Path4Med: Demonstrating innovative pathways addressing water and soil pollution in the Mediterranean Agro-Hydro-System

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Path4Med: Demonstrating innovative pathways addressing water and soil pollution in the Mediterranean Agro-Hydro-System

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1. Executive Summary

This deliverable (D2.2a) builds on the technology mapping and characterization presented in D2.1a, extending the analysis to include a baseline assessment of water quality and quantity, as well as current monitoring technologies, water, fertilizer and pesticides requirements. Whereas D2.1a focused on identifying what technologies exist and where they are used, this deliverable examines how these technologies are currently used in the Path4Med regions, what impacts have been observed, and what socio-economic and institutional factors that influence their adoption or rejection. A cost-benefit analysis is also conducted, alongside an assessment of barriers and enablers for uptake.

Demographic growth, economic activity, and climate change are increasing both seasonal and perennial water scarcity in the EU. A substantial part of the territory is already affected by water abstraction exceeding available supplies, and current trends indicate increasing water stress. Agriculture, which is highly dependent on water availability, plays a significant role in this context. While irrigation shields farmers from irregular rainfall and enhances crop yield and quality, it also represents a considerable drain on water resources. In 2016, only about 6% of EU farmland was irrigated, yet the sector accounted for 24% of all water abstraction.

Recognizing these challenges, the Water Framework Directive (WFD), introduced in 2000, set ambitious targets for achieving "good" quantitative status for all groundwater bodies by 2027. While improvements have been observed across most Member States, in 2015, around 9% of groundwater in the EU remained in "poor" quantitative status. The European Commission has assessed the WFD as largely fit for purpose but highlighted significant delays in achieving sustainable outcomes.

In parallel, soil degradation—caused by erosion, nutrient loss, and chemical contamination—continues to threaten agricultural productivity and water quality. Poor soil health can exacerbate runoff and pollution, making integrated soil and water management critical for sustainable outcomes.

The deliverable categorizes technologies such as GIS and Remote Sensing, IoT-based systems, soil sensors, precision irrigation tools, and soil conservation techniques. These

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technologies are evaluated for their specific purposes and Technology Readiness Levels (TRLs). In addition, the document identifies barriers to adoption and offers actionable recommendations to foster effective water and soil management practices.

It also emphasizes the tight interdependencies between water use and soil health, advocating for an integrated approach that combines technological innovation with ecosystem-based strategies.

In this context, the Common Agricultural Policy (CAP) has the potential to incentivize sustainable agriculture by linking payments to environmental standards. Current and future CAP policies embed sustainability objectives, supporting practices such as water retention measures and investments in new irrigation technologies,as well as soil-friendly practices like cover cropping, reduced tillage, and nutrient management, which influence agricultural water use in different ways.

This deliverable also provides key baseline data and analytical insights that directly support the goals of Work Package 5 (demonstration co-design and implementation) and Work Package 6 (environmental and socio-economic impact assessment) of the Path4Med project.

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2. Introduction

Path4Med (Demonstrating Innovative Pathways Addressing Water and Soil Pollution in the Mediterranean Agro-Hydro System) is a Horizon Europe project that aims to co-develop, demonstrate, and scale integrated solutions for reducing soil and water pollution in rural catchments across the Mediterranean. The project supports the goals of the EU Mission "A Soil Deal for Europe" and the Water Framework Directive (WFD) by identifying nature-based, digital, and agronomic innovations that can restore soil health, improve water quality, and enhance the resilience of agroecosystems. Through multi-actor engagement, demonstration activities, and scenario-based planning, Path4Med works to ensure that promising technologies and practices are effectively tailored and adopted in context-specific ways.

Water and soil are among the most crucial components of sustainable agriculture, significantly influencing the industry, the natural environment, and the needs of other resource users. The catchment area, defined as the land from which all surface water flows into a specific body of water, such as a river, plays a pivotal role in any water supply system. This area not only serves as the source of water and sediment flow but also provides a variety of essential services, including freshwater supply, habitat for biodiversity, flood control, flow regulation, and cultural benefits (Pant et al., 2018; NHMRC, 2017). The quality of water from a catchment is heavily influenced by its natural characteristics, soil conditions, land use practices, the effectiveness of water and soil quality protection systems, and overall environmental conditions (Almaarofi et al., 2017). Crucially, the health of soils within these catchments underpins their capacity to deliver these ecosystem services, as soil degradation directly affects water infiltration, quality, and storage, thereby influencing the overall resilience of catchment systems (European Commission, 2024; Lehmann et al., 2020). Furthermore, conflict and warfare in regions such as Ukraine have intensified soil degradation and disrupted soil and water management, exacerbating risks to catchment health and necessitating urgent policy and technological responses (European Commission, 2024).

