the most centralized (in Hungary). Thus, the NSWRM Guidelines and campaigns should target local and regional actors in decentralized countries, as well as state-level institutions and decision-makers in centralized states.

4.1.2 Stakeholder engagement

Stakeholder engagement, as a part of Step 2 of the ToC framework, is important because achieving a scientific solution does not necessarily result in resolving a real-world problem. It is essential throughout the entire project lifecycle, from problem identification and assessment to solution design and implementation. Stakeholders' feedback improves the prioritization and comparison of project solutions, while also promoting pragmatic research through collaboration. Engaging stakeholders also helps manage expectations, resolve local conflicts, improve the reputation of science, and ensure that proposed solutions are actually implemented in the local environment.

In this chapter, we describe the concept of stakeholder involvement applied in the OPTAIN project. Additionally, two important outputs of the stakeholder engagement process are presented, namely the selection of the most relevant NSWORMs and indicators needed to assess their effectiveness.

4.1.2.1 Multi-actor platforms

Within the OPTAIN project, a concept of stakeholder involvement in the form of multi-actor platforms (MARGs) was applied (Sundnes et al., 2018). This approach clarifies the role of stakeholders in the project and enables monitoring of the reference group's evolution throughout the different project phases (Figure 17a). MARGs provide OPTAIN with valuable, real-world insights that enhance the project's practical relevance. Members or MARGs are familiar with agri-environmental measures, policy, and subsidy contexts, and can assist in evaluating the suitability of various NSWORMs.

The first step of the stakeholder identification was the stakeholder mapping activity (Van den Brink et al., 2021). Using a top-down approach, CS leaders were responsible for

identifying and categorising stakeholders according to pre-defined criteria. In all CSs, stakeholders at the national, regional, and local levels were involved in achieving impact at different levels. The number of identified stakeholders per CS varied between 10 and 50.

Within the OPTAIN project, the stakeholders were involved in: a) identification of all relevant problems in each CS, b) selection of possible measures for addressing the identified problems (Figure 19), and c) discussion of the modelling and optimization results. Stakeholder involvement is further explained in OPTAIN reports D1.1 (Van den Brink et al., 2021) and D1.2 (Van den Brink et al., 2022).

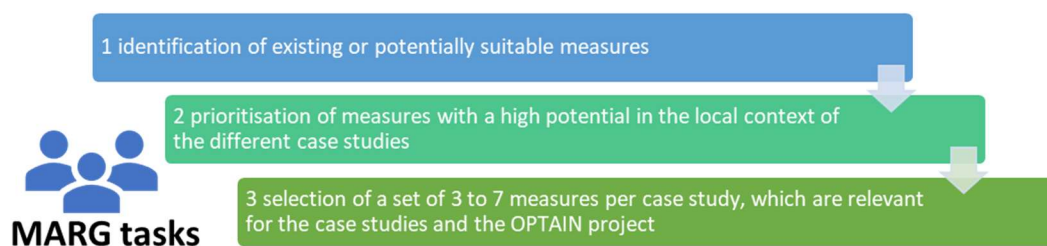


Figure 17: Involving stakeholders (MARG) in the selection of relevant NSWORMs

The involvement of local stakeholders throughout the NSWORM modelling process has proven essential for enhancing the relevance, accuracy, and legitimacy of the outcomes. Their contributions - ranging from identifying context-specific problems to selecting appropriate measures and engaging in model discussions - demonstrate the value of integrating local knowledge. While not always explicitly stated, stakeholder participation also plays a role in validating assumptions and ensuring that modelling efforts reflect real-world conditions. The structured engagement through MARG fosters a sense of shared ownership and supports the co-creation of solutions that are both scientifically sound and socially accepted.

4.1.2.2 Measure selection

Stakeholder participation is crucial for the effective implementation and management of relevant solutions, as well as for improving their public acceptance. However, the measure's implementation also requires a solid policy and management capacity based on the existing policy framework and incentives. To be successful, measures should have the potential to be cost and resource-efficient, and should generate more synergies than trade-offs, both at local and regional levels. This ability depends on the environment in which the solutions are applied, the ability to adapt to local conditions (not only in the short term, but also in the long term), and the potential for scaling up (Čerkasova & Idzelytė, 2021).

To address the issues listed above, a description of all relevant measures (existing, planned, or potential) was compiled for OPTAIN milestone MS4, resulting in 212 NSWORMs collected from all the CSs. These measures were then compared with the NSWORM.eu categories and WOCAT Sustainable Land Management Groups, considering also potential remaining questions of their relevance. After the first series of MARG workshops, some CSs further added locally relevant NSWORMs that were missing from their stakeholders' perspective. Finally, a list of 235 existing or potentially suitable NSWORMs was obtained (steps 1 and 3 in Figure 17).

The prioritisation and selection of measures, performed by MARG groups (steps 2 and 3 in Figure 17), resulted in 66 NSWORMs, divided into 29 OPTAIN-relevant NWRM categories (Figure 18). These measures were included in the OPTAIN catalogue of NSWORMs (D2.1; Lemann et al., 2022). They were also added to the WOCAT database in the form of factsheets (Figure 19), which allow for standardized documentation. Through the WOCAT database, all data can be accessed: a) through an automatically generated PDF with a unique URL for each measure, b) using the database visualization explorer (<https://explorer.wocat.net/>).

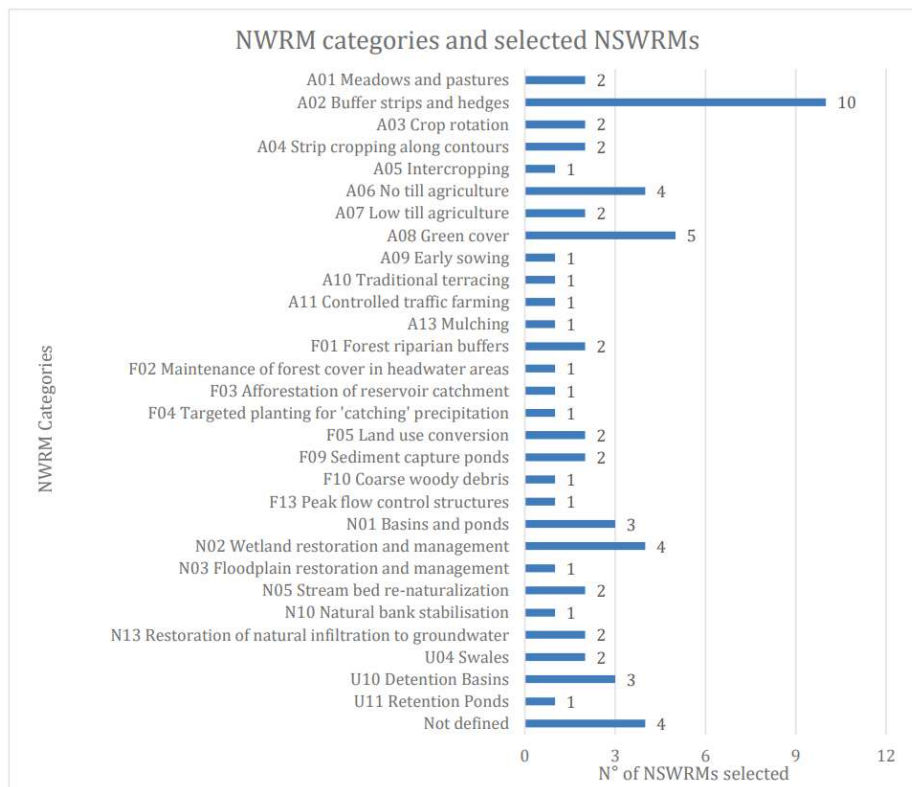


Figure 18: NWRM categories with the number of selected NSWORMs in OPTAIN

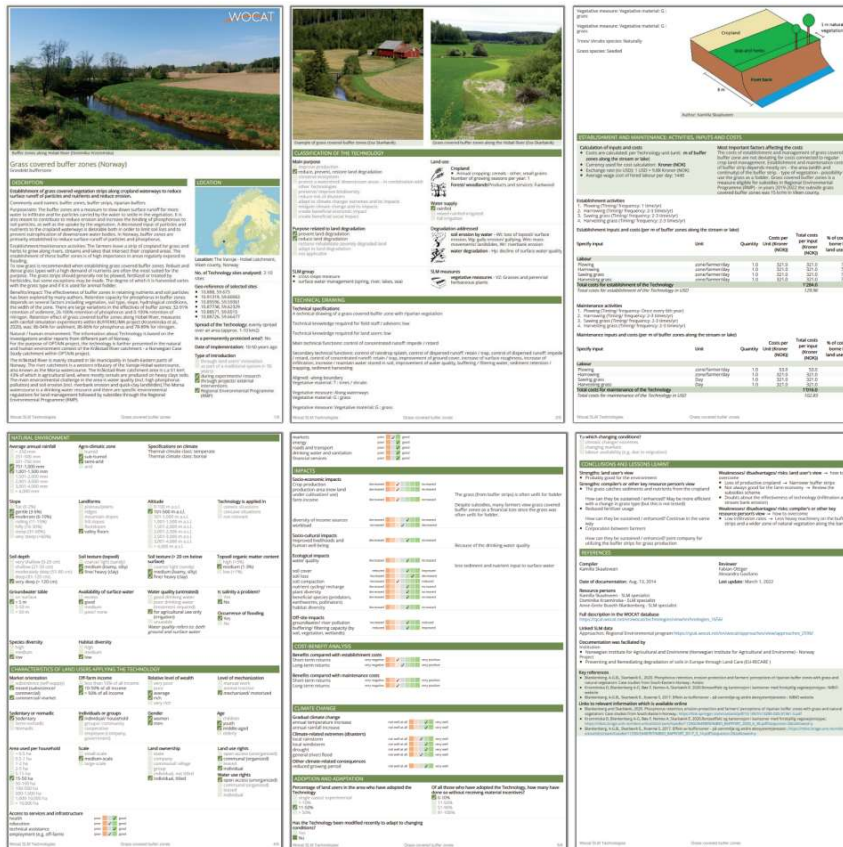


Figure 19: Example of NSWRM factsheet in the WOCAT Database

To summarize, the selection of identified measures was evolving within the process of stakeholder workshops. However, due to the foreseen data-demanding modelling tasks of the OPTAIN project, the final selection of modelled measures has changed as data was limited, or new data sources were identified, or new measurements were gathered.

4.1.2.3 Selection of indicators

To date, several existing approaches for assessing the effectiveness of NSWRM have been reviewed in the literature, resulting in a diverse panorama of conceptual and methodological frameworks (see e.g., Pugliese et al., 2022; Rödl & Arlati, 2022; Calliari et al., 2019). Given the multi-functional nature of NSWRM, their assessment must consider the co-benefits associated with them, as well as concrete actions to increase their effectiveness from technical, environmental, and socio-economic perspectives.

The development of appropriate performance indicators can help to measure the effects of NSWRM. Furthermore, they can facilitate comparability between different sites, climates, and allocation scenarios (Kabisch et al., 2017), necessary to investigate which local conditions result in the best performance, and to facilitate presentation and discussion on a quantitative and objective basis.

OPTAIN assesses the site-specific impacts of the selected NSWRM based on:

- the current state of the regional socio-ecological environment, as provided by MARG, operational experience, and historical knowledge,
- review of relevant literature and information systems (e.g., WOCAT, nwrn.eu), and

- integrated modelling and multi-criteria optimisation, considering local climate projections.

Consistency and comparability between the CSs were ensured through comprehensive harmonisation and the development of common protocols for all the project's key approaches.

To address local challenges and the multi-functional role of NSWORMs, it is essential to consider all aspects of water and nutrient management sustainability, especially in agriculture. To this end, two main categories of indicators that are closely related, but fulfil different functions, have to be considered:

Environmental Performance Indicators (EPIs): indicators focusing on the environmental impact of NSWORMs, such as changes in water quantity and quality (including nutrient flow), soil erosion, and crop yields at field- and catchment-level. The EPIs were developed to monitor progress towards achieving the relevant environmental and sustainability goals.

Socio-Economic Performance Indicators (SPIs): indicators addressing the economic and social dimensions of NSWORMs, based on the Triple Bottom Line framework. They include financial aspects such as the cost of implementing NSWORMs and their economic impact on farm-level outcomes (e.g., gross margin and agricultural value). Additionally, the SPIs consider broader societal benefits, including improved resource quality and greater resilience to climate and environmental risks.

Within OPTAIN, the most informative/important indicators were selected using a participative approach involving local MARGs (Figure 20). Most of the CSs listed between 1 and 4 indicators that are of high importance, both at the field and catchment levels. However, in CSs addressing more complex problems, more than 8 indicators were proposed. At the field-scale level, the most important indicator across all the OPTAIN CS is crop production (important for 13 out of 16 CSs). Additionally, indicators concerning water quantity (soil moisture, surface runoff, soil erosion, and timing and duration of drought) are of high relevance. At the catchment scale, the most informative indicators are river/stream water quality and the discharge at the catchment outlet (important for 12 out of 16 CSs).

Environmental indicators		Socio-economic indicators	
Farm level	Catchment scale	Farm level	Catchment scale
Crop production	Nutrient's concentrations and loads in the stream/river	Implementation costs	Implementation costs
Soil moisture	Discharge at the outlet	Maintenance costs	Maintenance costs
Soil erosion	Surface runoff (in connection to soil erosion)	Gross margin	Increased/decreased vulnerability to natural/extreme event hazards
Nutrient loss	Suspended sediment concentration and loads in the stream/river	Increased/decreased vulnerability to natural/extreme event hazards	Water quality improvement

Figure 20: Set of indicators identified as the most important/informative by the CSs

The selection process in D2.2 resulted in a list of 25 environmental and 17 socio-economic indicators that cover the most relevant issues of the OPTAIN CSs. The use of the indicators contributed to a harmonized approach by establishing a common language across project members and activities. It also aided the comparison of modelling results across CSs, the facilitation of dialogue with stakeholders, and the wider dissemination of project results (Krzeminska & Monaco, 2022).

Furthermore, the selection process evolved through the following deliverables: D4.3, D4.4, D5.2 and D5.3. The selection of indicators used was chosen by each partner based on the specific requirements of their pilot case (altogether 131 unique indicators).

The socio-economic performance indicators (SPIs) from WP2 were used in collaboration with stakeholders to interpret the modelling results and translate them into monetary terms for Task 4.5 using a data-driven approach. Deliverable D4.5 involved developing a conceptual economic model to evaluate the effects of NSWORMs on different farm types under various climate and implementation scenarios. The socio-economic assessment integrates quantitative and qualitative methods to analyse the results from Work Package 4, including modelling under various scenarios, surveys and local case studies. It also aims to assess the economic efficiency and societal impact of the measures after implementation.

This complements biophysical modelling by addressing aspects that are difficult to quantify using models alone. Contributions from task leaders and modellers were crucial, especially in refining the biophysical models and collecting data on performance indicators across the 14 case studies. The report outlines the conceptualisation of the socio-economic assessment, presents the modelling outcomes and provides a qualitative SWOT analysis and farm survey results. It also discusses the challenges encountered during the process (Monaco et al., 2024).

4.1.3 Modelling

Modelling of the NSWORM effectiveness (together with the optimisation) is a core part of the OPTAIN project. Considering the ToC concept, modelling is partially contributing to step 3, as it maps causal relationships between different "compartments" within the agricultural catchments (e.g., soil and water) in the form of processes. However, it mainly contributes to step 4, as it defines the external boundaries of the OPTAIN project, i.e., how the NSWORMs integrate into agricultural catchments and how they affect water and nutrient balance, while also considering expected future scenarios (e.g., future climate). In other words, modelling is used to assess the interaction between the NSWORMs and the outside world.

Within the OPTAIN project, the effects of the anticipated change were assessed by modelling the effectiveness of relevant NSWORMs both at the catchment- and field-scale using the SWAT+ and SWAP models, respectively (Figure 21), considering the costs of their implementation and maintenance, as well as the current situation and needs of different CSs. The main goal was to evaluate the environmental impact of: a) individual measures, and b) the combination of different NSWORMs.

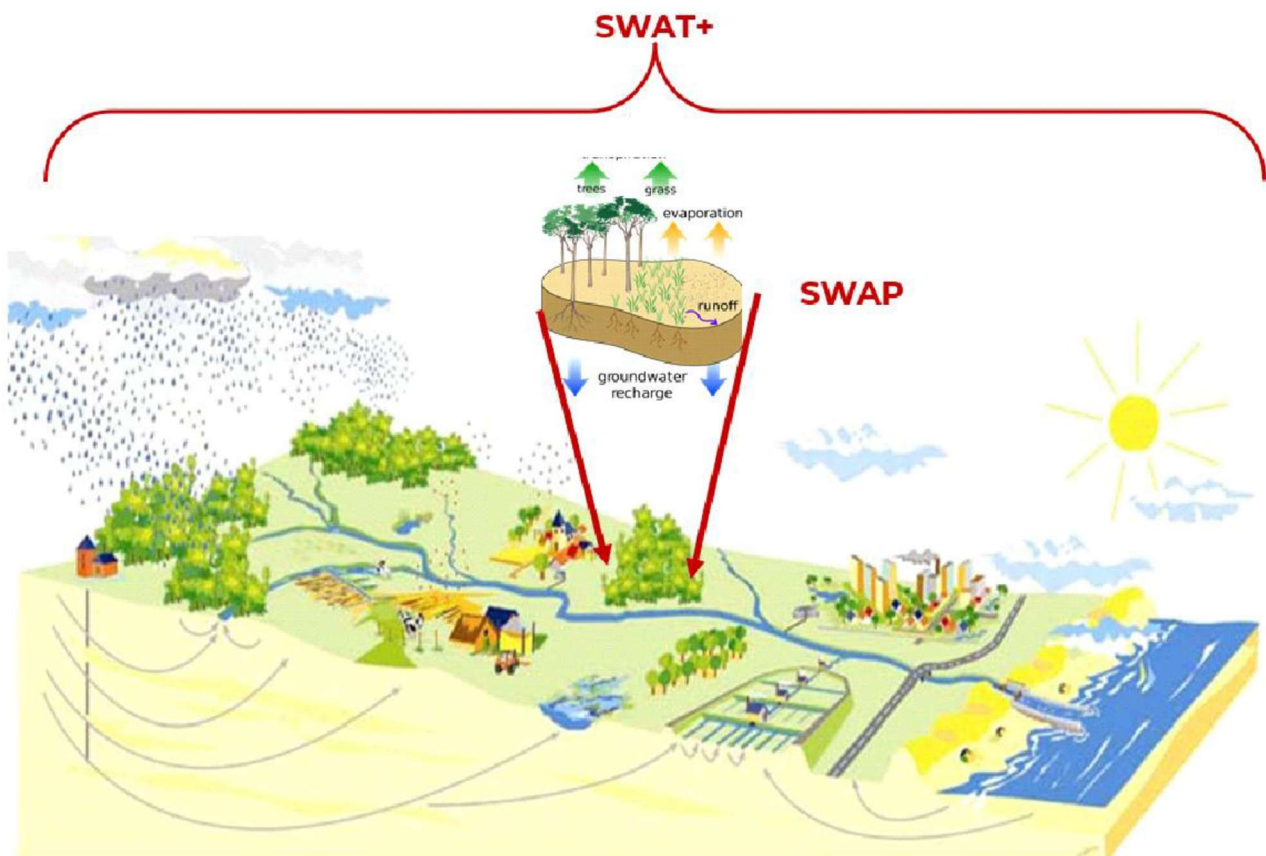


Figure 21: Spatial validity of the SWAP and SWAT+ models (Farkas et al., 2023).

SWAT is a conceptual, continuous-time watershed model used to simulate the quality and quantity of surface and ground water, and predict the environmental impact of land use, land management practices, and climate change (Arnold et al., 1998; Arnold and Fohrer, 2005). It is widely used in assessing soil erosion prevention and control, non-point source pollution control, and regional watershed management. The SWAT+, the most recent version of the SWAT model (Bieger et al., 2017), incorporates many improvements, e.g., increased flexibility of water routing across a landscape providing a better connectivity representation, inclusion of complex land- and reservoir management operations, and advanced soft calibration routine that helps the modellers to check the water and mass balance elements and prevents unrealistic parametrisation via auto-calibration.

The SWAP model (Marval et al., 2022) simulates the transport of water, solutes, and heat in the vadose zone, as well as the interaction with vegetation development. The SWAP modelling aimed to provide data on soil water balance elements using a more sophisticated, field-scale soil hydrological model, and to cross-validate the obtained results with those of the catchment-scale model for relevant fields, as represented by Hydrologic Response Units in SWAT+.

Within the project, protocols were developed for both the SWAT+ and the SWAP modelling (see OPTAIN deliverable D4.2; Schürz et al., 2022), describing the new tools for supporting catchment- and field-scale modellers, and providing detailed guidelines for all steps of the modelling procedure. D4.2 (Schürz et al., 2022) also incorporates the basic concept of the cross-validation of the two models. Modelling protocols ensured harmonized model setups across all CSs, as well as good quality and comparability of the results.

SWAT+ and SWAP were applied for scenario analyses to evaluate the effects of water retention measures on water regime and nutrient transport at present and future climate conditions. The SWAT+ projects incorporate various combinations of structural and management measures to support the OPTAIN optimisation purposes. In the SWAP model, management scenarios were tested in a more process-based way as compared to SWAT+. Further, the scenario results were cross-validated and analysed. SWAT+ model was applied to all OPTAIN CSs, while the SWAP model was only tested on 7 CSs (Figure 22).

No	Basin	Country	Field-scale	Catchment-scale
CS1	Schwarzer Schöps	Germany		+
CS2	Petite Glâne	Switzerland	+	+
CS3a	Csorsza	Hungary	+	+
CS3b	Felső-Válicka	Hungary		+
CS4	Upper Zglowiaczka	Poland	+	+
CS5	Pesnica	Austria/Slovenia		+
CS6	Kobiljski potok-Kebele	Slovenia/Hungary		+
CS7	La Wimbe	Belgium		+
CS8	Dotnuvėlė	Lithuania	+	+
CS9	Cherio	Italy		+
CS10	Hobøl	Norway	+	+
CS11	Tetves	Hungary	+	+
CS12	Čechtický	Czech Republic	+	+
CS13	Dviete	Latvia		+
CS14	Sävjaån	Sweden		+

Figure 22: The case studies for application of fields- and catchment-scale models

More information on the SWAT+ and SWAP modelling is available in the OPTAIN deliverables D4.2 (Schürz et al., 2022), D4.3 (Farkas et al., 2025) and D4.4 (Piniewski et al., 2024).

In this chapter, we will first discuss the data needed for the OPTAIN modelling tasks, tackling also the solutions for overcoming data scarcity and the process of obtaining data on climate scenarios.

Firstly, we will briefly present both modelling approaches (catchment and field-scale), focusing on novel solutions developed within the OPTAIN project, and the grouping of NSWORMs needed to aggregate the project results. This will be followed by the summary of the modelling results, provided in D4.4 (Piniewski et al., 2024), highlighting the outcomes of the modelling tasks from four different perspectives: considering EBRs, groups of measures, specific management objectives, and impacts of future climate conditions. At the end of the chapter, we will present additional results gained through the application of the database approach (see Chapter 3.2.2) to provide new insights into the effectiveness of NSWORMs.

4.1.3.1 Data for modelling

Data collection itself was performed under WP3 ("Data collection and harmonisation for model-based assessment"). More information on the modelling input data is available in the reports D3.1, D3.2 (Szabó et al., 2022), D3.3 (Čerkasova et al., 2022) and D4.4 (Piniewski et al., 2024).