The health of a catchment directly affects all systems reliant on its resources (Charrière & Aumond, 2016). Facing the challenge of producing nearly 50% more food by 2030 and

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doubling output by 2050, it becomes imperative for farmers to enhance water-use efficiency and management. Agriculture currently accounts for over 40% of global water withdrawals (OECD, 1998), necessitating innovative approaches to meet growing demands amidst rising urbanization, industrialization, and climate change. Achieving this will likely require the implementation of technologies that sustain catchment areas and build resilience against anomalies.

Technologies that support the principle of "measure it to manage it," such as advanced water meters (Tom et al., 2011; Liu & Mukheibir, 2018), sustainable building materials, treatment technologies, and smart monitoring devices, are essential for effective catchment management (Gould, 1995; Malaeb & Ayoub, 2011; Abioye et al., 2022). This includes tools that monitor not only water parameters but also soil moisture, nutrient levels, and erosion risk (Mulla, 2013; Brevik et al., 2015).

With water scarcity, soil degradation, and pollution presenting significant challenges for sustainable development, effective baseline assessments of water quality and quantity are essential. Agriculture, as the largest user of freshwater resources, not only depends on water for crop and livestock production but also contributes to water pollution, impacting ecosystems and human health. To address these issues, robust monitoring technologies are necessary to understand the current state of water resources, enabling more informed management strategies that align with FAO's emphasis on sustainable water use and pollution mitigation.

Advanced monitoring technologies, such as IoT-enabled sensors, offer real-time tracking of water parameters, while biosensors and DNA- and RNA-based indicators are crucial for baseline assessments, helping to identify specific pollutants and assess biological health. Earth Observation, integrated with AI systems, provides a large-scale perspective on water dynamics, addressing both water quantity and quality. Cloud platforms enable data sharing and collaboration, facilitating a more cohesive approach to integrated water resources management. Together, these technologies support sustainable production by enhancing our understanding of water quality risks, providing a basis for safe water reuse, and supporting the transition toward a more circular water management system, as advocated by FAO.

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The assessment of baseline water quality, quantity, and monitoring technologies in this deliverable is conducted within the framework of existing EU water policies. The Water Framework Directive (WFD) (2000/60/EC) provides the regulatory foundation for water protection and monitoring across Europe, setting ecological and chemical water quality standards. The technologies examined align with WFD objectives by enhancing water monitoring, pollution control, and sustainable resource management.

This deliverable aims to document addressing water and soil pollution and map technologies based on function, assessing their TRLs, and providing a baseline assessment of water and soil quality, quantity and monitoring systems. It evaluates current water, fertilizer and pesticide requirements and conducts a cost benefit analysis of relevant technologies. Additionally, it identifies factors influencing the adoption or non-adoption of these solutions. The focus is on pollution reduction, water conservation, and soil management technologies relevant particularly in rural catchment areas.

This deliverable contributes essential knowledge to guide the next phases of the Path4Med project. It supports WP3 in validating and demonstrating monitoring technologies; WP4 in building context-specific scenarios and assessing transition pathways; and WP5 in co-designing and implementing demonstrations with local stakeholders. Within WP2, it also informs Task 2.2 on policy and institutional coherence and provides critical inputs for Task 2.6, which focuses on impact assessment across environmental, economic, and social dimensions. By providing baseline data, adoption factors, and preliminary cost-benefit insights, this deliverable strengthens the project’s capacity to evaluate and compare the effectiveness of different technological and management solutions across sites and scales.

2.2 Background:

The **Baseline assessment of water and soil quality, quantity, and monitoring** technologies (Task 2.1) aims to provide a comprehensive understanding of the current state of water and soil resources, agricultural practices, and related technologies in Mediterranean agro-hydro systems. This task involves gathering baseline data on water and soil conditions, as well as reviewing current monitoring practices currently in place, as

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described in the **Methodology** (Section 3) and **Categorization and Analysis of Technologies** (Section 4).

In addition to assessing current water and soil conditions, the task reviews the technologies and practices in use across the project's regions, and examines requirements for water, fertilizers, and pesticides. These agricultural input dimensions are further explored in Section 6.