SWAT/SWAT+ input data

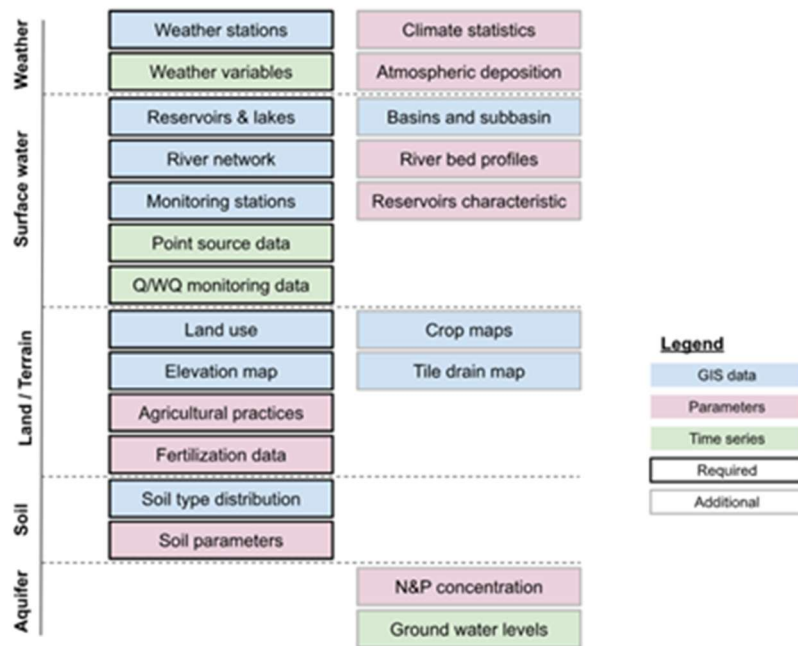


Figure 23: Input data requirements for SWAT+ modelling (Plunge et al., 2023)

SWAT+ and SWAP require different types of data as input (e.g., topography, weather observations, crop yields, soil types, land use, etc.) available in various formats (shapefiles, raster files, database files, tabular or textual data, etc.). The data requirements for modelling are presented in Figure 23 (SWAT+ modelling) and Figure 24 (SWAP modelling).

Input data preparation for both models and their parameterisation was carried out in the most harmonized way possible to enable cross-validation of the two models and a sound cross-CS assessment of the NSWRM effectiveness.

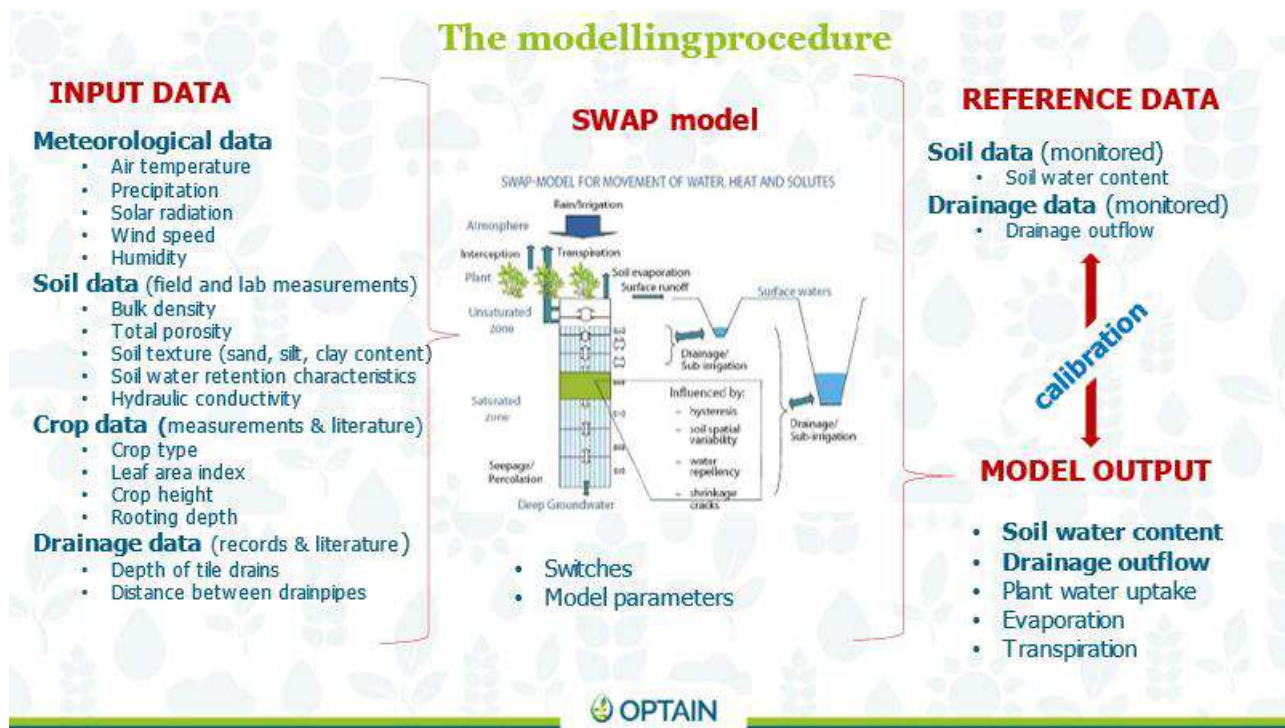


Figure 24: Overview of the modelling procedure when using the SWAP field-scale model and the data required for running and calibrating the waters model (Schürz et al., 2022)

Solutions to overcome data scarcity

In OPTAIN, the focus is on analysing the effectiveness of NSWORMs in retaining water, sediment, and nutrients. Therefore, it is important to have field-based input data on soil type and crops, both for catchment- and field-scale modelling tasks. At the catchment scale, the collection of these data can be hampered, due to missing relevant measurements or problems accessing the data for some parts or the entire target area. Preparation of input parameters for field-scale modelling is less demanding compared to catchment-scale modelling. Therefore, less data has to be obtained indirectly or from open-access datasets.

An important aim of the OPTAIN project is to derive missing information on necessary model input variables in a harmonized way for a cross-case assessment of the NSWORM effectiveness. To perform environmental and socio-economic analyses, methods for filling in the missing input data had to be developed, which was a specific objective of the deliverable D3.3 (Čerkasova et al., 2022). The deliverable D3.3 documents the development and implementation of data pre-processing tools within the OPTAIN project, aimed at harmonising and restructuring input data collected by case study leaders for modelling purposes. The tools address inconsistencies in data sources, formats, and availability, enabling standardised preparation of input data for both basin-scale (SWAT+) and field-scale (SWAP) models. Developed using open-source technologies (Python, R, JavaScript), the scripts support tasks in WP3 and WP4 by semi-automating repetitive procedures, enhancing efficiency, and managing data scarcity.

Most often, the soil hydraulic properties data are missing, which can be derived through the use of pedotransfer functions. Another example is socio-economic data, required to estimate the impact of NSWORM implementation on, for example, farm- and catchment-scale agricultural gross margins. For the evaluation of the economic sustainability of

NSWRMs, socio-economic data have to be collected for each CS separately. The obtained data are used for cost-benefit analysis, the assessment of long-term benefits for farmers, and for non-monetary values related to environmental concerns.

The OPTAIN project demonstrates that in data-scarce catchments, reliable assessment of NSWWRMs is indeed feasible through the strategic use of open data, empirical methods, and predictive models. By systematically addressing data gaps, e.g., on soil properties, crop maps, and socio-economic indicators, and by using tools like pedotransfer functions, satellite imagery (e.g., Sentinel-1), and national statistics, the project ensures that key environmental and management variables can be approximated with sufficient resolution. The development of harmonized workflows and guidelines further supports consistent and accurate modelling across diverse case studies, validating the hypothesis that robust NSWRM evaluation is achievable even under limited data conditions.

More information on missing data and solutions is available in deliverable D3.2 (Szabó et al., 2022) D3.3 (Čerkasova et al., 2022).

Climate scenario data

To assess the impact of future climate scenarios, a common climate database was used, consisting of bias-corrected Regional Climate Model (RCM) simulations from the EURO-CORDEX project, and the Representative Concentration Pathway (RCP) scenarios 2.6, 4.5, and 8.5. Bias correction was done using ERA5-Land reanalysis data with nonparametric empirical quantile mapping. Moreover, for field-scale modelling, universal kriging was used to interpolate gridded, bias-corrected climate model simulations to the locations of the modelling sites.

Bias-corrected EURO-CORDEX RCM simulations were prepared for all OPTAIN CSs, ready to be used in modelling tasks. Furthermore, the ERA5-Land reanalysis was prepared for all pilot field locations. These results were used for model calibration in case locally measured meteorological data were unavailable. Catchment- and field-scale models were run for each RCM model simulation and scenario, for the entire period, including the reference one. The changes in the future climate were calculated as a difference from the reference period, separately for each run.

The results of bias-corrected EURO-CORDEX RCM simulations for three time periods: first (2011-2040), second (2041-2070), and third (2071-2100), are briefly summarized below:

- **Temperature Changes:** Annual temperature changes for the first period range from 0.8°C (RCP2.6) to 1.2°C (RCP8.5), with slight variability between the locations. Temperature increases are generally higher in winter and autumn and lower in spring and summer. In the second period, changes range from 0.9°C to 2.8°C, and in the third period, they are even more extreme, from 1°C to 4.4°C. The reliability of temperature projections is high according to D3.1 (Honzak & Pogacar, 2022).
- **Minimum and Maximum Temperature Changes:** The projected changes for minimum and maximum temperatures are similar, with high reliability. Minimum temperature changes range from 0.8°C (RCP2.6, 1st period) to 4.6°C (RCP8.5, 3rd period), and maximum temperature changes range from 0.7°C to 4.4°C.
- **Precipitation Changes:** Precipitation projections are less reliable. They are projected to be higher in the Boreal region, with annual precipitation increases

ranging from 4% (RCP2.6) to 10% (RCP8.5) in the first period, and from 6% to 19% in the third period.

- **Solar Radiation:** Projections for solar radiation are mostly reliable for winter changes in RCP4.5 and RCP8.5, with decreases up to 12% in the third period (for RCP8.5).
- **Wind Speed and Relative Humidity:** Projections for wind speed and relative humidity are mostly unreliable and should be used with caution. Rare reliable changes in wind speed range from -6.1% to -1.1%, and changes in relative humidity range from -2.7% to 2.2%.

Additional information on the climate scenarios used as input to OPTAIN modelling is available in Deliverable D3.1 (Honzak and Pogacar, 2022).

4.1.3.2 *SWAT+ modelling*

The OPTAIN modelling approach presents the first fully scripted SWAT+ modelling workflow in R, covering all steps: input data preparation (SWATprepR), model setups (SWATbuildR), management practice scheduling (SWATfarmR), model setup verification (SWATdoctR), calibration (SWATrunR), climate change scenarios, and NSWRM scenario runs (SWATmeasR).

Deliverable D4.4 (Piniewski et al., 2024) presents the results of 8 successful applications of the modelling workflow, including evaluations of model performance and assessments of climate change impacts on water and nutrient balances. These CSs collectively offer valuable insights into the effectiveness of NSWRM in enhancing water retention and reducing nutrient runoff. It is important to note that the implementation and scale of these measures varied across sites, reflecting local conditions and priorities.

The integration of the SWAT+ model into the project introduced several unforeseen challenges. While the use of advanced modelling tools inherently carries some risk, the ambition of harmonizing modelling approaches across all 14 CS sites added further complexity. This ambition led to an underestimation of the support required by the CS modelers. Despite the dedicated efforts of experienced SWAT+ experts, several CS teams encountered difficulties in completing all modelling tasks on schedule. These challenges stemmed from a combination of factors, including differences in technical expertise, data availability, and unexpected external events. Given the central role of the SWAT+ model setups in supporting OPTAIN optimization work, all CS teams should finalize their modelling tasks to ensure the overall success of the project.

While some workflows were tailored to specific case studies, most functions and workflows were generalised and can be implemented in other SWAT+ model applications. One of the primary and innovative contributions of OPTAIN was the new Contiguous Object COnnectivity Approach (COCO), which can represent landscape features at the field scale and account for connectivity between land phase objects. This fundamental change in process-based hydrological modelling enables a more realistic representation of measures in the model setup and more realistic model outputs related to the simulated effectiveness of measures. The workflow allowed for the assessment of NSWRM effectiveness at both the catchment-scale (e.g. water and nutrient flows at the catchment outlet) and at the field scale, where the measures were applied or in its proximity (e.g., reduction of erosion entering the channel by a riparian buffer).

4.1.3.3 SWAP modelling

The purpose of SWAP modelling was to: a) cross-validate the outputs of the SWAT+ model, particularly regarding water balance components, b) identify the most effective approach for implementing management-related measures within both modelling frameworks, and c) evaluate the potential of introducing drought-tolerant crops in relevant CSs, as this option cannot be directly implemented in SWAT+. To achieve these goals, field-scale modelers had to follow standardized project protocols. They had to develop SWAP model setups that accurately represent all relevant crop rotations and associated management operations for the study fields. Additionally, these setups needed to be harmonized with the corresponding SWAT+ parameterization at the field scale, where applicable, and synchronized across all CSs involved in field-scale modelling to ensure methodological consistency and comparability.

Table 6 provides an overview of how various NSWORMs can be represented in the SWAP model in terms of their effects on water and solute transport. Some NSWORMs can be incorporated directly into the model by adjusting specific parameters that are explicitly designed to simulate the physical processes influenced by the measure. In contrast, other measures require an indirect approach, where expert judgment is necessary to identify and modify relevant parameters to reflect the expected impacts of the measure. This indirect method involves estimating how the measure would alter soil or crop characteristics and translating those changes into model inputs. However, it is important to note that structural measures, except for land use changes such as afforestation, cannot be represented in SWAP (being a field-scale soil hydrological model). This limitation stems from the model's focus on soil-plant-atmosphere interactions at the field level, which does not accommodate the spatial or infrastructural complexity of larger-scale structural interventions (Schürz et al., 2022).

Table 6: Possibilities of incorporating the OPTAIN measures in the SWAP model (Marval et al., 2022)

Group of measure in OPTAIN	Specific measure in OPTAIN	Incorporation in the SWAP model		
		direct	indirect	no
Structural measures				
Buffer strips/grassland cover	Riparian buffer			X
	Edge-of-field filter strips			X
	Hedges/Field division			X
	Arable land, Recharge zone			X
	Erosive slopes			X
Retention/detention ponds	Surface runoff, sediments			X
River restoration	Floodplain			X
	Channel			X
Afforestation	Afforestation	X		
Wetlands	Wetlands/Constructed wetlands			X
Management measures		direct	indirect	no
Tillage adjustment	No till agriculture (Direct seeding)/No tillage in autumn	X		
	Mulch seeding with permanent minimum tillage		X	
	Low till agriculture	X		
	Mulching		X	
	Subsoiling	X		
Terracing	Hillside terraces and hillside terraces with dry-stone walls			X
Cropping adjustment	Crop rotation	X		
	Intercropping		X	
	Green cover		X	
	Early sowing	X		
Others	Drought - resistant plants		X	

Cross-validation of the SWAP and SWAT+ models

The cross-validation between the SWAP and the SWAT+ model proved to be a complex task. It could only be performed for selected components of the water balance, namely evaporation, transpiration, drainage, and runoff. For the baseline scenario, the two models generally produced comparable results across most CSs. However, when various measures were implemented, the discrepancies between the simulated soil water balance elements became more pronounced. These growing differences were not solely attributed to model performance but were also influenced by the constraints imposed by each model's structure and parameterization, which affected how the measures could be implemented.

Despite these challenges, the integration of the SWAP model into the scenario analysis and cross-validation process has proven valuable. It contributed to a deeper understanding of the effects of NSWORMs at the field level. It also enabled a broader evaluation of the outputs from both the SWAP and SWAT+ models, enhancing the overall robustness of the project's findings and laying the foundation for integrated use of field- and catchment-scale models to enhance hydrological analysis and water management strategies (as reported in deliverable D4.3; Farkas et al., 2025).

To conclude, the key achievements of SWAP modelling included:

- Development of new tools and a unified approach for applying the SWAP model under varying data conditions.
- Successful calibration and validation across diverse pilot sites.
- Development of a novel methodology for harmonising and cross-validating field-scale (SWAP) and catchment-scale (SWAT+) hydrological models.
- Providing insights into the effectiveness of NSWORMs, showing that some impacts (e.g., of afforestation) are broadly consistent across regions, while others are highly site-specific.
- Recognition of discrepancies in model outputs under NSWORM scenarios due to differences in implementation methods.

4.1.3.4 Grouping of NSWORMs

Throughout the project, different groupings of NSWORMs were applied, based on a combination of functional, environmental, and socio-economic criteria, as detailed in several project deliverables:

- Deliverable D2.1 (Lemann et al., 2022) provided a coherent catalogue of the most promising NSWORMs, compiled and categorized according to their primary environmental functions, such as water retention, nutrient retention, and erosion control using the NWRM categories. This classification helps stakeholders and researchers to understand which measures are best suited for specific challenges in their agricultural catchments. The 67 measures were considered grouped into 31 NSWORM groups.
- Deliverable D2.3 (Marval et al., 2022) provided an alternative grouping of NSWORMs to support standardized parameterization of hydrological models. The measures were grouped based on their functional characteristics and modelling requirements. The report considers 23 measures were considered grouped into 10 NSWORM groups.
- Deliverable D4.1 (Čerkasova & Idzelytė, 2021) grouped NSWORMs according to the general NWRM catalogue to investigate biophysical effects of the measures, as well as their implementation possibility and related specific requirements. The report considers 41 measures that were not further divided in NSWORM groups.
- Deliverable D4.4 (Piniewski et al., 2024) did not explicitly introduce new NSWORM groupings. Instead, it built upon the functional and modelling-based classifications established in deliverables D2.1 and D2.3. In D4.4, the focus was on evaluating the effectiveness of individual and combined NSWORMs - such as no-till and low-till practices, buffer strips, grassed waterways, and ponds - within realistic catchment scenarios. The grouping of measures was thus implicit, based on how the measures are implemented. The deliverable uses two NSWORMs classification types: (i) firstly including 19 measures were considered grouped into 4 NSWORM groups (for modelling) and (ii) then further refining results into 16 measures grouped into 7 NSWORM groups (for cross-case study comparison).

For the project synthesis in D6.3, it was decided to aggregate the modelling results according to three broader categories:

- a) Land Management Measures (LMM),
- b) Structural Linear Measures (SLM), and

c) Structural Areal Measures (SAM).

The proposed classification (Figure 25) is based on the functional characteristics of the measures, their spatial implementation, and mode of intervention, rather than on individual performance comparisons.

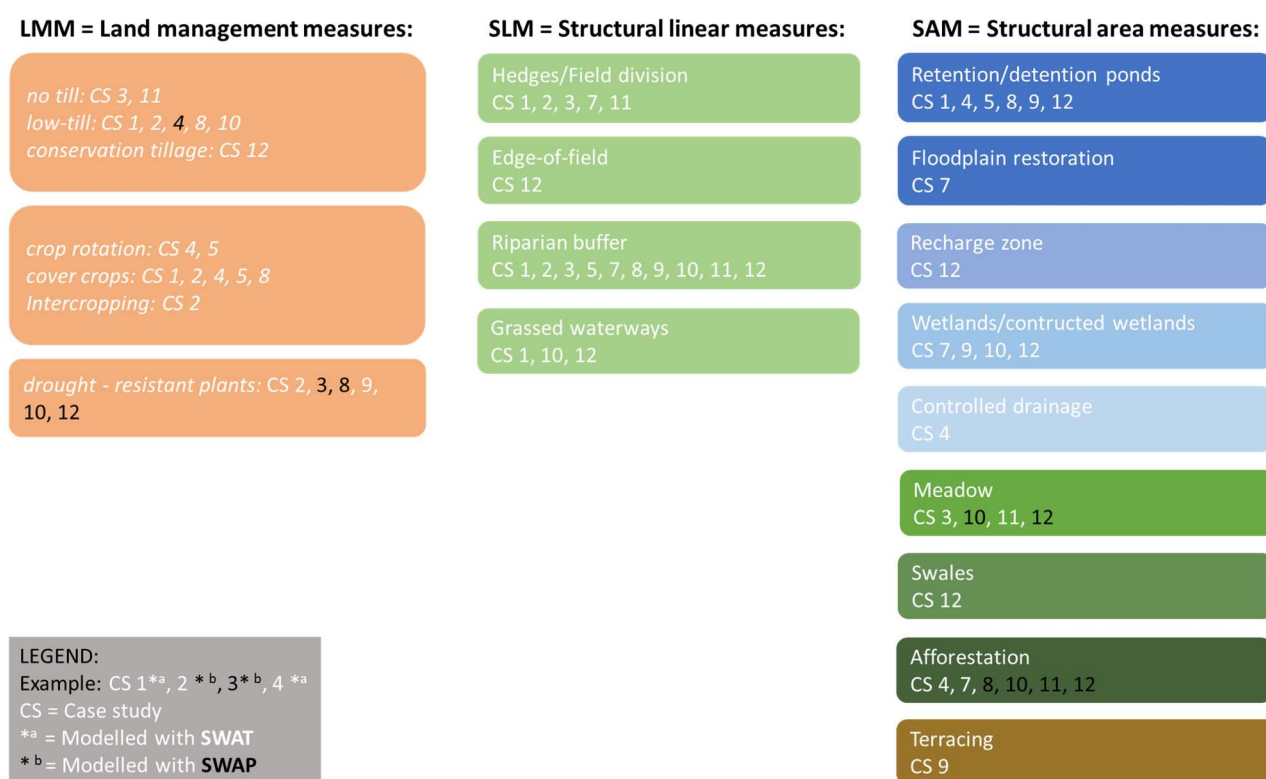


Figure 25: Grouping of NSWRMs, applied for project synthesis purposes

LMMs refer to practices involving the active management of cropland over time, thereby influencing the temporal variability of soil properties and processes (Hassink et al., 1997; Marval & Fucik, 2022). These measures are dynamic, requiring continuous management to sustain their benefits. Examples include reduced tillage, cover cropping, crop rotation, drought-resistant plants, and intercropping. Their impact is primarily seen at the field scale, where they enhance soil structure, increase organic matter, and improve infiltration rates.

SLMs are physical or biotechnical interventions designed to intercept and manage water flow along linear pathways, such as field edges, drainage channels, or riparian zones. These measures - including grassed waterways, vegetative buffers, and hedgerows - function by slowing runoff, trapping sediments, and filtering pollutants before they enter water bodies. Their effectiveness is highly dependent on correct placement within the landscape, particularly in areas where water flow concentrates.

SAMs are larger-scale interventions that modify land use to create distributed water retention. These measures often require engineering input and may involve land-use changes beyond agricultural fields, such as (constructed) wetlands, afforestation, terraces, controlled drainage, retention/detention ponds, and floodplain restoration. SAMs alter hydrological connectivity at a sub-catchment or catchment level, providing long-term benefits such as groundwater recharge and habitat restoration. However, their implementation can be complex, involving regulatory approvals, multi-stakeholder coordination, and trade-offs with agricultural productivity.

4.1.3.5 Modelling results synthesis using the database approach

The modelling process within the OPTAIN project has encountered several delays across the CSs due to a combination of technical and methodological factors and due to innovative and novel properties of the SWAT+ model. However, significant progress has been made, with open potential for future modelling processes development and for upgrading results. The status of the data available for the summary of modelling results is provided Table 7.

Table 7: Overview of the data collected for the summary of the modelling results

Case study	Catchment	Biogeographical region	Included in D4.4	Assessment of NSWRM effectiveness from SWAT+ model	Assessment of NSWRM effectiveness from SWAP model
CS1	Schwarzer Schöps, DE	Continental	Yes	Yes	No
CS2	Petite Glâne, CH	Continental	Partially	Yes	Yes
CS3	Felső-Válicka, HU	Pannonian	Yes	Yes	Yes
CS4	Upper Zgłowiączka, PL	Continental	Yes	Yes	Yes
CS5	Pesnica, SI	Continental	Yes	Yes	No
CS6	Kobilje/Kebele, SI	Pannonian / Continental	No	No	No
CS7	Wimbe catchment, BE	Continental	Yes	Yes	No
CS8	Dotnuvėlė, LT	Boreal	No	Yes	Yes
CS9	Cherio River, IT	Continental	Yes	Yes	No
CS10	Kråkstadelva, NO	Boreal	Yes	Yes	Yes
CS11	Tetves, HU	Pannonian	Yes	Yes	Yes
CS12	Čechticky Catchment, CZ	Continental	No	Yes	Yes
CS13	Dviete, LV	Boreal	No	No	No
CS14	Sävjaån headwaters, SE	Boreal	No	No	No

This part of the report focuses on 11 OPTAIN CSs, where SWAT+ modelling results were successfully obtained using a harmonized database approach. Additionally, the field-scale SWAP modelling results, obtained at seven OPTAIN CSs, were collected using the same approach, enabling consistent comparison, synthesis, and visualization of results across diverse hydrological and geographical contexts.