A preliminary Cost-Benefit and Environmental Impact Analysis (Section 7) supports this task by exploring the feasibility and expected impacts of selected technologies. Further details on the data sources, structure, and limitations of the analysis are provided in Section 3 (Methodology). In addition, this task examines barriers and enablers of adoption, such as technical complexity, financial viability, institutional readiness, and stakeholder behavior (Section 5). These insights help clarify the conditions under which promising technologies may succeed or struggle in different contexts.

Task 2.1 is closely connected to other work packages in the Path4Med project. It supports efforts in policy and institutional analysis, impact assessment, technology validation, scenario development, and demonstration design. These linkages are described in more detail in the Introduction.

2.3 Keywords:

The following keywords reflect the main thematic areas, methods, technologies, and policy frameworks addressed in this deliverable. They support internal alignment across work packages and can assist in external indexing, stakeholder communication, and future dissemination activities.

Keywords:

soil and water management, diffuse pollution reduction, monitoring innovations, catchment management, smart water systems, remote sensing for water management, precision agriculture for water, sustainable irrigation technologies, soil pollution control, nutrient leaching prevention, sustainable irrigation practices, diffuse pollution reduction, soil erosion prevention, runoff management, sediment control, water-soil pollution linkage, and agro-hydro system management combined with terms related to impacts

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sustainable agriculture, improved water quality, reduced pollution loads, enhanced soil health, climate resilience, Mediterranean farming systems, agro-environmental technologies, improve water quality, enhance water use efficiency, minimize nutrient leaching, control agricultural runoff, soil erosion prevention, sustainable water management.

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3. Methodology

This deliverable is based on a combination of primary and secondary data sources. Primary data were collected directly from project partners through structured Excel templates and a consortium-wide questionnaire, capturing current practices, cost and benefit estimates, and adoption conditions for a range of technologies used in Mediterranean agro-hydro systems. The Excel templates contained detailed information on technologies and practices implemented across different regions, including digital and nature-based monitoring approaches as well as current requirements for water, fertilizers, and pesticides in agricultural systems. Secondary data were obtained through a targeted literature review that identified relevant technologies and practices from past and ongoing projects at European and international levels. These input-related aspects are further elaborated in the Fertilizer and Pesticide Use Data section (Section 6), which links agricultural practices to pollution pressures.

3.1. Literature review and technology mapping

The initial list of baseline technologies was developed through a comprehensive approach combining both partner driven review and a formal literature review. Partners contribute insights and data based on their direct experience with technologies implemented in past and ongoing projects, ensuring practical relevance and up to date knowledge. Simultaneously, a systematic literature review was conducted (D2.1a) to capture a broad spectrum of innovations, emerging solutions and scientific findings documented in academic and technical sources. This dual approach provides a robust and well- rounded foundation for mapping current technologies relevant to the project's scope.

3.2. Partner-submitted Technology Templates

In parallel, project partners submitted structured Excel templates documenting the technologies they have developed, implemented, or plan to use across demonstration sites. These templates captured:

- PARTNERS COUNTRY
- EXPERTISE CATEGORY

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- SUBTEAM
- SPECIFIC ROLE/CONTRIBUTION
- TYPE OF ORGANIZATION
- RELEVANT TECHNOLOGIES/METHODS
- SOLUTIONS DESCRIPTION
- APPLICATION AREA
- TRL
- PROJECT/SOURCE
- OUTCOMES/RESULTS
- CHALLENGES

These data helped characterize how technologies are currently applied across diverse agro-hydro contexts and informed the cross-cutting analysis of agricultural practices, resource needs, and monitoring capabilities across Path4Med regions. A copy of the Excel template used for this data collection is provided in Annex I.

3.3. Questionnaire-Based Cost-Benefit and Environmental Impact Analysis

To complement the inventory, a structured questionnaire was distributed to all partners. A total of 29 questionnaires were completed by 13 organizations, representing a wide range of technologies and practices at different stages of deployment. The questionnaire collected information on:

- Technology classification and description
- Technology name and organization responsible
- Technology Readiness Level (TRL) and implementation status
- Main cost factors
- Expected economic benefits
- Estimated Return on Investment (ROI) period
- Environmental benefits
- Environmental risks or limitations
- Barriers to adoption
- Additional comments and qualitative feedback

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Responses were submitted in a predefined format with multiple-choice and open-text fields. While some quantitative estimates were provided, particularly ROI, most environmental assessments were qualitative. Benefits and risks were identified through partner judgment and categorization rather than monetization modeling. This reflects the early-stage deployment of many technologies and the challenges of performing life-cycle or valuation studies in the current phase.

The full version of the question can be found in Annex Y.

3.4. Data Analysis

Technology data from the partner-driven review and Excel templates were categorized by function, purpose, and Technology Readiness Level (TRL) to identify patterns relevant to Mediterranean agro-hydro contexts. This classification provided a descriptive overview of technology types, monitoring approaches, and their implementation status.

Questionnaire responses were analyzed using a combination of semi-quantitative and qualitative methods. Closed-ended responses were aggregated to show the frequency of reported cost categories, environmental benefits and risks, and adoption barriers were reported. Results are presented in tables and charts in Section 7. Open-ended responses were reviewed to extract illustrative examples and context-specific insights. No formal scoring or statistical modeling was applied.

This analysis provides early signals on feasibility and adoption potential, as well as gaps in available data. A more robust impact assessment will be conducted under Task 2.6, using evidence from demonstration activities and stakeholder engagement.

From the set of technologies identified through partner contributions and previous project experience, a preliminary categorization and analysis was carried out to assess their relevance for addressing water and soil challenges in Mediterranean agro-hydro systems. The selection was informed by criteria such as efficiency, cost-effectiveness, Technology Readiness Level (TRL), applicability to different catchment areas or regions, environmental impact, and data accuracy, particularly for sensor technologies such as IoT and biosensors. Particular attention was given to data-driven and scalable

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technologies such as IoT sensors, biosensors, and Earth Observation tools. This is due to their potential to support real-time monitoring and adaptive management strategies.

The assessment primarily applied qualitative and semi-quantitative methods, drawing on partner responses, documentation, and context-specific knowledge. While no formal scoring or ranking model was used, the process aimed to highlight technologies with the greatest potential for supporting Path4Med's goals related to monitoring, pollution reduction, water conservation, and soil health improvement. The results of this categorization are presented in the subsections that follow.

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4. Categorization and Analysis of Technologies

Technologies are grouped by their specific functions and contributions to water and soil management objectives. This functional categorization enables a systematic analysis of their roles in sustainable water use, pollution reduction, and climate resilience across Mediterranean agro-hydro systems. Table 4.1. presents the main functional categories and associated tools, methods, or strategies.

Table 4.1: Categorization of Technologies

Approaches and Strategies	Tools / Solutions / Methods
Monitoring and Assessment	Geographic Information Systems (GIS) and Remote Sensing (RS), Artificial Intelligence for Metering, DNA/RNA monitoring indices, soil sensors, Water quality and quantity sensors, Hydrological and water quality monitoring and assessment, Hydrometeorological monitoring and assessment (eg establishment of meteorological stations, dynamic estimation of evapotranspiration, etc), Classical water quality indicators (based on WFD), WFD indicators: priority substances and substances of emerging concern
Water Conservation and Management	Drip Irrigation Technology, Irrigation Management Mobile Apps, Rainwater Catchment Systems
Pollution Reduction	Nanotechnology, Reverse Osmosis (RO) Technology, Buffer strips (NbS), Treatment wetland (NbS), Biofilters (sand, woodchips)
Sustainable Infrastructure	Greening of Water Infrastructure
Climate Adaptation and Resilience-Building	GIS and RS (Climate Adaptation)
Public Engagement and Behavioral Change	AI-based Gamification in Water Metering

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4.1. Monitoring and Assessment Tools

These technologies are essential for understanding soil and water dynamics, enabling early detection of degradation and pollution. Key tools include:

- **Geographic Information Systems (GIS) and Remote Sensing (RS):** GIS and RS technologies are used to model land cover, climate, and water changes, forecast hazards, monitor pollution sources, and support erosion risk assessment for resilient catchment management.
- **Artificial Intelligence (AI) for Metering, Measuring, and Managing:** AI-powered digital meters provide real-time water use monitoring and data transmission for efficient management. Machine learning detects anomalies like leaks and predicts water quality status cost-effectively, while AI and data analytics optimize water demand and usage, promoting water-conscious behaviors across user profiles.

- **DNA/RNA monitoring indices:** DNA and RNA monitoring indices use molecular methods to assess biodiversity, detect pollution, evaluate soil and water health, and provide early warnings for pathogens or invasive species, enabling proactive environmental management.
- **Soil Sensors:** Soil sensors measure parameters like soil moisture and relay this information to automated irrigation systems, ensuring crops receive the optimal amount of water without waste.