Catchment scale results are represented by five selected indicators (Nload and Pload, Sedload, Q_max_aa, and Q_min_aa), each showing the impact on different fields of interest, namely on nutrient, sediment, flood, and drought management, respectively.

Field-scale analysis of the results is represented by four SWAT+ indicators (N_loss, P_loss, Sed_loss, and sw_vp), and three SWAP indicators (runoff, soil_wat_storage, and drainage/percolation). N_loss and P_loss are important from the nutrient management perspective, Sed_loss for sediment management, sw_vp, soil_wat_storage, and drainage/percolation for water availability, and runoff for flood/drought management.

The figures in the following sub-chapters consist of graphs, marked with letters A-D, which are explained in Subchapter 3.2.2.

4.1.3.5.1 Synthesis of catchment scale results for European biogeographical regions

Nitrogen load in the river channel (Nload)

Results illustrate the percentage change, weighted percentage change, and per-hectare change in Nload across different EBRs and for various groups of measures, as described in Chapter 4.1.3.4.

Figure 26A shows how LMM, SAM, and SLM influence N load compared to the status quo. A combination of all groups of measures resulted in -10% N load reduction. The LMM demonstrated significant reductions in average annual N load (-6%), particularly in the Boreal region (-43%), with a broad range of values (from -43 to +9%). Reduced values are primarily associated with conservational soil tillage methods (e.g., low-till and no-till) and increased crop rotation management. SAM (-1%) and SLM (0%) exhibit mixed effects. The results for LMM in the Continental region (+1.5%) with conservation soil tillage methods (e.g., low-till and no-till) and the SLM in the Pannonian region (+2.2%) show a slight increase in N load, possibly related to unintended hydrological impacts of crop rotational and buffer strip measures, respectively.

Figure 26B presents weighted changes compared to the status quo, emphasising the regional differences in overall N load reduction. The combination of all measures resulted in a reduction of the average annual N load (-5%). Differences between regions were not observed as the modelled measures addressing local challenges were selected, and because all catchments exhibited agricultural characteristics. Here, LMM conservation soil tillage methods in the Boreal Region again emerge as the most effective strategy (-18.5%).

Figure 26D presents a change per hectare, providing a local perspective. A combination of all groups of measures resulted in a 4.5 kg/ha/year N load reduction. Results reveal that SAM (-49kg/ha) and SLM (-21kg/ha) achieve the highest average efficiency in reducing N load per unit area, particularly in erosion-prone catchments of the Continental region with -59kg/ha and -35kg/ha, respectively. SAM results indicate especially high variability in N loads when modelling ponds or constructed wetlands in the Continental region (range from -778kg/ha/year to +57kg/ha/year). This suggests a high variety of different local geophysical and climate conditions.

Across all figures, the calibrated models' results show high variability with an average decrease in Nload.

Phosphorus load in the river channel (Pload)

Modeling results for Pload are presented in Figure 27. Please note that for the Pannonian region, the SWAT+ models were not calibrated against the observed P loads and are given only as uncalibrated values (*).

Figure 27A shows how LMM, SAM, and SLM influence P load compared to the status quo. A combination of all groups of measures resulted in –10% P load reduction. The LMMs (low tillage and cover crops) generally lead to moderate but consistent reductions in P load (-5%), especially in Continental region (-6%), reflecting their widespread applicability in improving soil and nutrient management practices. In contrast, SLM (-2%) and SAM (-1%) exhibit more variable outcomes (meadow, wetland), with some CSs displaying notable decreases due to their targeted nature of measured (pond, buffer strips), while others show neutral (hedge) or even slightly increased loads (meadows), likely due to unintended hydrological or sediment-related effects. The divergence between the results of calibrated models and all modelling results underscores the importance of model calibration, particularly for the effectiveness assessment of structural measures. In other words, without proper model calibration, the results exhibit greater variation and are thus more uncertain.

Figure 27B highlights how the spatial distribution of measures influences overall catchment-scale results. A combination of all groups of measures resulted in –3% weighted P load reduction. The LMM results have a higher impact due to their extensive implementation across large agricultural areas (cover crops, no-till, low-till), whereas SAM (pond, terrace, wetland) and SLM (buffer strips, hedge) may show stronger localised impacts that, when weighted by catchment-wide or regional contributions, appear less pronounced. Figure 29B emphasises that while structural measures can be highly effective in specific contexts, their catchment-wide benefits depend on regional characteristics such as land use and hydrological connectivity.

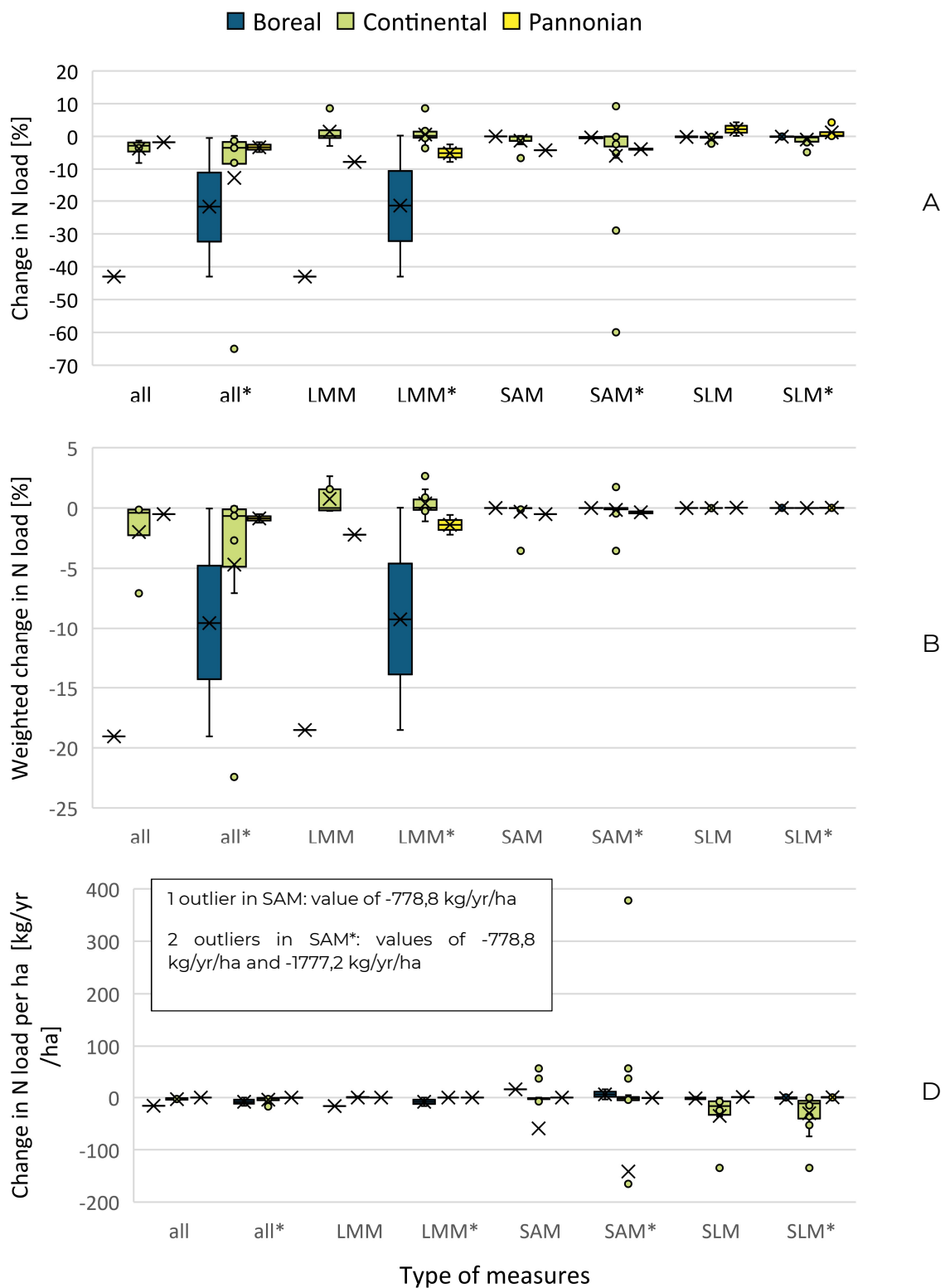


Figure 26: Change in N load in river channel (Nload) compared to status quo [%] (A), percentage change [%] of N load weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of N load per ha [kg/yr/ha] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

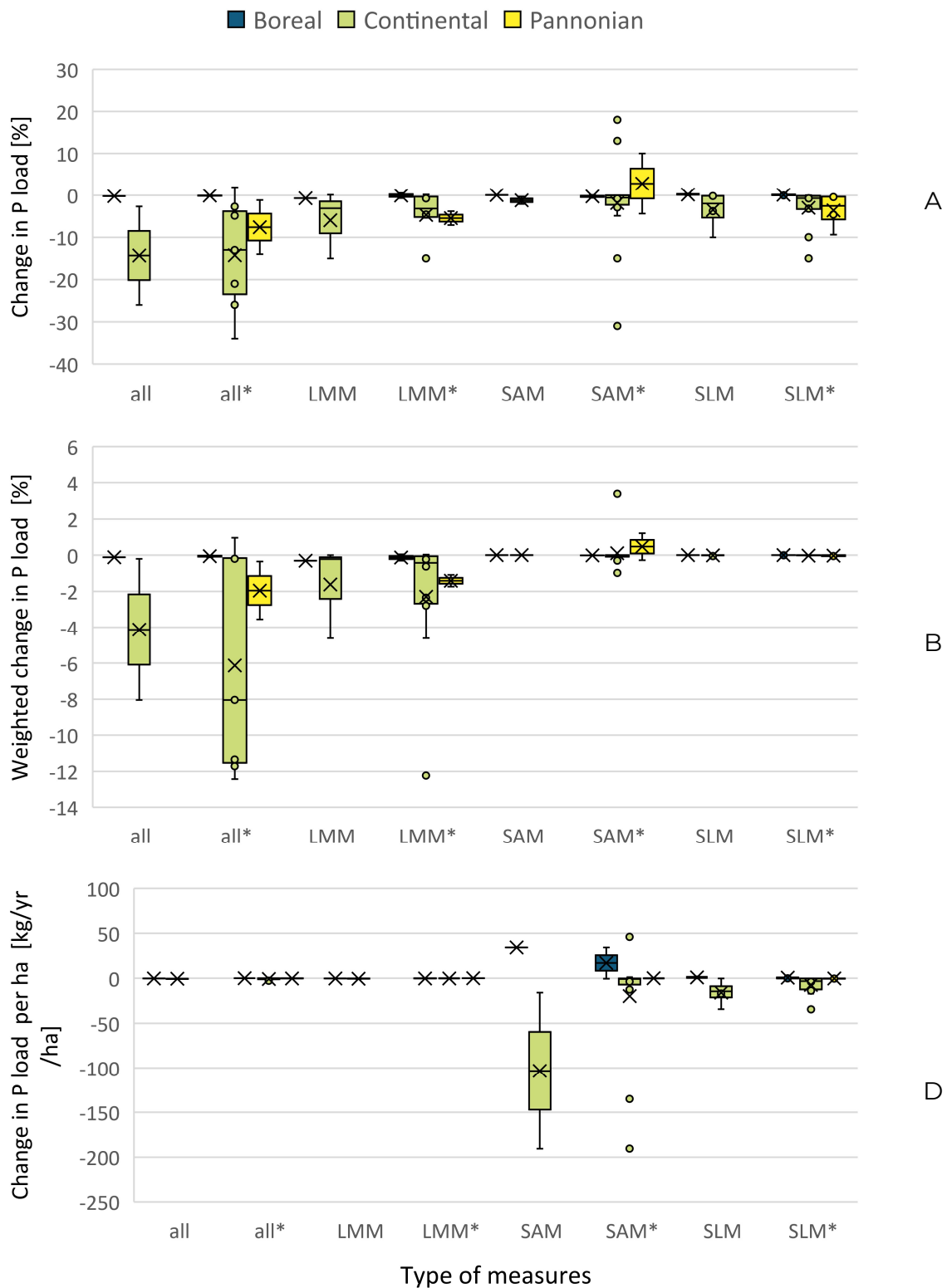


Figure 27: Change in P load in river channel (Pload) compared to status quo [%] (A), percentage change [%] of P load weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of P load per ha [kg/yr/ha] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

Figure 27D provides insights into the efficiency of each measure group at a finer spatial scale. A combination of all groups of measures resulted in 0.4 kg/ha/year P load reduction. Here, structural measures (wetlands, ponds) frequently stand out for their ability to deliver significant per-hectare reductions, especially in the Continental region. The effectiveness of SAM (-103 to +34kg/ha/year) is more variable compared to SLM (-16 to +1 kg/ha/year). Considering SAM and SLM, the highest average annual reduction of 103 kg/ha and 16 kg/ha, respectively, was observed in Continental region due to ponds and wetlands (SAM) and buffer strips and grassed slopes (SLM). The LMM with less than 1 kg/ha/year change are less impactful on a per-hectare basis.

Together, all three graphs illustrate the complementary roles of LMM, SLM, and SAM in P management, with LMM offering broad but incremental benefits to water quality in river channels and structural measures providing targeted, high-efficiency solutions at specific sites where implemented.

Sediment load (Sedload)

The sediment loads in river channels (Sedload) are presented in Figure 28. Note that for the Pannonian region, the SWAT+ models were not calibrated against sediment load measurements.

Figure 28A reflects the broad applicability of NSWRM for minimizing soil disturbance and enhancing erosion control. A combination of all groups of measures resulted in -12% Sed load reduction. The LMM (-8%), SLM (-4%) and SAM (-0.6%), however, exhibit variable impacts, with certain regions (Continental) showing substantial reductions (-9%) due to their targeted interception of sediment transport pathways (e.g., ponds up to -3%, buffer strips up to -8% and grassed slopes up to -25%).

Figure 28B presents that widespread adoption of LMM in catchments often translates into significant cumulative sediment reductions (-2%). In contrast, the localized nature of SLM and SAM means their weighted contributions to river water quality may appear negligible (cca. 0%), despite their high efficiency in critical areas. These results underscore that while structural measures excel in specific hotspots, their broader impact depends on regional erosion susceptibility and hydrological connectivity.

Figure 28D reveals SLM as the standout for per-hectare sediment reduction. A combination of all groups of average annual measures resulted in -0.12 tons/ha/year Sed load reduction. Especially, effective are SAM and SLM with 25 and 5 tons/ha/year Sed load reduction, most of which is related to high efficiency in the Continental region. Though their performance may fluctuate based on the design and placement LMMs are less impactful per unit area (-0.08 tons/ha/year).

Results illustrate how LMM provide foundational sediment control, while SLM and SAM offer precision solutions for high-risk areas. The variability across regions and measure groups underscores the importance of integrated strategies that combine the broad reach of LMM along with the focused intervention of structural SLM and SAM to optimise sediment management and river water quality improvements at the CS level, reaching up to 38%.

Maximal river flow (Q_{max_aa}) for flood management

Figure 29 shows how different groups of measures alter the average annual maximum river flow across EBRs. Please note that for the Continental and Pannonian regions, all SWAT+ models are calibrated.

Figure 29A presents average reductions in Q_{max_aa} . A combination of all groups of measures resulted in -11% reduction. Reductions are most prominent in the Pannonian region (-18%), followed by the Continental (-9%) and Boreal (-6%) region. The LMM reflects their capacity to enhance soil water storage and moderate flow variability over time. LMM, SLM and SAM, show regionally variable effects. The Pannonian region is experiencing the most pronounced decreases (-3 to -8%) in Q_{max_aa} followed by Continental (-0.7 to -2%) 2nd Boreal (-0 to -4%).

Figure 29B presents the catchment-scale influence of measures. The spatially widespread adoption of LMM (e.g. low till) on agricultural land contributes to a reduction of average maximum flows across all regions (-1%), especially the Boreal and Pannonian. SLM and SAM, while highly effective in specific settings, may exhibit smaller weighted impacts due to their limited spatial extent. However, they remain critical in areas prone to flow extremes (Pannonian region).

Figure 29D reveals that all groups of measures have minimal impact on Q_{max_aa} (from the per ha perspective). However, the most variable results were obtained for the SAM in the Continental region, probably due to the larger number of CS representatives; however, the differences are less than 0.1 %.

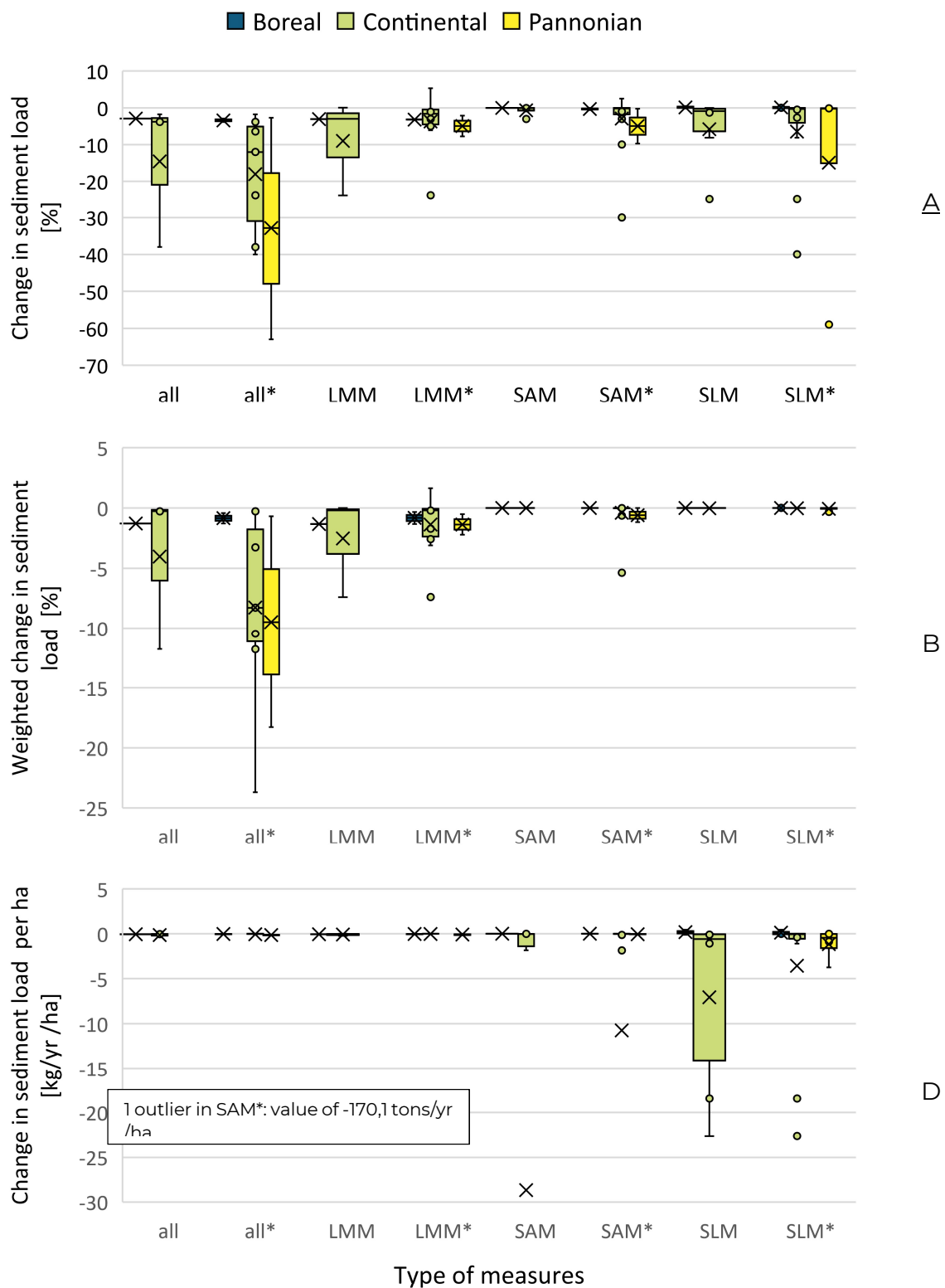


Figure 28: Sediment load in the river channel (Sedload) change compared to status quo [%] (A), percentage change [%] of Sedload weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of Sedload per ha [kg/yr/ha] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

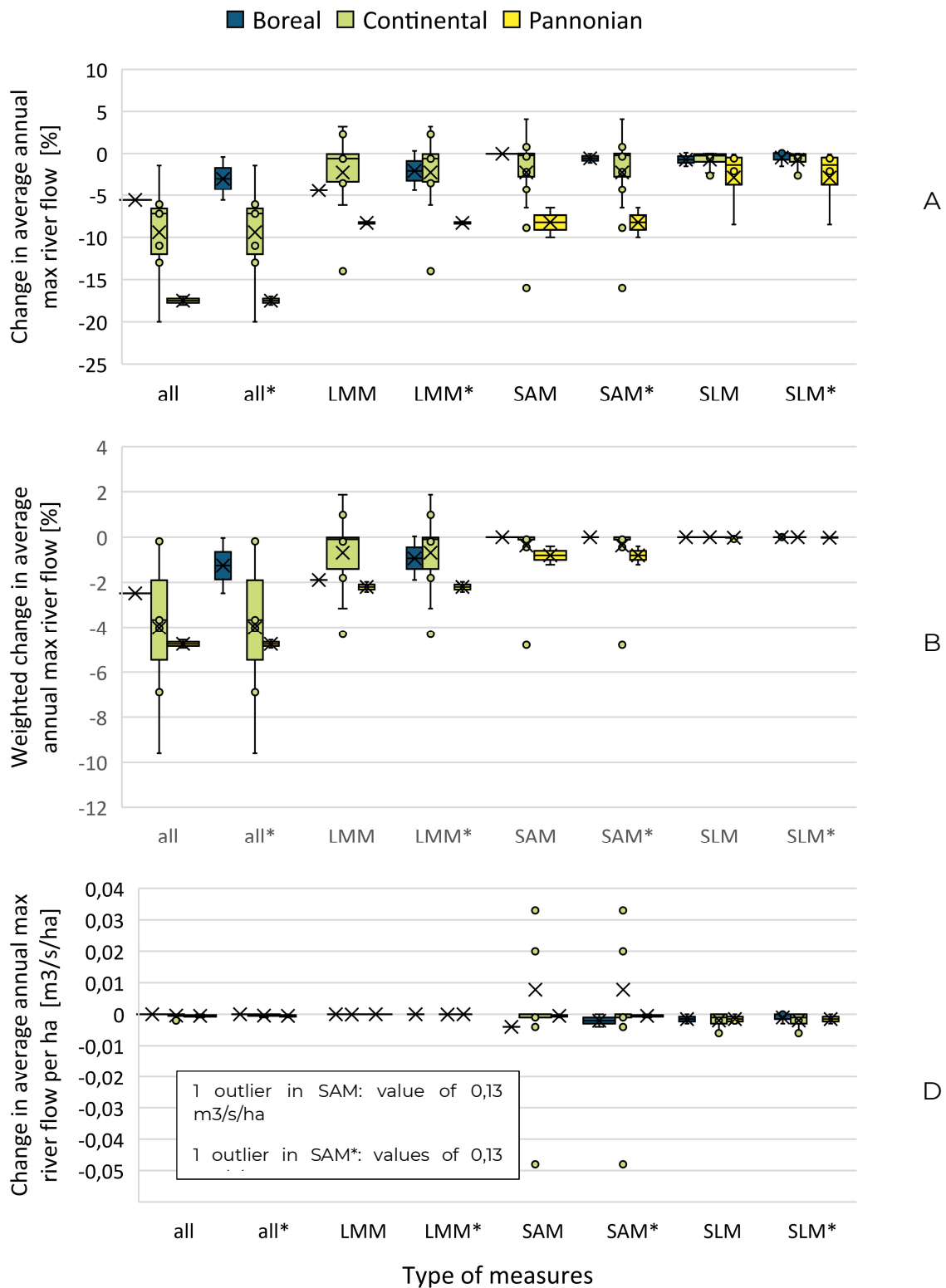


Figure 29: Average annual maximal river flow (Q_{max_aa}) change compared to status quo [%] (A), percentage change [%] of Q_{max_aa} weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of Q_{max_aa} per ha [$m^3/s/ha$] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

Minimal river flow (Q_min_aa) for drought management

Figure 30 shows how different groups of measures alter the average annual minimum river flow across EBRs. Please note that for the Continental and Pannonian regions, all SWAT+ models were calibrated.