- **Hydrological and water quality monitoring and assessment:** Monitoring water resources allows for the evaluation of their availability for both human and environmental needs, contributing to the optimization of water management and the reduction of environmental impacts.
- **Hydrometeorological monitoring and assessment (e.g. establishment of meteorological stations, dynamic estimation of evapotranspiration, etc):** This

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involves the collection and analysis of both hydrological and meteorological data to understand the interactions between water and weather systems. This includes the establishment of meteorological stations to measure variables like temperature, precipitation, wind, and humidity, which are essential for predicting weather patterns, providing valuable insights for water resource management, agricultural planning, and environmental monitoring.

- **Classical water quality indicators (based on WFD):** Classical water quality indicators, as defined by the Water Framework Directive (WFD), assess the ecological health of water bodies using biological, chemical, and hydromorphological parameters. Biological indicators, such as fish populations and macroinvertebrates, reflect the ecosystem's health. Chemical indicators, including nutrients and contaminants, help monitor pollution levels, while hydromorphological indicators evaluate physical characteristics like river morphology and flow patterns. Together, these indicators provide a comprehensive understanding of water quality, guiding effective management and protection of aquatic ecosystems.
- **WFD indicators: priority substances and substances of emerging concern:** The WFD indicators assess the ecological status of water by evaluating the degree of deviation from natural conditions, with a primary focus on biological quality indicators.

4.2. Water Conservation and Management

These technologies aim to improve the efficiency of water use in agriculture, one of the largest water-consuming sectors in Mediterranean regions. By reducing waste and matching water delivery to crop needs, they directly address water scarcity and improve drought resilience. Many also support co-benefits such as energy savings and reduced nutrient leaching. Technologies include:

- **Drip Irrigation Technology:** Drip irrigation efficiently delivers water to plant roots, reducing water use by 30–70% and boosting crop yields while conserving water and energy, making it ideal for mixed farming systems.

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- **Irrigation Management Mobile Apps:** Mobile apps allow farmers to remotely monitor and adjust irrigation systems based on real-time data, weather conditions, and crop needs. This helps optimize water use while maintaining crop yields.
- **Rainwater Catchment Systems:** Properly designed rainwater catchment systems can provide clean water for drinking, agriculture, and livestock by using hygienic, nontoxic materials.

4.3. Pollution Reduction and Treatment Solutions

This category includes technologies designed to prevent, intercept, or treat pollutants before they enter water bodies or degrade soil health. It includes both engineered and nature-based approaches aimed at nutrient capture, filtration, and restoration of water quality in agricultural landscapes. Technologies include:

- **Nanotechnology:** Nanotechnology, including silver nanoparticle-coated filters, is vital for removing bacteria, pesticides, and pollutants from water, enhancing filtration and desalination processes in catchment areas.
- **Reverse Osmosis (RO) Technology:** RO technology is used for desalination by removing over 95% of dissolved salts through a semipermeable membrane, making saline water suitable for agricultural and domestic use.
- **Nature-Based Solutions (NbS):**
    - **Buffer strips (NbS):** Buffer strips are vegetated areas (grasses, shrubs, or trees) planted between agricultural land and water bodies. They serve as natural filters, trapping sediment, nutrients (especially nitrogen and phosphorus) and pesticides before they enter watercourses. Buffer strips also reduce erosion, enhance biodiversity, and provide habitat corridors. As a low-cost, low-maintenance NbS, they are highly effective in mixed and sloped farming systems and are increasingly integrated into agri-environmental schemes across Europe.
    - **Treatment wetland (NbS):** Constructed or restored wetlands are engineered to mimic natural wetlands' ability to treat wastewater and runoff. They use plants, soils, and associated microbial communities to

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degrade pollutants, absorb nutrients, and trap sediments. These systems are particularly effective for removing nitrogen, phosphorus, pathogens, and even some emerging pollutants. Treatment wetlands are scalable and adaptable, making them suitable for rural catchments, agricultural drainage, and livestock runoff management.

  - **Biofilters (sand, woodchips):** Biofilters are passive treatment systems that filter water through layers of media such as sand, woodchips, or compost. As water passes through, physical filtration, microbial activity, and chemical processes remove nutrients and contaminants. Woodchip biofilters, in particular, support denitrification, converting nitrates to nitrogen gas. These filters are used at field edges, drainage outlets, and livestock yards to intercept and treat runoff before it reaches natural water bodies.

4.4. Sustainable Infrastructure and Climate Resilience

This group of technologies supports longer-term resilience and sustainability of agro-hydro systems, particularly in the face of climate variability, floods, and land degradation. They include green infrastructure that stabilizes catchments and GIS-based tools that enable landscape-level planning and forecasting. Technologies include:

- **Greening of Water Infrastructure:** Green infrastructure (e.g., vegetation buffers) helps to reduce storm runoff, lower evaporation rates, stabilize catchment banks, and filter pollutants, contributing to carbon neutrality and catchment sustainability.
- **GIS and RS (Climate Adaptation):** These tools provide valuable data on climate patterns and landscape changes, aiding in disaster preparedness and resilience against floods and other natural hazards.

4.5. Engagement and Behavioral Change Tools

Technical solutions alone are not sufficient for transformation. This category includes social innovations designed to influence behavior and encourage more sustainable water

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use. These tools are increasingly important in closing the loop between monitoring, awareness, and practice change. Technology included:

- **AI-based Gamification in Water Metering:** AI-driven gamification strategies encourage users to compete in reducing water consumption, fostering responsible water use and awareness of water conservation.

4.6. Modeling Tools

Modeling tools provide a systems perspective and are essential for scenario analysis, planning, and tracking of pollution reduction outcomes. In Path4Med, these tools also support demonstration planning and help quantify the potential impacts of alternative land and water management strategies. Key tool:

- **QSWAT (Quantum Soil and Water Assessment Tool)** for hydrological and water quality monitoring requires multiple datasets to effectively model hydrological and water quality processes. The key data inputs include: a) **Digital Elevation Model (DEM):** Used for watershed delineation and streamflow modeling. b)**Land Use and Land Cover (LULC) Data:** Helps define hydrological response units (HRUs) and simulate land-water interactions., c) **Soil Data:** Essential for defining infiltration rates, soil erosion potential, and water retention characteristics., d) **Climate Data:** Includes temperature, precipitation, humidity and wind speed, influencing evapotranspiration and water balance. d) **Stream Network Data:** Necessary for routing water flow and simulating hydrological processes. e) **Water Quality Data:** Provides insight into pollution sources, sediment transport, and nutrient loading. f) **Observed Streamflow Data:** Used for calibration and validation of hydrological models. g) **Reservoirs, Ponds, and Wetlands Data:** Helps model water retention, storage, and flood mitigation efforts.

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Table 4. 2: Required data for QSWAT simulations

Required Data	Purpose	Source
Digital Elevation Model (DEM)	Watershed delineation, flow direction modeling	Copernicus DEM
Land Use and Land Cover (LULC) Data	HRU classification	ESA CCI Land Cover, CORINE, MODIS
Soil Data	Define soil properties	FAO HWSD, SoilGrids
Climate Data	Temperature, precipitation, humidity, wind	ERA5, National Meteorological Agencies, Local meteo stations
Stream Network Data	Hydrological modeling	HydroSHEDS, Local Authorities
Water Quality Data	Pollution monitoring	National Environmental Agencies, UNEP GEMStat
Observed Streamflow Data	Model calibration and validation	River Gauge Stations, National Hydrological Services
Reservoirs, Ponds, Wetlands Data	Water storage and retention modeling	National Hydrological Maps

The categorization presented in this section highlights the diverse range of technologies available for addressing soil and water challenges in Mediterranean agro-hydro systems. These technologies differ in function, complexity, and readiness, but all contribute to key Path4Med objectives such as pollution reduction, improved monitoring, water conservation, and climate resilience. Many combine digital tools with nature-based approaches, while others focus on real-time data collection or support scenario modeling for long-term planning.

To ensure effective implementation, it is important to assess how these technologies perform under different conditions and how they can be integrated into broader decision-support systems like QSWAT. The next section presents specific evaluation criteria used for monitoring and modeling tools, with a focus on Earth Observation data integration. This provides a basis for the subsequent analysis of input requirements, economic and environmental impacts, and adoption barriers in Sections 6 through 8.

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5. Criteria for Water & Soil Technologies

To guide decision-making about technology selection, integration, and demonstration across Path4Med regions, it is important to establish a clear set of evaluation criteria. These criteria help assess not only the technical performance of innovations, but also their environmental contributions, cost-effectiveness, social acceptance, and policy alignment.