Figure 30A shows that a combination of all groups of measures resulted in –3% reduction of Q_min_aa. Reductions are most prominent in the Continental region (-4%), followed by the Pannonian (-2%) and Boreal (-0%) region. LMM measures (e.g. no-till, cover crops) generally lead to modest increases in Q_min_aa (2%)², where the EBR range is –4% (Boreal) to +8% (Pannonian), reflecting LMMs ability to improve soil moisture retention and sustain baseflow during dry periods through gradual, landscape-scale interventions. SAM measures exhibit the most variable impacts (1%), with the EBR ranging from 0 (Boreal) to –6% (Pannonian), indicating that wetlands and ponds retain water, potentially resulting in lower minimum flows in reach. SLM is the least effective across all the EBRs.

Figure 30B emphasizes the catchment-scale implications of the measures. The LMM measures contribute to consistent (but moderate) average increases (1%) in low-flow conditions, especially in the Pannonian region (2%). Structural measures (SAM, SLM) show negligible effects on Q_min_aa across all the EBRs.

Figure 30D reveals that none of the groups of measures had significantly altered Q_min_aa (from the per ha perspective) in the EBRs.

Results demonstrate that LMM measures have a small but reliable potential to serve as a foundational approach for sustaining minimum flows across diverse landscapes, for providing sufficient water resources, and supporting aquatic ecosystems during critical low-flow periods. While SAM and SLM measures are less efficient.

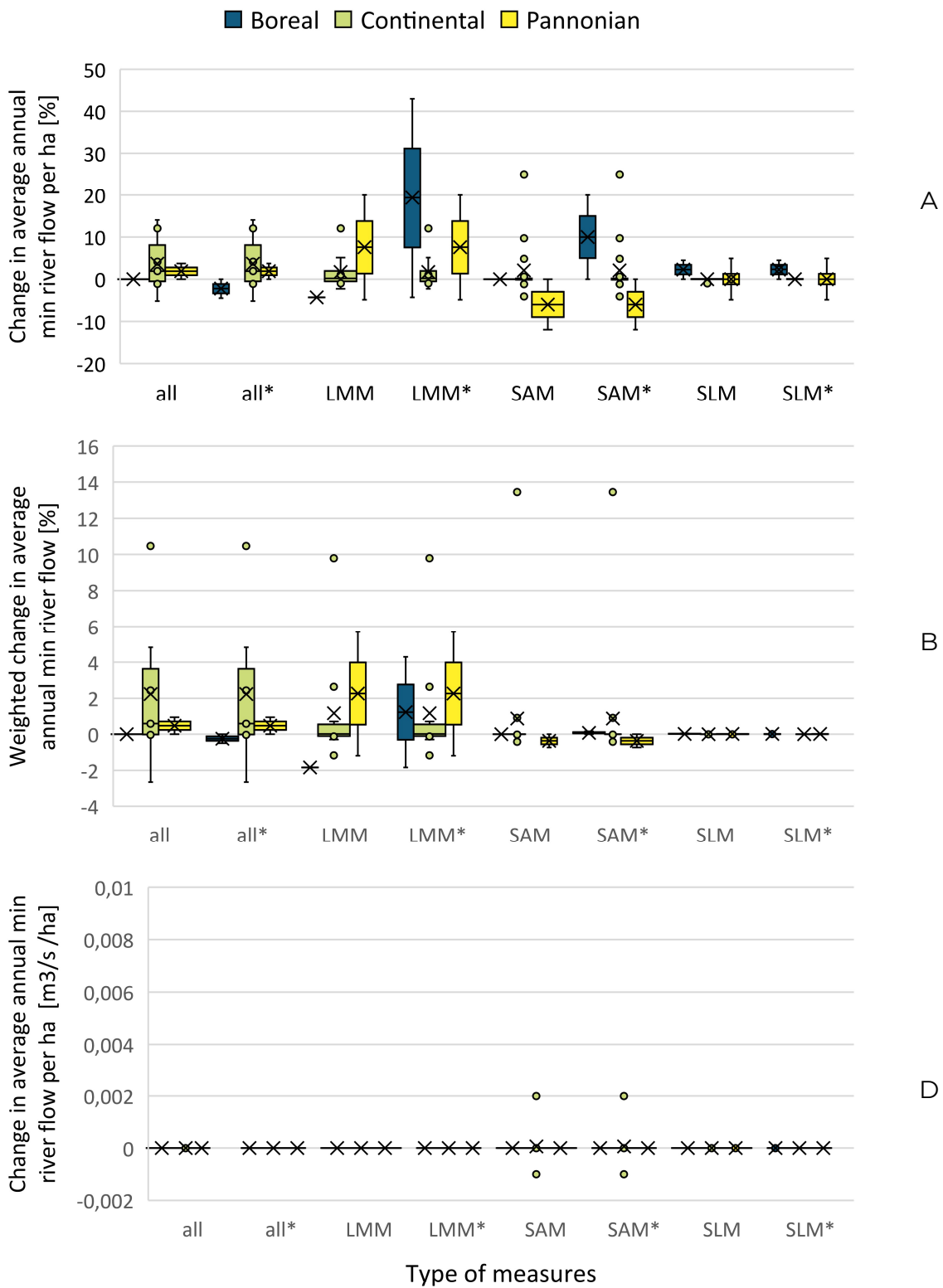


Figure 30: Average annual minimal river flow (Q_{\min_aa}) change compared to status quo [%] (A), percentage change [%] of Q_{\min_aa} weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of Q_{\min_aa} per ha [$m^3/s/ha$] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

4.1.3.5.2 Synthesis of field scale results for European biogeographical regions

Nitrogen loss (N_loss)

Results on Figure 31 present how different measures influence N loss from the surfaces (cropland, grassland) on which they were modelled across different EBRs.

Figure 31A reveals that a combination of all groups of measures resulted in 13% reduction of N loss. Reductions are most prominent in the Boreal region (-43%), followed by the Pannonian (-21%) and Continental (-4%) regions. The LMM achieved high average reductions in nitrogen loss among EBRs of 8%, especially in Boreal (-42%) and Pannonian (-14%) regions, which are the impact of no-till (-14%), low-till (-42%) and cover crops (0 to -13%). The SAM and SLM demonstrate more variable outcomes, where the Pannonian region shows a decrease in SAM (-27%) related to the implementation of meadows. Still, for SLM, it even exhibits slight increases (+5%) in N loss, where hedge and riparian buffer strips were implemented. While the Boreal region does not show any concrete changes, in the Continental region, the results of the measures were mixed on average, with less than 1% decrease, where measures resulted in the highest 15% decrease and 10% increase for grassland in recharge areas and controlled traffic farming, respectively.

Figure 31C highlights the weighted catchment-scale contribution of the measures to N loss. The LMMs show considerable reductions in N loss (-8%), which highlights the large spatial scope and importance of this group of measures in CS, especially in the Boreal (-44%) and Pannonian (-21%) regions. SAMs and SLMs have almost no effect on N loss across all the EBRs in comparison to the total CS area. Except the Pannonian region with a 12% reduction in N loss.

Figure 31D presents a change per hectare, providing a local perspective. A combination of all groups of measures resulted in an 8 kg/ha/year N loss reduction. Results reveal that among EBRs, the highest reduction for LMMs (-4 kg/ha/year) was achieved in the Boreal region (-24 kg/ha/year). The SAM (-1 kg/ha) and SLM (-0.3k g/ha) achieve low average efficiency in reducing N loss per unit area in all EBRs. SAM results indicate higher efficiency in N loss reduction (-2 kg/ha/year).

Phosphorus loss (P_loss)

Figure 32A shows that a combination of all groups of measures resulted in 33% reduction of P loss. Reductions are most prominent in the Boreal region (-65%) and Continental (-16%) regions. In contrast, structural measures in all EBRs resulted as less effective from the P-loss perspective with SAM of 0% and SLM of -2%. In the Pannonian region, SAM can also contribute to increased P losses (meadows +39%).

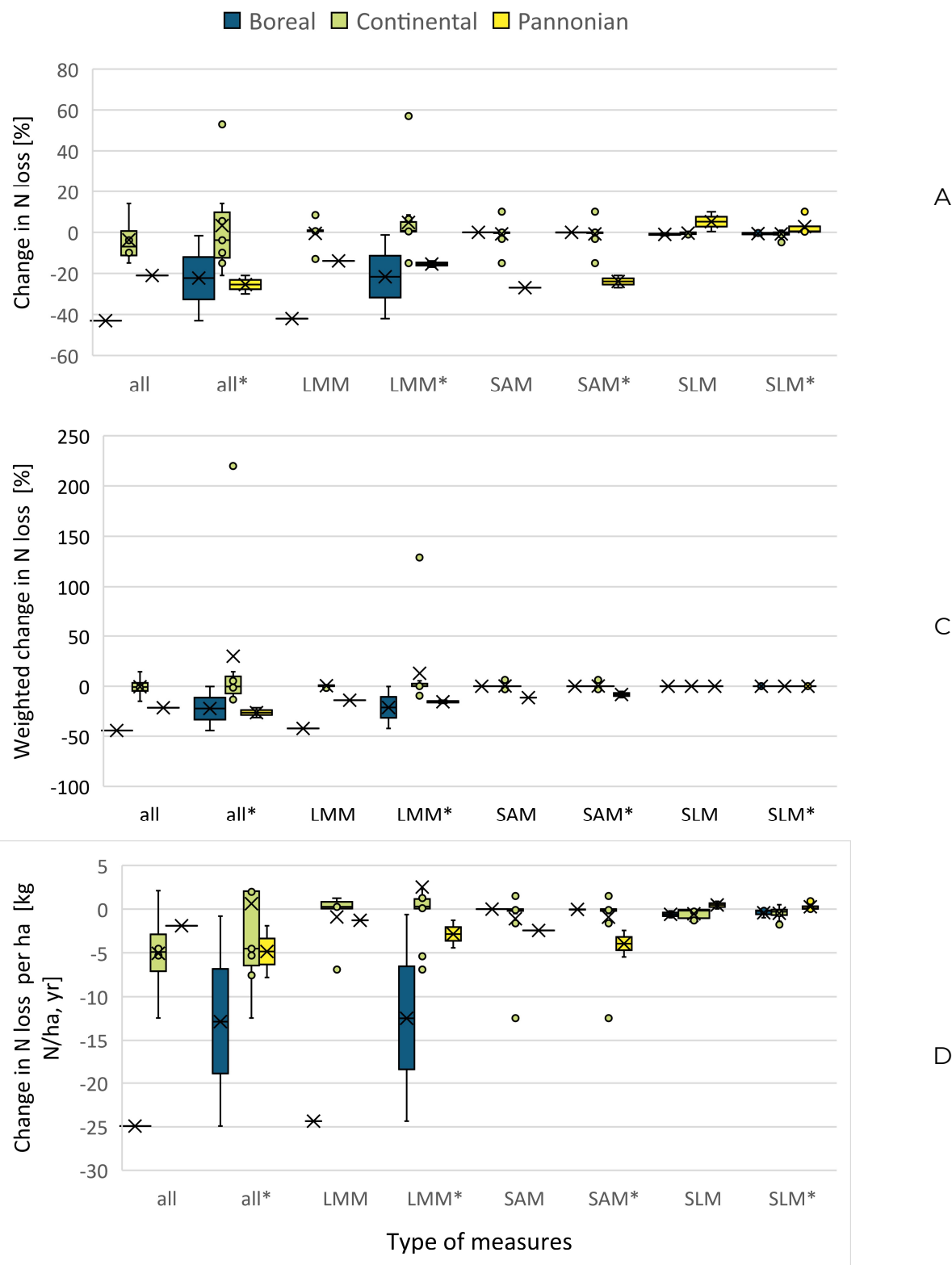


Figure 31: Nitrogen loss (N_loss) change compared to status quo [%] (A), percentage change [%] of N loss weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of N loss per ha [kg/ha/year] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

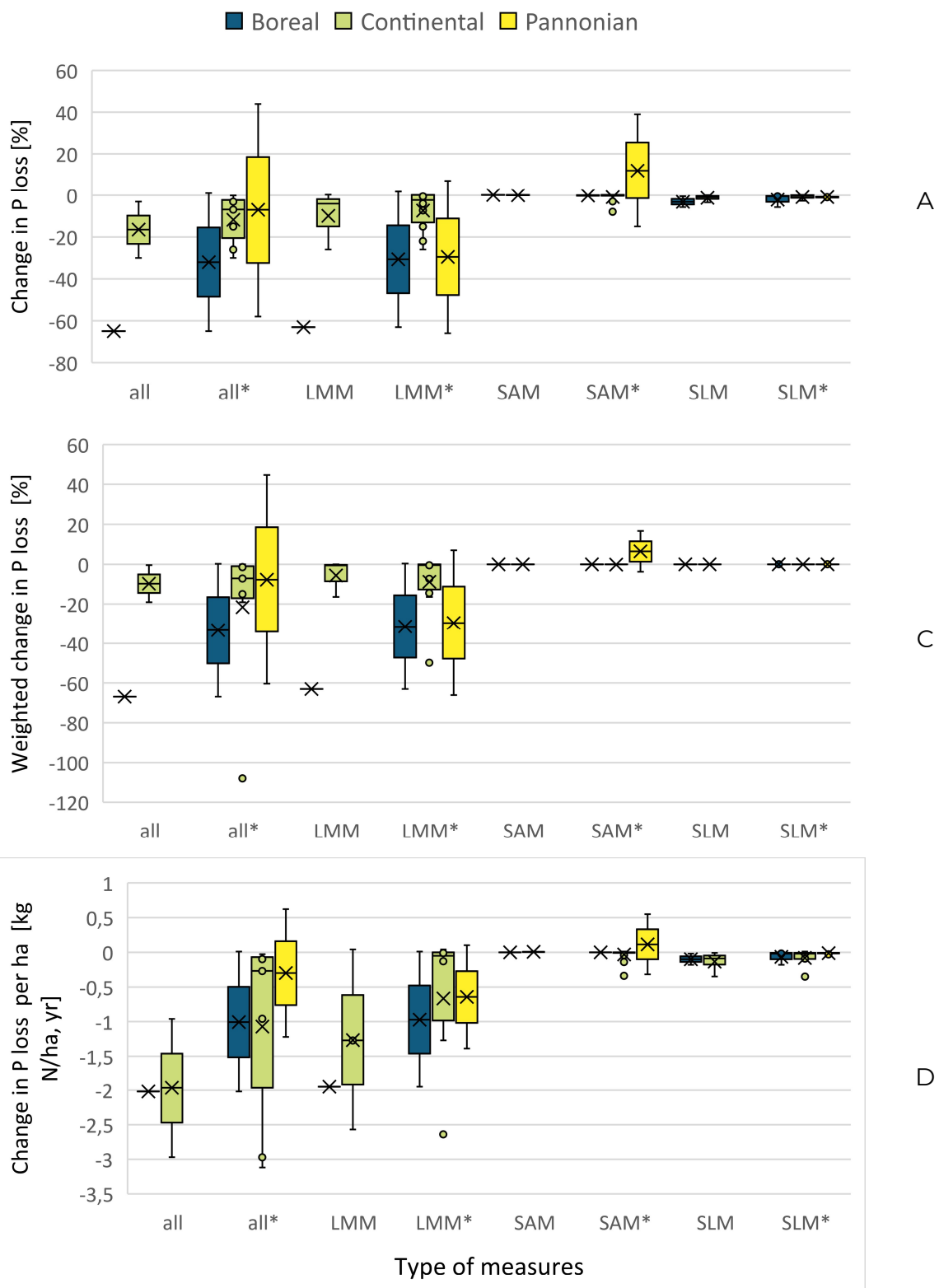


Figure 32: Phosphorus loss (P_loss) change compared to status quo [%] (A), percentage change [%] of P loss weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of P loss per ha [kg/ha/year] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

Figure 32C shows similar results, with less variability compared to Figure 34A, which means that LLMs represent a significant spatial proportion of EBRs and thus their contribution to lower P losses (-1.3%) is related to the spatial distribution of measures such as low-till and cover crops.

Figure 32D presents a change per hectare, providing a local perspective. A combination of all groups of measures resulted in a 2 kg/ha/year P loss reduction. Results reveal that among EBRs, the highest reduction for LMMs (-1.4 kg/ha/year) was achieved in the Boreal region (-2 kg/ha/year). The SAM (-0 kg/ha) and SLM (-0.12 kg/ha) achieve low average efficiency in reducing N loss per unit area in all EBRs.

Sediment loss (Sed_loss)

Figure 33A shows that a combination of all groups of measures resulted in a moderate 42% reduction of Sed loss. Reductions are most prominent in the Boreal region (-68%) and Continental (-29%) regions. The LMMs typically deliver moderate reductions in sediment loss (30%), reflecting their broad effectiveness in minimising soil erosion through improved land management practices. The highest modelled reductions are observed in Boreal (low-till up to -54%), Continental (cover crops up to -84%) and Pannonian (no-till up to 84%) regions. SLM (-2%) and SAM (-11%) also exhibit reductions in Sed_loss, but less profoundly. For the Boreal (-19%) and Continental (-6%) regions, is SLM more effective than SAM, and vice versa for the Pannonian region.

Figure 33C highlights the catchment-scale contributions of the analyzed groups of measures. The LMMs of all EBRs show considerable reductions in Sed_loss (-20%) from fields (low-till -54%, cover crops - 5%). On the other hand, structural measures exhibit almost no change in terms of sediment loss reduction. This is related to the fact that these measures occupy smaller areas and are not placed directly on agricultural land, where they would prevent negative processes, but in their surroundings (below, above or near the surface of the sediment source). Thus, SAM and SLM measures only have an impact on the transport of sediment coming from agricultural land. They retain it and prevent transport into surface watercourses. These effects are explained in detail in the description of sediment load.

Figure 33D presents a change per hectare, providing a local perspective. A combination of all groups of measures resulted in a 1.3 tons/ha/year Sed loss reduction. Results reveal that among EBRs, the highest reduction for LMMs (-0.6 tons/ha/year) was achieved in the Boreal region (-0.9 kg/ha/year). The SAM (-0.15 tons/ha) and SLM (-0.4 tons/ha) achieve low average efficiency in reducing Sed loss per unit area in all EBRs.

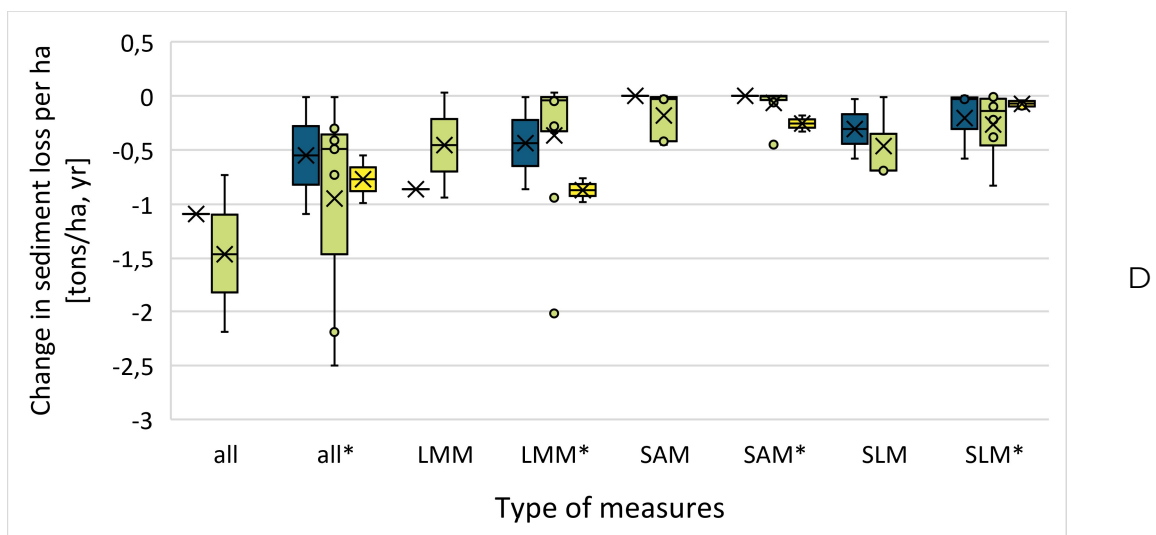
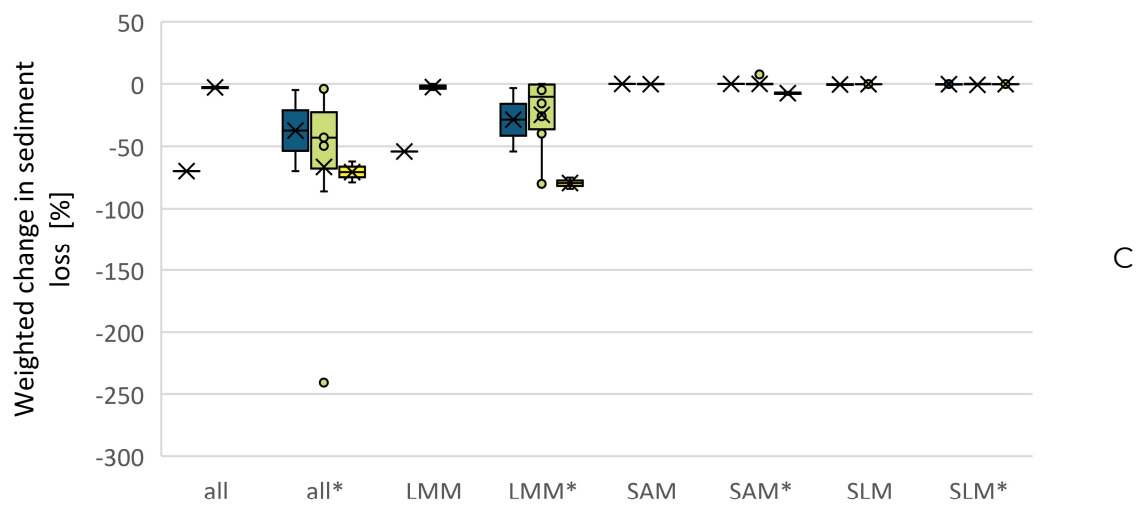
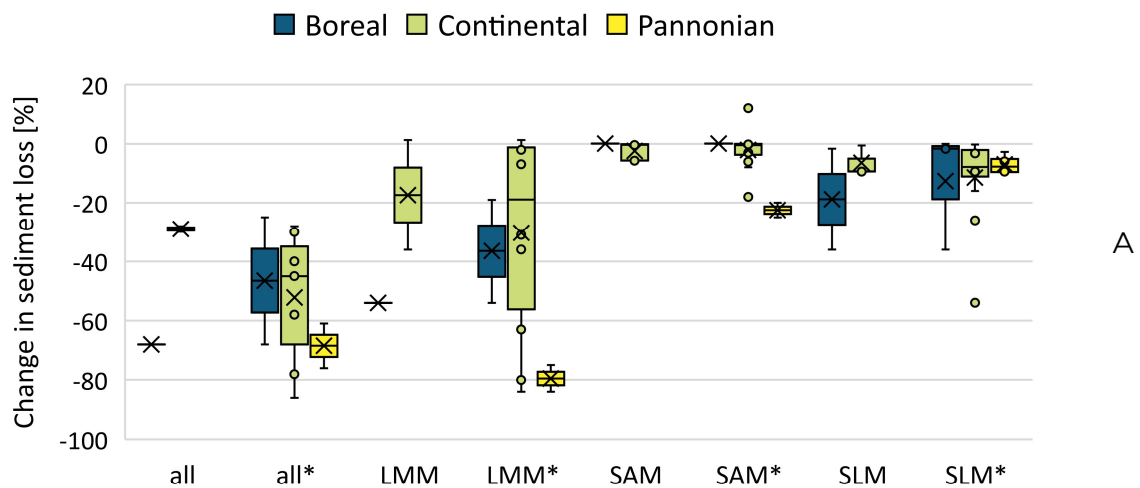


Figure 33: Sediment loss (Sed_loss) change compared to status quo [%] (A), percentage change [%] of Sed loss weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of Sed loss per ha [tons/ha/year] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

Soil water content during the vegetation period (sw_vp)

Figure 34 presents how different groups of measures influence soil moisture content across different EBRs during the vegetational period (months 4 to 10). Please note that all CS SWAT+ models are calibrated against measured soil water content.

Figure 34A demonstrates that a combination of all groups of measures resulted in a moderate 4% increase in soil water content during the vegetation period. With the most prominent increase in the Pannonian region (+27%) and a slight reduction in the Boreal (-0.5%) and Continental (-1.7%) regions. LMMs generally increase soil water content (through gradual improvements in soil structure and water retention capacity), with effects being most pronounced in the Pannonian region (36%), followed by a negligible impact in the Continental and Boreal regions. Structural measures (SAM, SLM) results show more variable impacts, with negligible or no effects on the sw_vp in EBRs.

Figure 34C emphasises the broader catchment-scale implications. Again, LMM shows the most consistent improvements in soil water storage, especially in the Pannonian region (low till), while structural measures show negligible efficiency from the sw_vp perspective.

Figure 34D highlights that different groups of measures in the studied EBRs have a minor or even negligible impact on soil water content in the vegetation period. The spatial efficiency of each measure group reveals that SLM often delivers the most significant per-hectare increases in soil water content. This is shown in the Pannonian region (+0.02 mm/ha/year), where SLMs (hedge +0.5mm/ha) and SAM (low-till 0.02 mm/ha) show relative contribution to the sw_vp increase in mm/ha. An increase of half a millimetre of water per ha is not much, but it can be crucial in drought conditions.

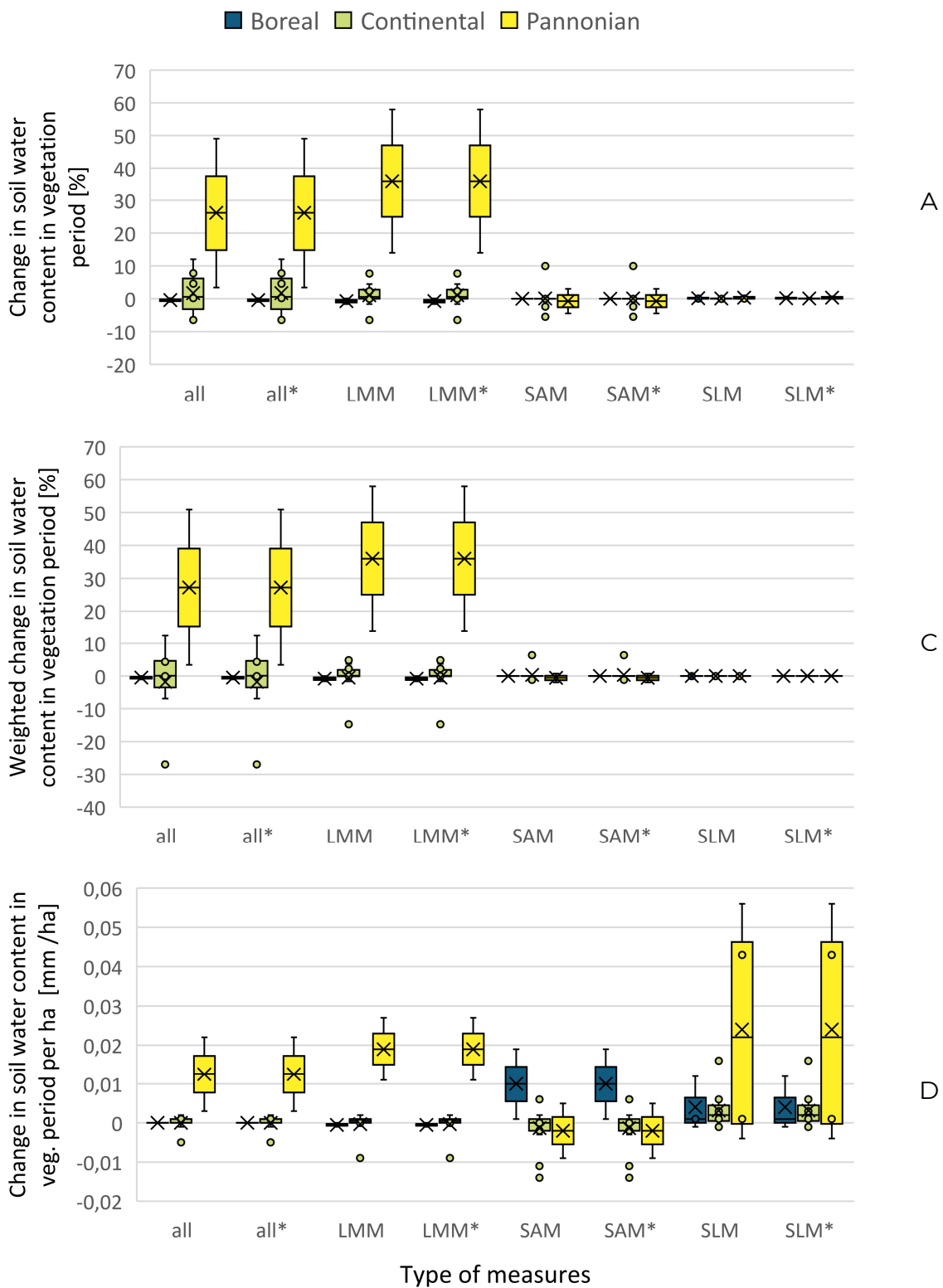


Figure 34: Soil water content in vegetation period (sw_vp) (months in a year 4 to 10) change compared to status quo [%] (A), percentage change [%] of sw_vp weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of sw_vp per ha [tons/ha/year] of NSWRM implemented (D) for different EBRs and groups of measures. The star mark (*) indicates combined results of all calibrated and uncalibrated models. Results without a star apply to the calibrated models.

Runoff

Figure 35B and Figure 35D compares the effectiveness of LMMs and SAMs in altering surface runoff for the Boreal and Continental regions, based on the SWAP modelling results. The data shows LMMs and SAMs are on average consistently reducing runoff with -79% (-1 mm/year) and -76% (-0,85 mm/year) respectively. Overall, we can conclude that on average for the Boreal region, SAMs (-80%; -0,6 mm/year) are more effective considering field-scale results than LLM (-70%; -0,53 mm/year), while for the Continental region, SAM is less effective (-73%; -1 mm/year) than LMM (-84%; -1,3 mm/year). It must be stated that the runoff corresponds to the amount of water generated on this area and does not include the run on to this particular area.

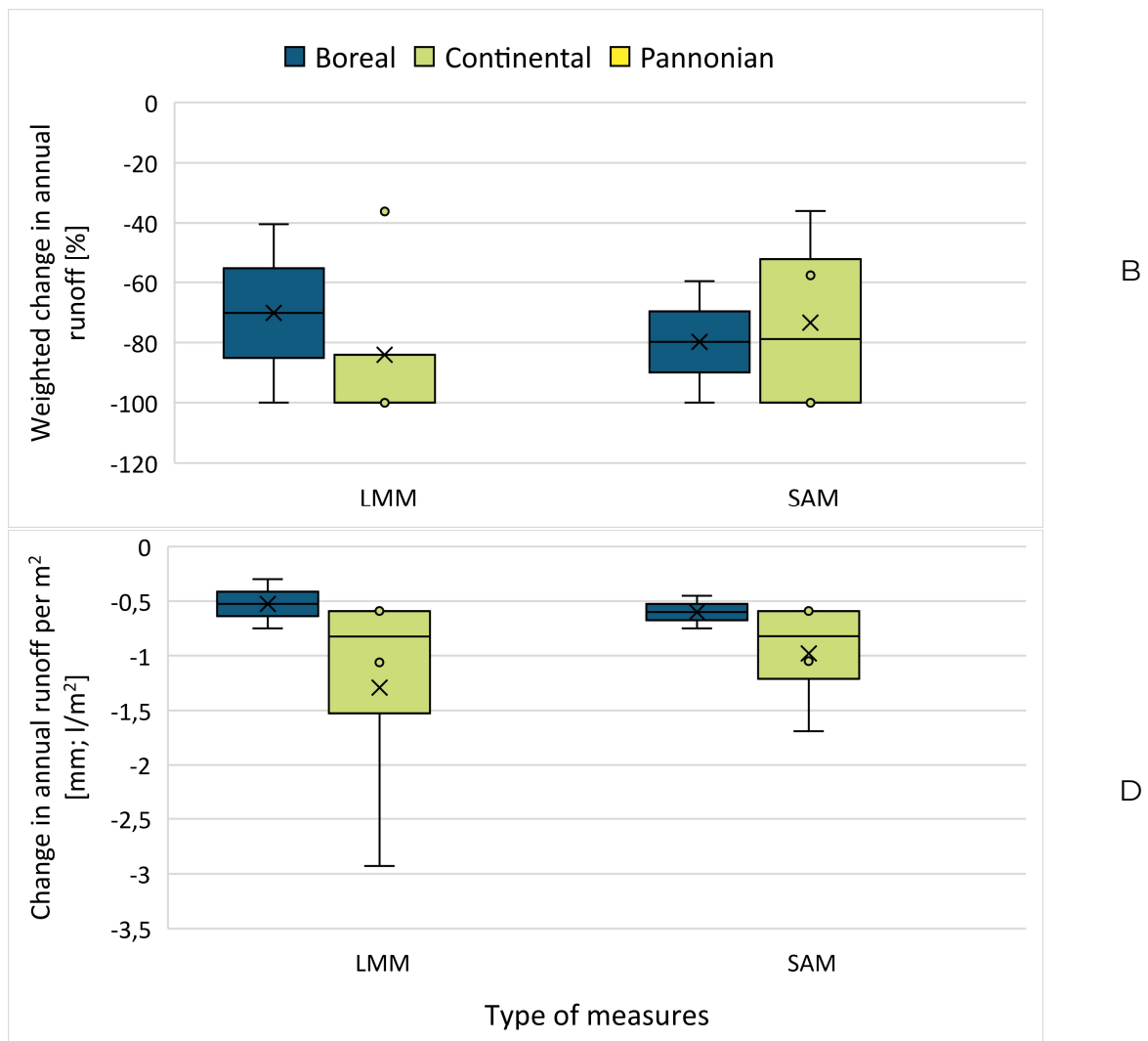


Figure 35: Percentage change [%] of annual runoff weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of runoff per m² [mm; l/m²] of NSWRM implemented (D) for different EBRs and groups of measures.

Soil water storage (Soil_wat_storage)

Figure 36 compares how LMM and SAM influence soil water storage across different EBRs, based on the SWAP modelling results. It reveals that LMM, on average, decreases soil water storage (-36%; -27 mm/year) with the highest impact in the Boreal region (-80%; -37 mm/year), followed by the Pannonian region (-23%; -13 mm/year) and the Continental region (-6%; -25 mm/year). SAMs demonstrate more variable regional effects with a +76% (+4 mm/year) increase. For the Boreal region, the effectiveness of SAM reaches on average +149% (+41 mm/year). As for the Continental region, the SAMs increases soil water storage by +3%.

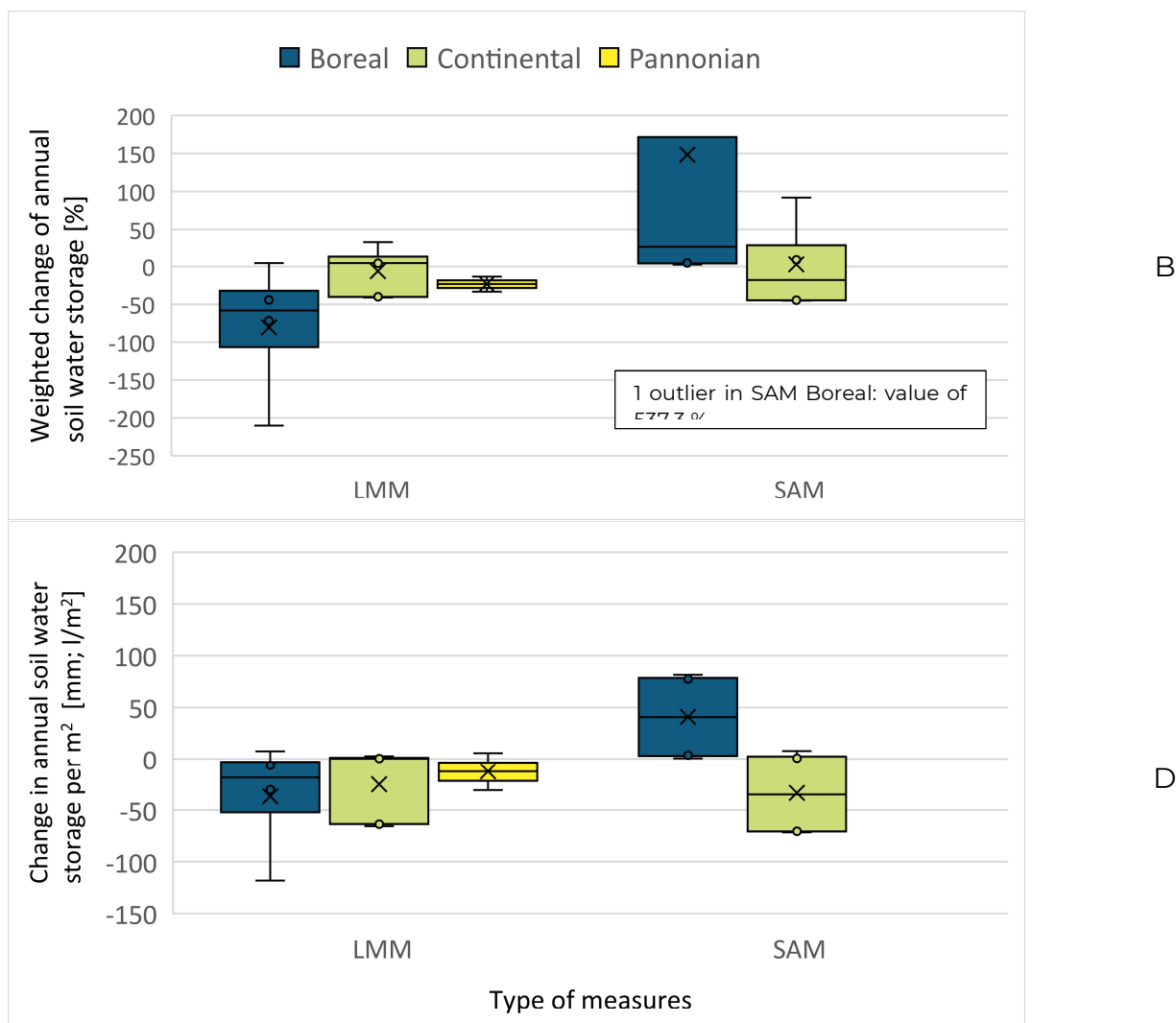


Figure 36: Percentage change [%] of annual soil water storage weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of soil water storage per m² [mm; l/m²] of NSWRM implemented (D) for different EBRs and groups of measures.

Drainage/percolation

Figure 37B and D evaluate how LMM and SAM influence water movement through soils comparatively in all three EBRs. The data indicates that LMMs in studied EBRs increase drainage/percolation rates (+22%; +121 mm/year). The highest average increase in percolation was observed in the Boreal region (+42%; +191 mm/year), followed by the Pannonian (+10%; +208 mm/year) and the Continental (+8%; +7 mm/year). SAMs show more variable effects with an average increase of +9% (+38 mm/year). For the Boreal region, the results demonstrate increase (+34%; +64 mm/year). The Continental region shows the decrease of -16%.

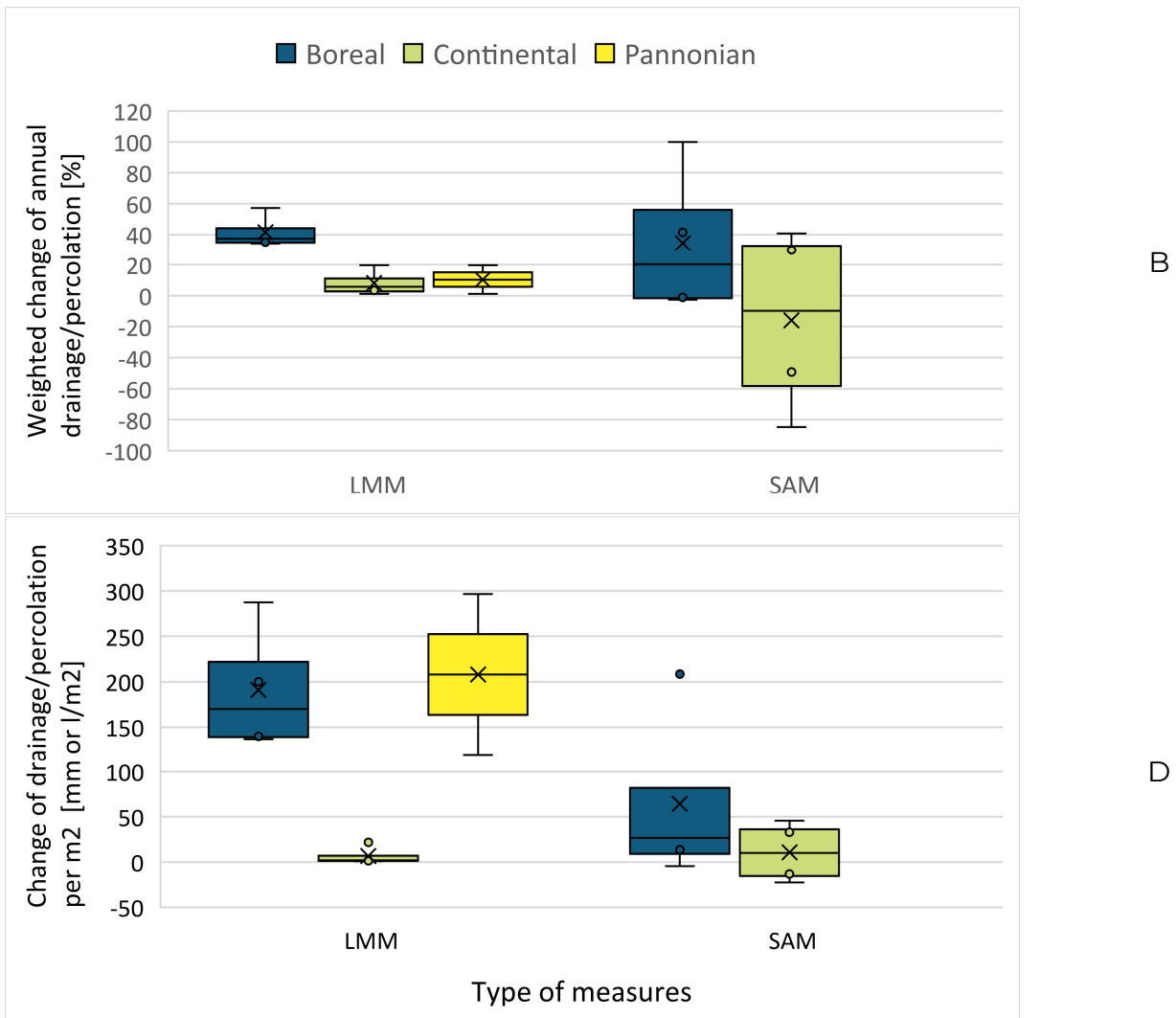


Figure 37: Percentage change [%] of annual drainage/percolation weighted by the ratio between the implemented NSWRM area and the total catchment area (B), and annual change of drainage/percolation per m² [mm; l/m²] of NSWRM implemented (D) for different EBRs and groups of measures.

4.1.3.6 Summary of modelling results

The summary of the results from deliverables D4.4 (Piniewski et al., 2024) was prepared using a multiple-perspectives approach to provide a comprehensive understanding of the project's results, impacts, and interrelationships. This synthesis is structured across four key perspectives: 1) biogeographical regions, 2) groups of measures, 3) management goals, and 4) climate change impacts.

4.1.3.6.1 Biogeographical regions perspective

The first perspective involves synthesizing the results of deliverable D4.4 (Piniewski et al., 2024) across different EBRs, allowing for the identification of spatial patterns and regional variations in the effectiveness of NSWORMs.

Continental EBR

The implementation of NSWORM in continental EBR demonstrates significant hydrological and agricultural benefits across multiple case studies. In CS1, **low tillage with cover crops** reduced soil loss by over 50% and nutrient losses by 13-23%, while increasing soil moisture retention. **Controlled drainage** in CS4 showed significant promise in mitigating high flows, improving low flow conditions, reducing soil loss, and decreasing nitrogen loads. CS5 found **cover crops** decreased sediment loads by 3% and nutrient losses by 2.9%, with combined measures providing the most comprehensive water quality improvements despite slight grain yield reductions of 0.7%. CS7 demonstrated that **buffer strips** reduced N loads in river water while increasing the number of low-flow days, with minor trade-offs in crop yield.

For the continental region, **low tillage systems** (CS1, CS10) have proven to be the most effective approach, despite requiring careful management to balance agricultural productivity and environmental benefits. The spatial extent of implementation also proved critical, as demonstrated in CS4, where measures covering over 50% of the catchment area showed the most pronounced hydrological impacts.

Boreal EBR

In the boreal EBR, NSWORM implementation has a moderate but meaningful impact on water retention and nutrient management, though with some regional variations. In CS10, **low tillage** practices proved most effective, reducing N and P losses by 18% and 60%, respectively. Additionally, they increased soil water content by 23-27% during early summer months, though late-season moisture decreased by 18-22%. **Grassed waterways** in the same catchment contributed to a 20% reduction in sediment loss and 2-5% declines in nutrient loads. However, their small spatial coverage limited basin-wide effects. CS8 lacked detailed NSWORM analysis but highlighted the region's vulnerability to early spring waterlogging, suggesting water retention measures could improve trafficability.

The demonstrated ability of **low tillage** to simultaneously improve water retention (5% increase in soil moisture) while sharply reducing P losses (60%) indicates these measures could help address both nutrient pollution and seasonal water management challenges in boreal agricultural systems.

Pannonian EBR

In the Pannonian EBR, NSWRM implementation demonstrates substantial benefits for erosion control and water retention, with varying effects on crop production. In CS3 and CS11, **no-till with cover crops** proved the most effective measure, reducing sediment loss by 75-84% and phosphorus loss by 66-69%, while increasing soil moisture by up to 48%. **Conversion to grassland** showed significant but smaller impacts, decreasing sediment loss by 20-25% and nitrogen loss by 21-27%. However, due to the loss of arable land, total grain production was reduced by 26-44%. **Riparian buffers** showed limited catchment-scale effects (1-10% sediment reduction) and localized benefits in critical areas. The measures' hydrological impacts were notable, with **no-till** reducing maximum flows by 6.7-8.4% and **meadows** decreasing peaks by 5.9-6.3%. However, some trade-offs appeared, as **grassland conversion** increased phosphorus loss by 39% in CS11, while **riparian buffers** unexpectedly reduced minimum flows by 33%. Crop yield responses varied, with **no-till** increasing winter wheat yields by 3.6-5.1% but showing negligible effects on other crops.

These results highlight the Pannonian region's strong potential for soil conservation through agricultural measures, though successful implementation requires careful consideration of the balance between erosion control, water regulation, and maintaining agricultural productivity in this drought-prone landscape. The effectiveness of vegetation-based measures (e.g., **no-till** and **grassland conversion**) points to their suitability for addressing regional challenges of soil erosion and seasonal water scarcity.

4.1.3.6.2 Groups of measures perspective

The second perspective summarizes D4.4 (Piniewski et al., 2024) results based on the selected groups of measures (see Chapter 4.1.3.4), facilitating comparisons and insights into the performance of similar types of interventions.

Perspective on Land Management Measures (LMM)

LMMs demonstrate significant potential for improving hydrological regulation, soil conservation, and agricultural sustainability across diverse biogeographical regions. In continental climates, **low tillage with cover crops** (CS1, CS10) reduced soil loss by 50-84% and N losses by 14-23%, while increasing soil moisture by up to 48% (CS3). **No-till systems** (CS3, CS11) proved particularly effective in Pannonian EBR, cutting sediment loss by 75-84% and P loss by 66-69%, while increasing winter wheat yields by 3.6-5.1%. **Cover crops** (CS1, CS5) reduced peak flows by 2.8% and sediment loads by 3%, though their water-saving benefits were partially offset by increased evapotranspiration in some cases. **Drought-tolerant crops** (CS9) showed mixed results, improving water resilience but reducing total production when replacing conventional crops. In boreal regions (CS10), **low tillage** increased summer soil moisture by 23-27% while reducing P losses by 60%. However, late-season moisture declined by 18-22%.

The effectiveness of LMMs varied by local conditions, with the greatest impacts occurring where measures addressed specific regional challenges, i.e., erosion control in Pannonian areas, water retention in continental zones, and nutrient management in boreal catchments. While most LMMs maintained or slightly reduced crop yields (typically <5%), their combined implementation often produced synergistic benefits for

water quality and soil conservation without substantially compromising agricultural productivity.

Perspective on Structural Linear Measures (SLM)

SLMs demonstrate targeted effectiveness in mitigating hydrological and water quality issues, though their impacts vary by measure type and implementation scale. **Grassed waterways** (CS1, CS10) reduced sediment losses by 20-30% locally while increasing water retention in flow pathways. However, due to small spatial coverage, they showed only limited catchment-wide effects (2-5% nutrient load reductions). **Riparian buffers** (CS3, CS5, CS10, CS11) reduced sediment loads by 2-10% (CS3, CS11). **Hedgerows** (CS3, CS7) exhibited negligible hydrological effects (<1%) but helped reduce sediment loss by 8-10% when strategically placed.

The most pronounced SLM impacts occurred where measures directly intercepted dominant pollution pathways, e.g., **grassed waterways** in erosive gullies (CS1) reduced local P loads by 8%, while strategically placed **riparian buffers** (CS5) attenuated peak flows by 7.4% in critical areas. However, SLMs generally required complementary measures for basin-scale effects, as their linear nature limited spatial coverage to 1-5% of catchment areas. Performance optimization depended on precise placement in flow concentration zones and integration with upstream land management practices, particularly in tile-drained landscapes where subsurface flows dominated nutrient transport.

Perspective on Structural Areal Measures (SAM)

SAMs demonstrated significant but variable impacts across continental EBR case studies, with effectiveness closely tied to spatial scale and placement. CS4 revealed that **afforestation** (5.1% coverage) reduced peak flows and sediment load and loss, while **floodplain restoration** in CS9 emerged as the most effective SAM, reducing extreme flows through natural water retention. **Wetlands and ponds** in CS10 exert negligible catchment-scale impacts due to small coverage, though model uncertainties were noted. **Meadow conversion** in CS3 reduced sediment loss by 25% but required substantial land-use changes (25% area conversion). It reduced the maximum flow by 6.3% and the minimum flow by 14%, while increasing soil moisture by 2.9%.

4.1.3.6.3 Management perspective

The fourth perspective organizes findings according to different management goals, including soil, water (flood and drought), and nutrient management. This enables a cross-cutting analysis of how NSWORMs contribute to various environmental and agricultural objectives.

Soil management

The implementation of NSWORMs across various EU CSs demonstrates significant but varying impacts on soil loss and sediment load reduction. Among the most effective measures, **no-till farming** (CS3, CS11) and **no-till farming combined with cover crops** (CS1) consistently reduced sediment loss, and showed notable decreases in N and P losses. **Afforestation** (CS4, CS7) and **grassed waterways** (CS1, CS10) also proved highly effective in stabilizing soil, particularly in continental CSs (CS1, CS7), where they minimized erosion and nutrient runoff. However, some unexpected outcomes emerged, such as increased

sediment loss under **cover crops** and **crop rotation** in Poland. To fully understand the soil loss dynamics under the modelled scenarios, further investigation into the mechanisms driving this increase would be beneficial.

In the Pannonian region (CS3, CS11), **no-till with cover crops** remained highly effective, significantly reducing sediment loss, while **grassland conversion** showed mixed results, reducing N loss but increasing P loss in CS11. **Riparian buffers** and **field-edge hedges** had limited impact in areas with extensive tile drainage (CS10), as subsurface flows bypassed these structures. Meanwhile, in CS5, combining multiple measures yielded the best results (sediment load reduction), though with diminishing returns due to overlapping effects.

The findings highlight that while NSWORMs generally improve soil retention, their success depends on regional factors, e.g., hydrological conditions, farming practices, and proper model calibration. The most robust strategy involves integrating **no-till** systems, **afforestation**, and **grassed waterways**, while recognizing that combined measures may not always provide additive benefits. Further research is needed to address inconsistencies, particularly regarding P dynamics and the influence of tile drainage on buffer efficiency. Overall, tailored approaches considering local biogeographical and agricultural contexts are essential for maximizing soil conservation benefits.

Flood management

The implementation of NSWORM shows good potential for flood mitigation through various hydrological modifications. Please note that in OPTAIN, the SWAT+ modelling approach was applied (Plunge et al., 2024), which provides results on a daily time step, thus limiting the model application for more detailed, event-based flood simulations (Yu et al., 2018). For flood modelling, an accurate simulation of the flood peak timing and magnitude, as well as the total amount of water transported during floods, is required (Boithias et al., 2017). Lumped models, such as SWAT, often consider more hydrological processes than distributed event-based models, and can perform long-term simulations, including low-flow and high-flow periods (Boithias et al., 2017). Therefore, SWAT is a valuable tool for hydrological modelling, but the limitations in the flood volume calculations and detailed routing need to be carefully considered when applying it for flood management, especially for managing extreme flood events.

In CS1, **low tillage combined with cover crops** proved particularly effective at reducing peak flows while increasing soil moisture retention, with similar results observed in CS3, where **no-till** practices reduced maximum flows by 8.4%. The CS4 revealed that **controlled drainage** and combined measures significantly decreased high-flow indicators, with **afforestation** also contributing to peak-flow reduction. CS5 showed that while **cover crops** modestly reduced peak flows, **detention ponds** produced mixed results - sometimes increasing peak flows due to altered runoff timing, highlighting the importance of careful placement and design. CS10 demonstrated that **grassed waterways** could effectively contribute to enhanced water retention.

The studies collectively suggest that effective flood management can benefit from a strategic combination of agricultural practices (e.g., **reduced tillage, cover crops**) and landscape-scale interventions (**afforestation, controlled drainage**), tailored to specific catchment characteristics. The most successful approaches addressed both peak flow reduction and increased water retention capacity, with spatial distribution and measure density proving crucial for achieving meaningful flood mitigation at the catchment

scale. These findings emphasize the importance of NSWORMs for flood risk management while highlighting the need for context-specific implementation strategies.

Drought management

The implementation of NSWORM across EU catchments demonstrates significant potential for drought mitigation through improved water retention and flow regulation. In several CSs (CS1, CS3, and CS11), **low/no-tillage with cover crops** effectively increased soil moisture while reducing peak flows, suggesting enhanced groundwater recharge during wet periods that could sustain baseflows during droughts. The results varied by region and type of measure. While **grassed waterways** in CS10 improved low flows, some interventions (e.g., **drought-resistant crops** in CS9) unexpectedly reduced minimum flows.

The most consistent drought mitigation benefits came from practices that enhance infiltration and soil water storage, particularly **no-till** agriculture, which maintained more stable soil moisture levels across seasons. In CS11, such measures helped narrow the difference between high and low flows, suggesting improved regulation of water availability.

While localized measures, such as **wetlands**, showed limited catchment-scale impacts, strategic combinations of agricultural practices (**cover crops, reduced tillage**) and landscape interventions (**afforestation, grassed waterways**) appear most promising for building systemic drought resilience across different EU EBRs.

Nutrient management

Various, but significant impacts on nutrient management were displayed. **No-till** farming combined with **cover crops** consistently emerges as one of the most effective measures, reducing N and P loads, particularly in CS3 and CS11. **Arable land to grassland conversion** is showing mixed performance, moderately reducing N loads in some cases while sometimes increasing P loads, highlighting the complex nutrient dynamics resulting from land use change. The **buffer strips** generally exert limited nutrient control effectiveness, particularly in tile-drained landscapes like CS10, where subsurface flows bypass surface interventions, though they can reduce P loads by up to 9.4% in some cases.

Multiple-measure combinations typically result in the greatest nutrient load reductions, although not through simple additive effects, as measures can often interact in a complex way. The CS1 demonstrates that comprehensive approaches can simultaneously address multiple water quality parameters, reducing sediment-associated nutrient transport while also decreasing days with high-nutrient concentrations. These findings emphasize that effective nutrient management requires tailored approaches considering local hydrology, agricultural systems, and the specific nutrient pathways in each catchment, with particular attention to balancing N and P dynamics, which often respond differently to NSWORM implementation.

4.1.3.6.4 Impact of future climate conditions (without implementing NSWORMs)

The third dimension focuses on the influence of climate change, summarizing its effects on water balance components, crop yields, and nutrient flows.

Temperature

The impact of future climate conditions reveals a consistent warming pattern across multiple CSs. For CS1, CS4, and CS5, projections under RCP8.5 for the period 2071–2100 indicate temperature increases of 3–5°C, with the highest warming occurring in winter and the lowest in spring. Similarly, CS2 and CS10 project annual temperature rises of 3–5°C under RCP8.5, with seasonal peaks in autumn (Tmax) and summer (Tmin) for CS2, and winter (Tmin) for CS10. CS3 and CS11 will be exposed to milder warming of 2.5–3.5°C under RCP8.5, concentrated in winter. In contrast, RCP2.6 scenarios generally limit warming to 1–2°C across all case studies, except for CS9, where RCP4.5 and RCP8.5 project increases of 1–3°C, with the highest rises in summer and autumn. CS7 also notes significant warming under RCP8.5, though specific magnitudes are not quantified. These trends highlight regional variability but underscore a dominant warming signal, particularly under high-emission scenarios.

Precipitation

The impact of future climate scenarios on precipitation varies across CSs, but generally indicates a trend toward wetter conditions, particularly under high-emission scenarios. For CS1, CS4, and CS5, RCP8.5 projections show a median increase of 16–17% in precipitation by the end of the century, with the highest rises in winter and spring. Similarly, CS2 projects a 20% increase under RCP8.5, while CS10 predicts a 7–12% rise depending on the scenario, with seasonal variability favoring spring and winter. CS3 and CS11 also show wetter conditions in the future under all RCPs, though summer becomes drier under RCP8.5 by the end of the century. In contrast, CS9 projects mixed trends, with RCP2.6 increasing annual precipitation, and RCP8.5 leading to declines, particularly in summer. CS7 notes minimal changes ($\pm 5\%$) compared to the baseline conditions. Overall, the projections highlight increased precipitation in colder seasons, while summer months may experience drying in some regions, emphasizing regional variability under future climate conditions.

Snow fall

The examination of the future climate impact on snowfall reveals a pronounced decline across all CSs due to rising temperatures. In CS1, CS2, CS4, and CS5, snowfall and snowmelt are projected to decrease by over 60% under RCP8.5 by the end of the century, driven by warmer winters, despite increased precipitation. Similarly, CS10 anticipates reductions of 30–70% depending on the RCP scenario, with the most severe losses under RCP8.5. CS3 and CS11 also project declining snowfall and soil moisture in upper layers, while CS7 notes reduced snowfall under RCP4.5 and RCP8.5. CS9 highlights extreme reductions, with snowfall decreasing by up to 75% under RCP8.5, while even RCP2.6 shows a 20% decline. These trends indicate a widespread reduction in snowpack, with significant implications for water storage, seasonal runoff patterns, and ecosystem dynamics, especially in colder regions.

Evapotranspiration

Future climate conditions are projected to increase both potential evapotranspiration (PET) and actual evapotranspiration (ET) across most CSs, though the magnitude varies by region and scenario. Under RCP8.5, PET is expected to rise by over 10% in CS1, CS4, and CS5. On the other hand, for CS2, PET increases are expected, in some cases exceeding 15% by the end of the century. Similarly, CS10 predicts PET growth of 3–12%,

and over 15% under RCP8.5, while CS3 and CS11 note PET increases linked to rising temperatures. Actual ET follows a similar trend, with moderate increases in CS1, CS2, CS4, and CS5 due to increasing precipitation and thus greater soil water availability. CS7 also projects rising PET and ET in the future, while CS9 highlights increased ET driven by warmer conditions. These changes suggest a shift toward higher atmospheric water demand, with implications for soil moisture, agricultural water use, and ecosystem hydrology.

Percolation

Under future climate conditions, percolation trends vary by region but generally show increases under higher-emission scenarios. In CS1 and CS4, percolation is projected to rise significantly under RCP4.5 and RCP8.5 due to wetter conditions, while CS10 anticipates a 23% increase by the end of the century under RCP8.5. CS3 shows mixed results, with percolation increasing up to 10% under RCP2.6 but varying under RCP4.5 and RCP8.5, whereas CS5 projects minimal change under these scenarios. In contrast, CS7 suggests a narrower range of -10% to +5% compared to baseline conditions, reflecting regional variability. These shifts highlight how increased precipitation and altered soil moisture dynamics may enhance groundwater recharge in some areas, though outcomes remain scenario- and location-dependent.

Soil moisture content

Future climate conditions are projected to alter soil moisture content with varying impacts across soil layers and regions. In CS1 and CS4, root zone soil moisture is expected to increase while topsoil moisture decreases by less than 5%, creating a divergence between layers. CS2 shows similar trends but with greater variability, as RCP2.6 increases annual soil moisture and RCP8.5 decreases it, particularly during summer months. More severe reductions are projected in CS9, where RCP4.5 and RCP8.5 could decrease soil water content by 10–25% during critical growing months (August and September). CS10 anticipates a 5–15% decline in the upper 30 cm of soil due to higher ET and percolation, though early spring drying may improve field trafficability in this boreal region. CS3 and CS11 also predict topsoil drying of up to 8%, with root zone moisture changes depending on RCP scenarios. These shifts highlight growing drought risks for agriculture, particularly in summer, despite some compensatory wetting in deeper soil layers under certain conditions.

Surface runoff

Surface runoff projections exhibit significant variability across CSs, with model uncertainty particularly pronounced in some regions. In CS1, surface runoff shows a consistent increase averaging over 20% under RCP8.5, while CS2 and project similar upward trends by the end of century, though CS4 notes exceptional cases where tile flow could increase by nearly 200% due to the catchment's water-limited nature. CS3 and CS11 expect surface runoff to increase (up to 45% and 25%, respectively), driven primarily by projected precipitation increases. In contrast, CS10 models a 10-17% decrease in surface runoff despite wetter conditions, suggesting complex interactions between precipitation patterns and landscape characteristics. CS5 shows clearer increasing trends only in late-century projections (10-20% under RCP2.6-RCP8.5), while CS7 presents a narrower range of -10% to +10% variation. These divergent responses highlight

how local hydrology, soil properties, and precipitation distribution patterns mediate the impact of climate change on surface runoff generation across different EU regions.

Discharge

Discharge indicators show complex but generally increasing trends across most case studies. In CS1, CS4, and CS5, average and high flows are projected to rise under RCP4.5 and RCP8.5, with CS1 showing a 100% increase in extreme high-flow days under RCP8.5. CS2 anticipates increased mean streamflow across all scenarios, while low flows decrease under RCP8.5 by the end of the century. CS3 and CS11 project 18-20% higher average flows under RCP8.5, and 100-200% more high-flow days. CS10 predicts a 40% increase in high-flow days under RCP8.5, though low-flow days show inconsistent trends. CS9 demonstrates divergent patterns, with RCP2.6 increasing high flows while RCP4.5 and RCP8.5 reduce flows and exacerbate droughts. These projections collectively indicate more variable streamflow regimes, with increased flooding risks in most regions but uncertain impacts on drought duration, highlighting the need for adaptive water management strategies.

Water quality

Future climate conditions are projected to significantly impact water quality across multiple CSs, with nutrient loads generally increasing under wetter scenarios. In CS1 and CS4, N and P losses are expected to rise under RCP4.5 and RCP8.5 due to increased runoff, though concentration thresholds may decrease due to dilution effects. CS3 and CS11 expect higher total N and P loads and losses in the future, under RCP2.6 & RCP8.5, but the reliability of their water quality model is lower due to a lack of calibration. CS5 anticipates modest increases in sediment and nutrient loads, while CS7 shows declining N and P loads under RCP8.5 but more frequent exceedances of concentration thresholds in milder scenarios. CS10 presents mixed results, with N loads decreasing up to 5% under RCP2.6 but increasing slightly (2%) under RCP8.5, and P losses rising to 10% in most scenarios. These trends suggest that while total nutrient export may increase with higher discharges, concentration dynamics will depend on complex interactions between hydrological pathways and land management, with divergent behavior of sediment-bound P and soluble N across different catchments.

Crop production

In the future, mixed impacts on crop production are expected across the CSs, with variability depending on crop type and emission scenario. In CS1, yields show minimal changes under RCP2.6 and RCP4.5 but a slight decrease of crop production under RCP8.5, while CS2 projects overall yield declines for most crops except winter rape and triticale under RCP4.5. CS3 anticipates 1-7.5% yield reductions for winter crops under RCP4.5 and RCP8.5, though Lucerne yield may increase by 17%, whereas CS4 shows spring barley and grassland yields rising 5-15%, and rapeseed dropping over 30% (due to extreme warming). CS5 predicts up to 15% declines for winter cereals under RCP8.5 but potential 40% gains for grapes and soybeans, while CS7 notes yield increases for alfalfa and oats but variability for other crops. CS9 projects yield increases under RCP4.5 and RCP8.5, and CS11 expects 1-8% yield decreases for most crops except Lucerne, which may increase by 15% under RCP8.5. These results highlight the crop-specific nature of climate impacts, with winter cereals and oilseeds generally more vulnerable than forage crops or drought-adapted species.

4.1.4 Optimization

Within the OPTAIN framework, optimization can be considered the final stage of the modelling process. As it investigates the effects of NSWRM combinations from different aspects (i.e., environmental, social, and economic), it mainly contributes to step 4 of the ToC concept (i.e., Defining the Scope and Boundaries).

The primary goal of the OPTAIN optimization is to identify spatially optimal configurations of NSWRM that can effectively address multiple, often conflicting, environmental and hydrological objectives at the catchment scale. The optimization framework integrates SWAT+ with tools developed within the OPTAIN project, such as SWATmeasR and the Constrained Multi-objective Optimisation of Land use Allocation optimizer (CoMOLA; Strauch et al., 2019), to simulate, assess, and refine the placement and parameterization of NSWRMs. By generating Pareto-optimal solutions, the method allows stakeholders to explore and compare implementation scenarios that represent trade-offs among different goals such as nutrient retention, flood mitigation, and ecosystem service enhancement. The indicators used to evaluate the performance of different NSWRM configurations typically include changes in nutrient loads, sediment transport, water flow dynamics, and economic and social impacts. By framing the optimization in a multi-objective context, the approach ensures that no single goal dominates the planning process, thereby supporting balanced and sustainable land and water management decisions.

The proposed multi-objective optimization (MOO) requires four components, as defined in D5.1 (Strauch and Schürz, 2024):

1. The definition of optimization objectives (or goals) for which the NSWRM plans are to be optimized,
2. The definition of the decision space, namely, which individual NSWRM (type and location) are to be implemented simultaneously in the catchment,
3. Functions evaluating the objectives based on the decisions, and
The MOO algorithm (OPTAIN uses a multi-objective genetic algorithm, NSGA-II (Deb et al., 2002), included in the CoMOLA software).

CoMOLA

CoMOLA is an MOO tool developed for identifying optimal spatial NSWRM configurations, allowing for case-specific customization. It is used to balance up to four objectives. The optimization indicators are grouped into EPIs and SPIs (see Chapter 4.1.2.3). Typically, a MOO setup includes one water-related EPI (like soil moisture or discharge), one nutrient-related EPI (such as N, P, or sediment load), one SPI for agricultural productivity (e.g., total yield or gross margin), and one SPI for NSWRM implementation and maintenance costs.

The result of CoMOLA is a set of Pareto-optimal spatial implementation plans for NSWRM. These plans represent trade-offs among multiple competing objectives, e.g., reducing nutrient loads, improving water retention, maximizing crop production, and minimizing costs. Instead of providing a single "best" solution, CoMOLA generates a range of optimal solutions, allowing users to choose the most suitable plan based on their priorities.

The MOO outputs can be difficult to read, understand, and work with directly, mainly because they present multiple dimensions. An interactive visualization was required to clarify and make tangible the relationships between the goals and the plans for implementing the measures, as well as between the objectives themselves. To reduce the number of Pareto-optimal solutions to a manageable size, an effective and meaningful process for eliminating and summarizing the Pareto-optimal solutions was required (Wittekind et al., 2025).

ParetoPick-R

Within OPTAIN, two main strategies for post-processing of the MOO results were implemented. The first one focused on visualisation tools to support the assessment, understanding, and communication of the complex MOO outputs. The focus of the second one was to reduce the number of optimal solutions in a meaningful way. Both approaches were implemented in a tool called ParetoPick-R (Figure 38). ParetoPick-R is based on R and Python (White et al., 2025), providing a user interface for researchers and stakeholders to analyse the MOO results for their respective CSs (Wittekind et al., 2025).

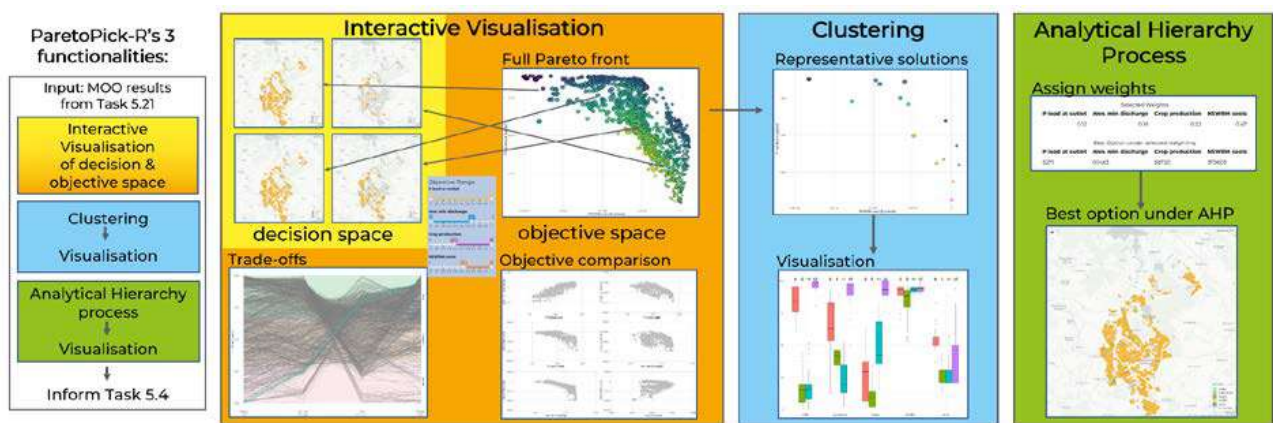


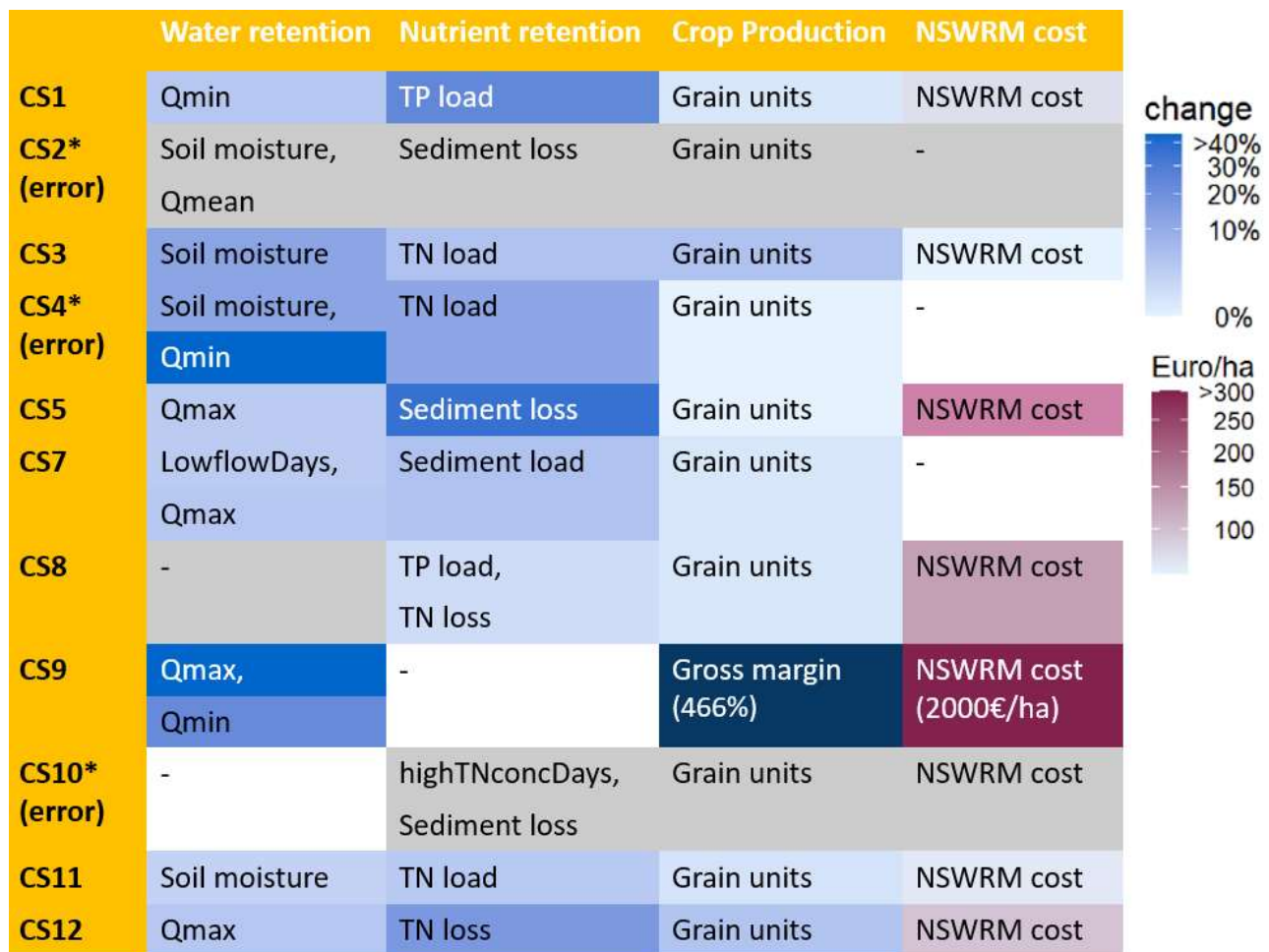
Figure 38: ParetoPick-R's functionalities and workflow (Wittekind et al., 2025)

ParetoPick-R offers an intuitive and interactive plotting techniques that reveal patterns and trade-offs in the four-dimensional objective space (i.e., the space defined by the values of four indicators, where each point represents the target values of a possible solution). In all CSs, the selected economic indicators were often similar, while water and nutrient retention indicators varied (Figure 39). Hydrological indicators were primarily based on SWAT+ daily streamflow simulations and included Qmin, Qmean, Qmax, and the number of LowflowDays. Some CSs also selected the mean soil moisture. The hydrological objectives generally aimed to maximize Qmin, Qmean, and soil moisture, and minimize Qmax and LowflowDays (see Figure 39).

Nutrient retention indicators were also derived from SWAT+ predictions of TN, TP, sediment loads, and, in one case, the number of days exceeding a threshold TN concentration. These were consistently minimized. Agricultural productivity was typically represented by grain units, allowing yields of different crops to be aggregated based on nutritional value. In CS9, gross margin was used instead, reflecting crop yield in economic terms. The fourth objective was to minimize the cost of implementing and maintaining NSWORMs. This included potential subsidies where reliable data were available.

The magnitude of objective changes varied across CSs (see Figure 39). In CS7 and CS8, selected NSWRM scenarios had minimal impact, while in other CSs, NSWRM scenarios significantly affected specific objectives (e.g., TP load in CS1, Qmin in CS4, Qmax and gross margin in CS9). Grain units were mostly unaffected, as NSWRM often required little or no change in cropland use. An exception was CS9, where terracing substantially influenced crop production by enhancing cultivability on sloped terrain.

Overall, the objectives were often in conflict, meaning no single solution could optimize all goals simultaneously. Therefore, stakeholder preferences were crucial for guiding the selection of preferred NSWRM strategies.



*Optimisation results not usable

Figure 39: Selected objectives and their magnitude of change across different CSs (Wittekind et al., 2025)

According to D5.3 (Wittekind et al., 2025), Figure 39 shows an overview of objectives defined in each case study, coloured by the maximum change in values according to the full set of Pareto optima. With note, that colour scheme ignores the direction of change (positive or negative) and the maxima cannot be achieved simultaneously in one solution. Note, NSWRM costs are divided by the entire catchment area. Real costs at selected sites would be much higher depending on the type of NSWRM. The colour ranges provided in the legend (left) do not capture the extraordinarily high maximum values of crop production and NSWRM cost of CS9.

Selection of the preferred Pareto-optimal solutions

The identification of the preferred Pareto-optimal solutions (from the actors' perspective) was performed through interviews with local stakeholders, selected among MARG members and different sectors (e.g., agriculture, water, nature conservation). Each stakeholder was interviewed individually, either in person or through an online session (Strauch & Wittekind, 2025).

Using the interactive ParetoPick-R app, the Pareto solution space was presented to stakeholders to help them understand trade-offs between four optimization objectives. Stakeholders viewed solution maps, analyzed relationships between objectives, and filtered options based on their preferences. Then, they used the Analytical Hierarchy Process (AHP) method, which is used to help assess MOO results by translating subjective preferences into quantifiable weights through pairwise comparisons. AHP supports decision-making, reduces bias, and fosters consensus. Within the OPTAIN, AHP facilitates inclusive evaluation of NSWRM plans, revealing shared and conflicting priorities. Its integration with post-processed visualizations and clustering enhances the discussion of solution feasibility and stakeholder alignment at the catchment level (Wittekind et al., 2025).

Stakeholder interviews were completed in time for inclusion in D5.3 (Strauch and Wittekind, 2025) for the 11 CSs. The remaining three case studies (CS6, CS13, and CS14) did not complete optimization due to ongoing model setup or data limitations. Additionally, CS2 and CS10 are in the process of repeating their optimization runs due to procedural issues, and CS4 requires engagement of additional stakeholders possessing regional expertise to ensure a comprehensive evaluation (Strauch and Wittekind, 2025).

A total of 50 stakeholders participated in the preference elicitation task across the CSs, with the number of interviewees per case study ranging from 1 (CS4) to 9 (CS1). Participants represented four sectors: agriculture (29), water (11), nature conservation (7), and spatial planning (3), and they were all familiar with their respective CS contexts.

Individual preferences varied, but sector-specific trends emerged clearly in most CSs, as presented in Figure 42. This figure illustrates the performance values, scaled between 0 and 1, of the solutions preferred by stakeholders, averaged per sector within each case study. Please note that these values reflect the performance of preferred solutions rather than direct weights assigned by stakeholders.

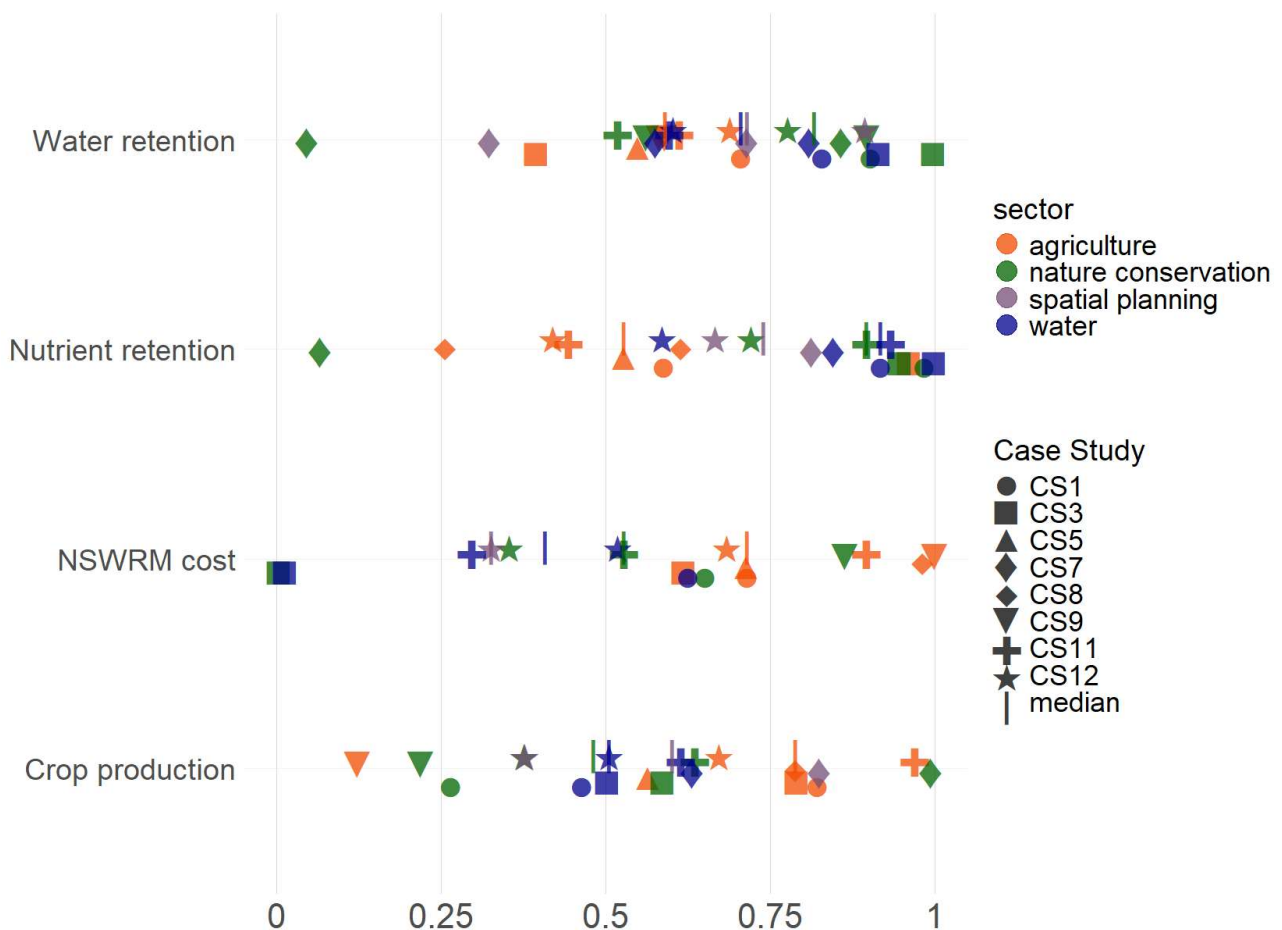


Figure 40: Objective preferences selected by different stakeholders across CSs

Due to the higher number of participants from the agricultural sector, results for this group are more robust. Agricultural stakeholders showed relatively consistent preferences across CSs, with all selected solutions scoring within the upper half of the performance scale (0.5–1) for economic objectives. Their preferred solutions generally prioritized crop production and minimized NSWRM implementation costs, often at the expense of water and nutrient retention, which were only moderately addressed (performance values between 0.25 and 0.75).

In contrast, the smaller number of stakeholders from the water, nature conservation, and spatial planning sectors limits the reliability of cross-sector comparisons. Nevertheless, these groups consistently placed higher emphasis on environmental objectives, favoring solutions with stronger water and nutrient retention performance.

More information on the OPTAIN optimization is available in deliverables D5.1 (Strauch & Schürz, 2024), D5.2 (Wittekind et al., 2025), and D5.3 (Strauch & Wittekind, 2025).

4.2 Regions' guidelines for optimised implementation of NSWRM

4.2.1 Governance arrangements

Considering the ToC concept, policy analysis is contributing to step 4, as it defines the external boundaries of the OPTAIN project, namely the alignment with current regulations and legislation, in particular with the objectives set by the EU WFD (i.e., good ecological status of water bodies) and the EU CAP. As found within the project,

compliance with these objectives is still (more or less) at the level of principle, not at the level of the actual agreement. The recommendations part mainly contributes to step 5 of the ToC, which includes providing guidelines for change. In the OPTAIN project, each CS has a different vision of change and different motivations for change. To support the NSWRM implementation, OPTAIN analyzed the political and administrative conditions under which NSWRLMs are initiated, and proposed legislative recommendations for the future harmonization of water and agricultural policies at local, regional, national, and EU levels.

In OPTAIN, the following EU policies that support the water–energy–climate nexus and are relevant for the implementation of NSWRLMs were reviewed: CAP, WFD, the Nitrates Directive, the Natura 2000 network, and the Paris Agreement.

A central EU strategy for supporting farmers, ensuring food security, and promoting sustainable rural development is the **CAP**, launched in 1962. It is structured into two main components. Pillar I focuses on income support through direct payments based on land area, with specific provisions for small farms and environmentally sustainable practices. Environmental mechanisms under this pillar include standards for good agricultural and environmental conditions (GAEC), green direct payments that reward practices such as crop diversification and grassland preservation, and a cross-compliance system linking payments to adherence with environmental and animal welfare legislation. Pillar II supports rural development through co-financed national or regional programmes that promote innovation, environmental protection, climate resilience, and ecosystem preservation. Countries select from a menu of policy measures, such as agri-environment-climate schemes, organic farming, and support related to Natura 2000 and the WFD. The CAP was reformed in 2021 to become greener and more performance-based, with new rules taking effect from 2023.

The **WFD** (2000/60/EC) establishes a framework for protecting surface and groundwater across the EU, aiming to achieve good ecological and chemical status through monitoring and planning. A key mechanism is the River Basin Management Plan (RBMP), which outlines actions to meet environmental goals and includes economic analysis and stakeholder participation. While the directive sets broad objectives, implementation and funding are left to individual Member States.

The key objective of the **Nitrates Directive**, adopted in 1991, is to reduce water pollution from agricultural sources, particularly nitrates. It requires member states to identify Nitrate Vulnerable Zones or to implement national action programmes, which must include measures such as limits on fertilizer and manure application, especially near watercourses and in wet conditions, along with regular monitoring and reporting every four years.

Natura 2000 is the EU's network of protected areas for biodiversity, covering 18% of the EU's land area and 8% of its marine territory. The network is based on the Birds Directive (1979) and the Habitats Directive (1992), which mandate the designation of Special Protection Areas, as well as Special Areas of Conservation. Many of these areas are on farmland, making the CAP—particularly its rural development funds—a key financial mechanism for supporting sustainable land use and conservation within Natura 2000 sites.

The **Paris Agreement**, ratified by the EU in 2016, is the first universal, legally binding international treaty on climate change. It aims to limit global warming to well below 2°C, preferably 1.5°C, above pre-industrial levels. The EU's current commitment includes a

target to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. This target is aligned with the European Green Deal and is implemented through national energy and climate plans and long-term strategies, as required by EU governance regulations.

Governance issues included insufficient or fragmented legislation, poor integration across sectors and administrative levels, and limited administrative capacity and expertise (Figure 43). These challenges often stem from sector-specific policies that do not align with broader environmental and societal goals, resulting in weak coordination and enforcement.

Policy instruments were also analysed, focusing on their ability to incentivize end-users, such as farmers, to implement NSWORMs. Three main types of instruments were considered: economic incentives (e.g., subsidies or penalties), technical infrastructure and support (e.g., tools and guidance for implementation), and informational or educational initiatives (e.g., outreach, training, and public awareness); see Figure 41. Effective policy implementation depends not only on the existence of such instruments but also on how well they are designed, communicated, and supported by governance structures.

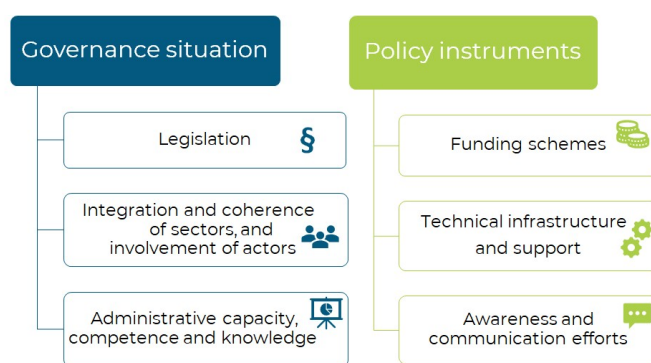


Figure 41: Main aspects used to analyze gaps and barriers for the uptake and adoption of NSWORM by classifying informants' perspectives and opinions of the policy situation, focusing on the governance and policy instruments.

To support the uptake of NSWORM, an assessment of policy gaps and compatibility was conducted. Policies were examined in terms of governance structures and the instruments used to promote adoption. The above listed policies promoting NSWORM implementation are all interconnected through a multi-level governance (impression created from Glavan et al., (2022)). Through the lens of legacy-driven multi-level governance, as described by Rowbottom et al. (2022). Under the WFD, countries realigned to multi-level arrangements, but historical governance choices created shape which field-level measures are feasible and when (e.g., SAM—soil/agronomic measures, SLM—structural land management, LLM—large-scale landscape management). Centralised, top-down legacies (e.g., infrastructure-centric traditions or rigid timelines) may constrain uptake by privileging uniform solutions and adding administrative layering, while decentralised, discretionary elements and hybrid designs enable context-specific combinations of SAM, SLM and LLM through local coordination and stakeholder engagement. Thus, the portfolio of practices attached to the case studies illustrates how policy legacy and institutional layering mediate the translation of EU objectives into on-the-ground action, thereby supporting the call for hybrid governance that pairs

enforceable national standards with flexible, locally co-produced implementation pathways.

4.2.2 Governance improvement potential: inter-national, trans-national boundary catchments

The OPTAIN research of barriers and solutions to the wider uptake and implementation of NSWORMs, that was conducted among 144 respondents (Cvejić et al., 2023), shows that the current agricultural policy, particularly the CAP, promotes the implementation of NSWORMs. However, analysis of stakeholder input reveals that this support is primarily directed toward soil and landscape management practices, while transformative hydro-morphological interventions receive comparatively limited attention. This selective focus tends to reinforce existing agricultural structures, favouring large-scale farms and contributing to the preservation of the status quo rather than enabling broader systemic change.

Financial incentives are the dominant form of support and are widely recognized as essential for encouraging the adoption of NSWORMs. However, these subsidies are most commonly linked to practices with clear and immediate economic benefits, such as conservation tillage, cover cropping, and nutrient management, rather than to structural or hydrological interventions like wetland restoration, floodplain reconnection, or river renaturation. Consequently, implementation is often short-lived, with measures being abandoned when financial support is withdrawn. While innovative proposals, such as integrated “retention packages” that combine soil and structural measures, are emerging, they remain underfunded and underutilized.

Knowledge dissemination and communication are identified as secondary but necessary forms of support. Despite progress, these efforts often lag behind financial mechanisms in effectiveness and tend to reach only a limited group of already-engaged stakeholders. This dynamic limits the dissemination of best practices and hinders the wider acceptance of innovative or less well-known hydro-morphological solutions. Informants also highlight administrative complexity, slow legislative adaptation, and a general lack of capacity and coordination among relevant authorities as major implementation barriers.

Moreover, policy coherence across sectors, including water, climate, spatial planning, and agriculture, remains weak. While some compatibility exists, particularly in areas such as flood protection and nutrient retention, other critical topics, including water scarcity and soil water retention, are poorly integrated. Spatial planning, in particular, is noted as the least supportive policy domain, suffering from fragmented governance, insufficient environmental integration, and low local engagement.

Despite the growing recognition of climate change impacts and the importance of water retention, hydro-morphological measures are continuously underprioritized. Grey infrastructure remains dominant in the policy imagination, and nature-based solutions are perceived as novel, risky, or administratively burdensome. As a result, the current policy framework, while nominally supportive of NSWORMs, effectively channels resources and attention toward incremental, soil-based interventions that align with existing agricultural practices and land-use patterns.

To summarize, NSWORMs have been identified as strategic measures for reaching agri-environmental policy objectives, namely good water quality and ecological status, balanced water quantity, protection of natural resources, as well as climate change

adaptation and mitigation. Therefore, they represent one of the baseline tools for the future integrated achievement of water and agricultural policy goals at different administrative levels (from local to EU). Agricultural policy does promote NSWORMs, but in practice, it disproportionately supports measures that favour large farms and maintain established practices, while failing to enable the transformative hydro-morphological changes needed to ensure long-term water resilience and ecosystem health.

4.2.3 Governance improvement potential: national, regional and catchment level

In addition, the OPTAIN cross-CSs' workshop on NSWORM promoters provided several important insights. As only one representative from each country attended, the evidence should be treated as indicative rather than comprehensive empirical research. Accordingly, the workshop results are presented as consolidated, all-country summaries rather than CS-specific findings.

Furthermore, the OPTAIN cross-case workshop on barriers and solutions to the wider uptake and implementation of NSWORMs, followed by a subsequent workshop focusing on NSWORM promoters, yielded several important insights. However, as only one representative from each country participated, the findings should be regarded as indicative rather than comprehensive empirical evidence. Consequently, the workshop outcomes are presented as consolidated, cross-country summaries rather than case study-specific results.

Change agents differ across contexts: In most regions, farmers, advisory services, and local agencies were recognised as key influencers. At the national level, ministries and regional authorities play crucial roles, especially considering the implementation of structural NSWORM.

Motivations are multifaceted: Financial incentives (e.g., subsidies, EU CAP payments) are important across all case studies, but environmental awareness and regulatory compliance are also strong motivators, particularly in regions under pressure from water quality directives or drought policies.

Barriers vary widely: The identified key obstacles are unclear institutional responsibilities (e.g., within RBMPs), land tenure issues (e.g., high share of rented land), limited funding, a lack of technical knowledge and administrative complexity.

Successful implementation depends on coordination: Effective transition management requires strong cooperation between technical actors (e.g., engineers, advisors), administrative bodies, and local stakeholders. In several countries, gaps in this coordination have slowed the uptake.

Momentum is sustained through trust and local engagement: Trusted intermediaries, such as agricultural advisors and local NGOs, are essential for maintaining stakeholder interest and facilitating ongoing learning and implementation support.

Monitoring and evaluation mechanisms are weakly institutionalised: While some countries have formal follow-up processes (e.g., linked to CAP or water agency reporting), others lack structured systems for tracking the long-term impact of NSWORM.

These findings inform the development of the implementation guidelines and highlight the importance of tailored strategies that take into account regional socio-political

conditions, institutional readiness, and stakeholder capacities. They also emphasise the need for an integrated, participatory approach grounded in a shared vision of sustainable land and water management.

4.2.4 Governance improvement potential: sub-catchment, cross-farm and farm level

Finally, the OPTAIN survey on farmers' and land owner's perceptions on sufficiency / insufficiency of incentives captures the opinions from 129 individuals in Belgium, Czech Republic, Germany, Lithuania, Poland, and Slovenia. It provides further directions of governance improvement potential at a sub-catchment, cross-farm and farm level.

Figure 42 illustrates the range of policy instruments identified in the OPTAIN project to encourage the adoption of sustainable water and land management measures. These instruments vary in their level of coercion, from mandatory requirements applied to all landowners (e.g., riparian buffers) to conditional measures linked to basic income support under the EU's CAP. They also include economic incentives, such as eco-schemes and rural development funding, as well as informational tools aimed at raising awareness and promoting voluntary uptake. This spectrum highlights the importance of combining regulatory, financial, and knowledge-based approaches to effectively motivate land managers and overcome the additional costs and effort associated with new practices.



Figure 42: Policy instruments to promote NSWORMs adoption in the OPTAIN project (Nesheim et al., 2025).

Additionally, Figure 43 presents how stakeholder rate the level of support available for different types of measures across various categories, including financial support for implementation and maintenance, information and advice, technical implementation, and access to machinery and instruments. The results reveal significant disparities in support, particularly in financial aspects. Buffer zones and retention ponds are perceived to suffer from highly insufficient financial support, especially for implementation and maintenance, representing major barriers to their adoption.

Cover crops and conservation tillage receive slightly better but still limited financial backing. In contrast, information and advice - especially regarding the application process for funding - are generally rated as mostly sufficient, highlighting their possible role as a motivating factor. Technical implementation support is moderate across measures, while access to machinery and instruments is generally adequate for larger farms, with the exception of wetland construction, where it remains a barrier. Smaller farms have a lower access to specialized machinery and have to rely on investments cross-farms or machine services, which is not always effective. Overall, the figure

indicates that while informational and advisory support is relatively strong, insufficient financial support remains a critical barrier to wider implementation of several key water and land management measures.

Measures	No. Resp.	Financial support		Information / advice		Machines, instruments
		Implementation	Maintenance	Applying for funding	Technical implementation	
Cover crops	49	2,8	3,3	3,7	3,4	3,3
Conservation tillage	37	2,6	2,6	3,7	3,5	3,2
Buffer zones riparian	47	2,2	2,1	3,3	3,2	3,3
Retention / detention pond	29	2,1	2,6	3,1	3,1	2,8
Wetland construction	12	3,0	2,7	3,8	3,7	2,4

1. Highly insufficient - important barrier	2. Insufficient support - a barrier	3. Some support - sometimes barrier	4. Mostly sufficient support - a motivation	5. Good support (important motivation)
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Figure 43: Perception of farmers and land managers on the sufficiency / insufficiency of incentives for promoting NSWORMs adoption in the OPTAIN project Nesheim et al., 2025.

Farmers and land managers shared valuable insights into the real-world challenges of adopting sustainable practices. Their comments revealed common frustrations and highlight areas where current policy instruments fall short.

“Support should fully compensate for yield losses that occur when adopting new cultivation technologies.”

“Reduced tillage requires significant investment in specialized machinery and new knowledge. The shift in production technology is substantial, yet knowledge transfer remains insufficient.”

“While support for introducing winter catch crops covers the sowing costs, there are additional costs for removing the catch crops before the next planting, and these are not compensated.”

“Financial support for purchasing machinery is too low, creating a major barrier to implementation.”

“Guidelines are often unclear and not adapted to real-world conditions. They fail to meet actual needs because consultation with practitioners has been insufficient.”

Figure 44: Insights of farmers and land managers into the real-world challenges of adopting NSWORMs (Nesheim et al., 2025).

The survey results reveal a number of shared challenges across different locations and types of measures. Overall, SLM and SAM were implemented only rarely, suggesting significant barriers to their wider adoption.

Economic support emerged as a key concern. While a few respondents considered the available financial support sufficient and helpful, many described it as highly insufficient.

On average, respondents perceived economic support as inadequate, highlighting it as one of the main obstacles to implementing sustainable water and land management practices, despite the existing investment programmes.

Administrative support received slightly more positive feedback. Most participants found it helpful and sometimes motivating, though it could also act as a barrier in certain cases. However, satisfaction levels declined when it came to support for administrative paperwork, indicating that bureaucratic complexity remains a practical challenge for many land managers.

The results of the survey indicate that achieving the ambitions of the European Green Deal and the Farm to Fork Strategy will require coordinated and joint actions at the supra-national level, along with stronger cross-sectoral collaboration. Efforts must go beyond individual measures and include raising awareness, shaping social norms, expanding knowledge, and compensating both direct and indirect costs associated with the adoption of sustainable practices. Building knowledge in this respect is especially crucial - it underpins our ability to understand how these objectives can be translated into practical actions and guides the development of effective, context-specific solutions.

The results presented in the figure underline the importance of sustaining momentum beyond the initial implementation of measures. While informational and advisory support is generally sufficient and motivating, persistent financial barriers - especially for implementation and maintenance - threaten the long-term adoption and effectiveness of measures such as buffer zones and retention ponds.

4.3 Knowledge sharing

The final task of the OPTAIN project is to facilitate the transfer of knowledge gained through the project, so that stakeholders can examine, evaluate, and implement sustainable water retention strategies in agricultural catchments in all EU regions via a Learning Environment (LE) platform (<https://le.optain.eu>) (the website is accessible with a username and password). The OPTAIN LE is an online platform to help build capacity, disseminate OPTAIN methodologies and results, and to convey the knowledge co-created by the project consortium to stakeholders and beyond. It serves as an interactive space where users can learn about NSWORMs, access a catalog of measures, explore 14 case studies, understand related policies and stakeholders' engagement, discover scientific innovations, and support decisions based on modeling and optimization.

The LE also includes links to both the WOCAT database and the NWRM.eu website, to visualise the factsheets produced in the OPTAIN project and to benefit from the standardisation and other reference systems available in these two catalogues. The LE enables different users to access and group the NSWORMs according to various preferences (e.g., country, environmental conditions, Sustainable Land Management groups), or to extract relevant values (minimum, range, maximum) from the quantitative information collected. This structured approach enhances knowledge sharing among stakeholders, supports evidence-based decision-making and adaptive learning through modular data enrichment (e.g., greenhouse gas assessments, climate resilience metrics), and links the NSWORM database with external platforms. As it contributes to sustaining momentum even after the OPTAIN project ends, LE can be considered as part of step 6 of the ToC.

5 DISCUSSION

This chapter synthesizes OPTAIN's results to assess the project's hypotheses on stakeholder engagement, standardized documentation, modelling under data scarcity, the performance of spatially targeted NSWORMs, the adequacy of policy support across EBRs. We interpret the evidence by linking project outcomes with local knowledge, and governance conditions to derive implications for implementation and policy.

5.1 Local stakeholders improve the relevance, accuracy, and legitimacy of NSWORM modelling by contributing local knowledge, validating assumptions, and co-owning the process

The involvement of local stakeholders throughout the NSWORM modelling process has proven essential for enhancing the relevance, accuracy, and legitimacy of the OPTAIN project results (Voinov et al., 2016; Voinov et al., 2018). Their contributions, ranging from identifying context-specific problems to selecting appropriate measures and engaging in model discussions, demonstrates the value of integrating local knowledge into modelling and decision-making (Arnott et al., 2020; Naugle et al., 2020; Bamzai-Dodson et al., 2021). While not always explicitly stated, stakeholder participation also plays a role in validating assumptions and ensuring that modelling efforts reflect real-world conditions (Moallemi et al., 2021; Zellner et al., 2024). The structured engagement through MARG fostered a sense of shared ownership and supported the co-creation of solutions that are both scientifically sound and socially accepted (Feo et al., 2022; Cronin et al., 2022). This collaborative approach strengthened the overall impact and applicability of the project's findings. However, such participatory processes must be carefully designed to avoid risks such as tokenism, power imbalances, high transaction costs, and scope drift, which can undermine their effectiveness (Antwi et al., 2025; Parsons et al., 2025).

5.2 Standardized NSWORM documentation in WOCAT supports knowledge sharing, cross-case comparison, and integration into learning platforms

The standardized documentation on NSWORMs, using the WOCAT Sustainable Land Management database as a foundation, ensures methodological consistency and semantic interoperability across diverse CSs (Haregeweyn et al., 2023; Liniger et al., 2019) and was the backbone of the OPTAIN research (Magnier et al., 2024). By employing a harmonized data structure and classification system, the WOCAT framework enables systematic cross-case comparison of NSWORM effectiveness, applicability, and contextual relevance (Giger et al., 2015; Piemontese et al., 2020). The integration of the standardized descriptions into the OPTAIN Learning Environment facilitates dynamic querying, multi-criteria filtering, and the generation of analytical outputs (e.g., statistical ranges, geospatial overlays, thematic aggregations) (González-Roglich et al., 2019; Liniger et al., 2019). This structured approach not only enhances knowledge sharing among stakeholders but also supports evidence-based decision-making and adaptive learning through modular data enrichment and linkages with external platforms such as NSWORM.eu (Haregeweyn et al., 2023; Magnier et al., 2024).

5.3 In data-scarce catchments, reliable NSWRM assessment is possible using open data, empirical methods, and predictive models, if key environmental and management data are approximated with sufficient resolution

The OPTAIN project also demonstrated that in data-scarce catchments, reliable assessment of NSWORMs is achievable when open data, empirical methods, and predictive models are combined in a coherent workflow and implemented at appropriate spatial–temporal scales, reserving limited in-situ data for targeted calibration and validation (Bieger et al., 2015; Msigwa et al., 2022; Nkwasa et al., 2022; Čerkasova et al., 2023).

Data gaps were systematically addressed by applying pedotransfer functions to estimate soil hydraulic properties from texture and organic matter, drawing on national statistics and local case-study knowledge to constrain crop calendars and agri-management, and using open Earth-observation products (e.g., seasonal land-use/phenology from Sentinel-2) to refine management assumptions and check model realism. Together - supported by the WOCAT standardised descriptions of NSWORMs - these inputs provided the resolution needed for process-based SWAT+ simulations in cases with sparse monitoring (Weber et al., 2024; Paschalis et al., 2022; Msigwa et al., 2022; Nkwasa et al., 2022).

To ensure comparability across diverse case studies, OPTAIN employed harmonised workflows and guidelines for data preprocessing, parameter estimation, calibration/validation, and scenario design. Scripted procedures, shared quality checks, and common reporting templates reduced analyst-to-analyst variability and made assumptions transparent, supporting reproducibility and cross-case synthesis. Recent SWAT+ tools and methods further enable this standardisation (Plunge et al., 2024; Tigabu et al., 2024; Das et al., 2024). This process integration, coupled with routine sensitivity/uncertainty checks proportional to data availability, underpinned consistent and accurate modelling across sites—thereby validating that robust NSWORM evaluation is attainable even under limited data conditions (Sánchez-Gómez et al., 2025).

5.4 Spatially targeted NSWORM combinations outperform single measures in retaining water and nutrients and can partly offset climate change impacts, even though field-level and catchment-scale effects may differ

The impact of NSWORM on water balance, crop yields, and nutrient fluxes under current climate conditions was investigated in seven CSs (1, 3, 4, 7, 9, 10, and 11) using a harmonized approach and scripted workflow, described in Chapter 4.1.3. The full-scale harmonisation is limited since the selection of measures and also their parameterisation varies between the CSs.

Different NSWORMs exerted different retention effectiveness. There was also variation between different CSs. Crop and soil management–related NSWORMs (e.g., low or no tillage, cover crops) were found to be effective in all five CSs where this type of measure was modelled (i.e., 1, 3, 4, 10, and 11). In most cases, low or no tillage and cover crops had no significant effect on crop yields, except in CS3, where yields increased by up to 28% (Qiu et al., 2024; Blanchy et al., 2023). Drought-resistant plants (tested only in CS9)

allowed savings in irrigation water, but at the cost of reduced crop yields (Moshelion, 2020).

Five NSWORMs were characterised by the conversion of cropland into permanent vegetation cover (greening). Not all of them were found to be effective. Hedges, for instance, were relatively ineffective in each of the four CSs (1, 3, 7, and 10), while grassed waterways had a larger effect (especially on sediment retention) in both CSs that tested this measure (1 and 10). A plausible (and trivial) pattern seems to emerge from the simulation results: the more targeted the spatial implementation of a measure, the greater its impact (Schramm et al., 2024; Fan et al., 2025). All CSs except CS4 included riparian buffers. In 50% of the cases (three out of six), riparian buffers showed a significant retention effect (particularly in CS7, where the number and size of the buffers are much larger than in other CSs) (Tsai et al., 2022). Afforestation was the NSWORM with the largest area of implementation. It helped to retain nutrients in CS4 and water in CS11, while it was relatively ineffective in CS7; such mixed hydrologic responses are consistent with broader evidence that forest expansion can reduce water yield depending on context (Teuling et al., 2019). Greening comes at a cost to crop production. In the majority of the CSs, greening measures were applied only to a small percentage of the total cropland. On the contrary, in CS11, afforestation was tested on approximately 50% of cropland, resulting in a corresponding reduction in total crop production.

Artificial impoundments did not show a significant impact on catchment-scale water and nutrient retention. Exceptions are detention ponds (in CS4 and CS9) and channel restoration (simulated as constructed wetlands along the channel in CS9) (Lam et al., 2024). The implementation of combined measures had the highest impact in all CSs. However, this kind of scenario may not be the most efficient, as some measures may partly overlap the effects of other measures (as observed in CS1 with low tillage, cover crops, and grassed waterways) (Schramm et al., 2024; Fan et al., 2025).

Overall, the novel modelling approach for assessing the effectiveness of NSWORMs, proposed in OPTAIN, appears plausible. However, the obtained results should be treated with caution, as the majority of modelling teams are likely to continue their efforts to make the modelling results as realistic as possible (by improving the goodness-of-fit in the calibration, adding additional variables in the calibration, and updating the parameterisation of the measures). There may still be inconsistencies and implausibilities in the behaviour of individual measures that require a more careful investigation by each CS. This is particularly true for the parameterisation of greening measures and impoundments (e.g., settling rates of nutrients and decision tables for water release).

5.5 Agricultural policy promotes NSWORMs but mainly supports soil and landscape measures, over broader, transformative hydro-morphological interventions

Findings through a governance lens are used to explain why some NSWORMs (NSWORMs) scale while others stall, and how policy design, institutional legacies, and on-the-ground incentives shape uptake across regions and levels of administration (Pe'er et al., 2020).

Across case studies, the same structural issues recur: insufficient or piecemeal legislation, weak cross-sector integration, and limited administrative capacity and expertise. These problems reflect a legacy of sector-specific policy design that is not fully

aligned with broader societal goals (e.g., water resilience, biodiversity, climate), producing inconsistent coordination and uneven enforcement (Grohmann, 2024)

Three families of policy instruments dominate the NSWRM space: economic incentives (payments, penalties), technical infrastructure/support (tools, engineering guidance), and informational/educational measures (advisory services, training). Merely having these instruments is not enough; their design quality, communication, and institutional backing determine whether they reduce risk and transaction costs for land managers or simply add administrative layers (Pe'er et al., 2020; Grohmann, 2024). Survey and workshop evidence sharpen this point. Financial incentives are widely viewed as necessary but insufficient: they tend to favour familiar soil and landscape practices (cover crops, reduced tillage, nutrient management) that fit farm-scale decision cycles, while more transformative hydro-morphological measures (e.g., wetlands, floodplain reconnection, channel renaturation, and much needed controlled drainage) remain under-prioritised, perceived as costly, complex, or risky (Raška et al., 2022; Zingraff-Hamed et al., 2021).

OPTAIN's governance analysis is consistent with a legacy-driven, multi-level governance perspective: historical choices—centralised, infrastructure-oriented programs; rigid timelines; fragmented competencies—shape which measures are feasible, where, and when. Conversely, hybrid arrangements that couple enforceable national standards with local discretion enable context-specific portfolios and sequencing of interventions. This helps reconcile field-scale agronomic practices with structural and hydro-morphological interventions across ownership boundaries (Wiering et al., 2018; Zingraff-Hamed et al., 2021).

In practice, legacy effects explain why portfolios diverge: some favour farm-scale measures with clear compliance rules; others mobilise cross-owner coordination for retention and restoration projects. OPTAIN's case-study portfolios illustrate how policy layering and institutional fit mediate the translation of EU objectives into local action, supporting the call for hybrid governance that balances uniform standards with locally co-produced pathways (Pe'er et al., 2020; Zingraff-Hamed et al., 2021).

Cross-country workshops highlight who motivates NSWRM implementation. Change agents differ by level: farmers, advisers, and local agencies dominate at regional and catchment scales; ministries and basin authorities matter most for structural NSWRM. Motivations are multi-faceted: incentives and eco-schemes are important, but environmental awareness and (to some extent) regulatory pressure also drive uptake, especially under water-quality or drought stress. Barriers vary from unclear responsibilities in implementation, land tenure, limited funding, knowledge gaps to administrative complexity. But a common denominator is the need for coordination capacity spanning engineers, advisers, administrators, and stakeholders. Trust-building via credible intermediaries is essential to sustain momentum, yet monitoring and evaluation of outcomes remain weakly institutionalised in many settings (Ingram & Maye, 2020; Seddon et al., 2020).

A survey of 129 land users and land owners (Belgium, Czech Republic, Germany, Lithuania, Poland, Slovenia) adds detail from the decision front line. The instruments span mandatory rules (e.g., buffers), conditionality under basic income support, eco-schemes and rural development funds, and information/advice. Respondents report large disparities in support: buffer zones and retention ponds suffer from highly insufficient financial backing for both implementation and maintenance; cover crops

and conservation tillage fare somewhat better but still face shortfalls. Information and advice especially on how to apply are generally rated as sufficient, suggesting advisory systems can motivate adoption where money is not the binding constraint. Technical support is moderate, and access to machinery is size-dependent: large farms usually cope; small farms often rely on sharing or services, which are not always effective and are sometimes difficult to establish (Ingram & Maye, 2020), indicating a potential for improvements.

Open-ended responses illuminate lived constraints: calls for compensation of yield losses during transition; the cost and learning curve for reduced tillage machinery; transaction costs around catch-crop removal; low investment support for specialised equipment; and guidelines that feel detached from field realities due to limited practitioner consultation. The insights into why some measures fail to enter the implementation phase span from cash-flow risks, capital constraints, to procedural burdens, even when actors are convinced of environmental benefits (Raška et al., 2022; Pe'er et al., 2020).

Taken together, the findings point to a systemic imbalance: Europe's current policy architecture does promote NSWORMs substantially, but in practice it tilts toward incremental, farm-scale interventions, reinforcing existing structures and favouring larger, capital-rich farms. This orientation helps with near-term compliance and diffusion of familiar practices but leaves hydro-morphological measures often essential for basin-scale water retention and ecological recovery under-enabled. The result is progress that is real but partial, with a true capacity for substantial improvements to deliver long-term resilience at EBRs scale (Pe'er et al., 2020; Seddon et al., 2020).

The surveys captured opinions of a limited number of respondents in Europe. Therefore, the findings are indicative rather than exhaustive. Therefore, generalisation to all EU contexts or even national-level status is limited. Several respondents reported perceptions of sufficiency rather than audited budgets or cost-effectiveness; triangulating these perceptions with administrative and environmental outcomes is an important next step. After all, results from harmonised modelling indicate that moderate to significant environmental benefits are achievable without causing substantial negative impacts on yield. The convergence of barriers and levers across countries and instruments gives the discussion external validity and practical value for improving the implementation design (Grohmann, 2024; Zingraff-Hamed et al., 2021).

The Commission frames the 2028–2034 CAP as “simpler, more targeted and future-oriented”, with stronger synergies via National & Regional Partnership Plans and reinforced risk-management and investment tools—useful for multi-actor NSWORM portfolios. Final adoption depends on Council/Parliament. At the same time The Water Resilience Strategy sets a cross-EU action plan to restore/protect the water cycle, build a water-smart economy, and secure safe/affordable water. Notably for agriculture, actions include a “Sponge Facility” (boost water retention on land), using CAP Strategic Plans to maximise water resilience, continued incentives for better water management in the next period. To further help mainstream NSWORMs through the post-2027 CAP and non-EU agricultural policies, countries should further promote as eco-schemes and agri-environment-climate interventions with clear performance indicators, and also promote currently under promoted, but highly efficient measures (e.g. controlled drainage). The EU Water Resilience Strategy provides complementary “sponge” pathways and finance for measures such as constructed wetlands, floodplain reconnection directly with the Water Resilience Strategy. By coupling CAP instruments with the water resilience mechanism, ministries should seek solutions in co-funding catchment-scale packages

while keeping administrative burden low. Here, regional and local governance levels should play a supporting and enabling role. Here OPTAIN's harmonised workflows and traceable indicators offer a significant bridge between environmental monitoring systems and contractual compliance in the environment domain. Finally, conditionality is tied to place-based measures. GAEC standards already set universal baselines for example for buffers and protection of wetlands/peatlands – but OPTAIN's optimal spatial targeting of combinations can convert these into catchment-specific plans that stack CAP support with Water Resilience Strategy. For agriculture and rural development administrations, that means moving from generic rules to mapped, sequenced interventions that fit local hydrology, land tenure, and governance capacity should be further promoted.

6 CONCLUSIONS

The OPTAIN synthesis summarized in this report takes into account results of 12 modelling teams in 14 small agricultural catchments in Europe, which were collected over a period for more than three years. The preparation of the deliverable was coordinated by a group of authors and contributors who agreed on the methodology and tools to carry out the analyses throughout the CSs. While this research employed a well-established and widely used hydrological and water quality model, SWAT+, the work performed within the OPTAIN project significantly advanced several aspects of using this tool for the benefit of the scientific and professional communities.

The interplay between the agricultural system and the structural features of farms is crucial to support farmers in their decision to implement NSWORMs. Their practical knowledge and attitudes towards NSWORMs are also important for successful implementation, especially when combined with sufficient financial support, effective training and advisory services, and streamlined bureaucratic procedures. On the other hand, farmers may remain sceptical without robust and timely evidence of benefits, or in case of unfavourable policy, market, or climate conditions. The results of the OPTAIN project illustrate not only the perspective of CS experts but also whether and how NSWORMs are attractive for farmers in real cases. A promoted use of modelling results is highly recommended to guide NSWORMs policy implementation at all levels.

SAM exhibit limited efficiency in the Boreal region, especially for constructed wetlands. Unless better evidence is obtained in the future on the positive effects of such measures, no recommendation to increase public funding (from CAP) can be made. This measure needs to be fully funded by the environmental sector or through shared funding between the environmental and agricultural sectors.

The results clearly show that measures reduce nutrient leaching, thereby increasing nutrient availability for crops, which supports more efficient nutrient management in agroecosystems. However, it is important to stress that flood protection planning cannot be based on the SWAT modelling results, as the model relies solely on precipitation data and does not include return periods. A key piece of evidence emerging from the results is that appropriate measures can significantly reduce sedimentation in watercourses and infrastructure, which in turn lowers maintenance and cleaning costs and contributes to more efficient long-term management of water resources and infrastructure.

OPTAIN's governance results argue for re-balancing Europe's NSWORM policy mix. To maintain momentum on soil and landscape practices, but unlock structural and hydro-morphological interventions that deliver basin-scale water retention and ecological gains. Doing so will require durable financing, lower transaction costs, stronger coordination capacity, and hybrid governance that joins national standards with locally co-produced pathways. Implemented together, these changes move NSWORMs from principle to practice and from incremental to transformational outcomes.

Future work should focus on identifying a comprehensive typology of incentives, including mandatory rules, conditionalities, economic subsidies, and information schemes. To further develop evidence base for optimal implementation of NSWORM and their combinations in the specific EBRs the OPTAIN deliverable D6.4 will explore policy and governance improvements in direction of (i) performance-based payments, particularly effective for biodiversity-related NSWORMs, (ii) collective funding schemes to

incentivize landscape-scale implementation, and (iii) tailored advisory services and multi-actor engagement platforms to foster social learning.

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