While much of the detailed cost-benefit and environmental analysis is presented in Section 7, this section outlines the criteria used to evaluate specific technologies, particularly those used in monitoring and modeling. These criteria are informed by partner experiences and data collected through the consortium questionnaire.

5.1 Evaluation criteria for Earth Observation Data and QSWAT Integration

The integration of Earth Observation (EO) data from the Copernicus program provides valuable insights for monitoring water quality, land use changes, and soil conditions. This data-driven approach enhances QSWAT-based modeling and supports decision-making in alignment with Water Framework Directive (WFD) indicators. The key criteria for leveraging Copernicus EO data include:

5.1.1. Data Availability and Accessibility:

- **Sentinel-2**: Provides high-resolution imagery for land cover classification, vegetation health assessment, and monitoring agricultural practices affecting water bodies.
- **Sentinel-1**: Utilizes radar technology for soil moisture assessment and flood monitoring, ensuring continuous data availability under all weather conditions.
- **Sentinel-3**: Supports water quality modeling through analysis of water surface temperature, chlorophyll concentration, and turbidity.

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5.1.2. Spatial and Temporal Resolution:

- **High-resolution data (10m–30m) from Sentinel-2** enables precise land cover and vegetation analysis.
- **Frequent revisit times (5–10 days)** facilitate near-real-time monitoring of water quality and soil conditions.
- **Sentinel-1's radar capabilities** ensure uninterrupted soil moisture monitoring, crucial for hydrological modeling and flood risk assessment.

5.1.3. Integration with Hydrological Models:

- **QSWAT can integrate Copernicus Digital Elevation Model (DEM) data** from the Copernicus Land Monitoring Service (CLMS) to improve watershed delineation accuracy.
- **Soil properties data from Copernicus Global Land Service** can refine soil erosion and infiltration models, enhancing predictions of water retention and runoff.
- **Sentinel-3 OLCI (Ocean and Land Colour Instrument) provides key water quality indicators**, such as chlorophyll-a, total suspended matter (TSM), and dissolved organic matter (DOM), which are essential for pollutant transport modeling.

By incorporating Copernicus EO data into QSWAT modeling, we can significantly improve the accuracy of water and soil management technologies. This ensures compliance with WFD directives and strengthens decision-support mechanisms for sustainable water resource management. These evaluation criteria have been developed based on insights

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gathered from partner questionnaires, ensuring a practical and evidence-based approach to technology assessment.

https://www.researchgate.net/figure/Evaluation-criteria-for-volumetric-soil-water-

Table 5.1.3: Evaluation criteria for volumetric soil water monitoring methods

	Neutron Moderation	TDR	FD (Capacitance and FDR)	ADR	Phase Transmission	TDT
Reading range	0-0.60 ft^3ft^{-3}	0.05-0.50 ft^3ft^{-3} or 0.05-Saturation (with soil specific calibration)	0-Saturation	0-Saturation	0.05-0.50 ft^3ft^{-3}	0.05-0.50 ft^3ft^{-3} or 0-0.70 ft^3ft^{-3} Depending on instrument
Accuracy (with soil-specific calibration)	±0.005 ft^3ft^{-3}	±0.01 ft^3ft^{-3}	±0.01 ft^3ft^{-3}	±0.01-0.05 ft^3ft^{-3}	±0.01 ft^3ft^{-3}	±0.05 ft^3ft^{-3}
Measurement volume	Sphere (6-16 in. radius)	about 1.2 in. radius around length of waveguides	Sphere (about 1.6 in. effective radius)	Cylinder (about 1.2 in.)	Cylinder (4-5 gallons)	Cylinder (0.2-1.6 gallons) of 2 in. radius
Installation method	Access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ* or PVC access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ*	Permanently buried *in situ*
Logging capability	No	Depending on instrument	Yes	Yes	Yes	Yes
Affected by salinity	No	High levels	Minimal	No	>3 dS/m	At high levels
Soil types not recommended	None	Organic, dense, salt or high clay soils	None	None	None	Organic, dense, salt or high clay soils (depending on instrument)
Field maintenance	No	No	No	No	No	No
Safety hazard	Yes	No	No	No	No	No
Application	Irrigation, Research, Consultants	Irrigation, Research, Consultants	Irrigation, Research	Irrigation, Research	Irrigation	Irrigation
Cost (includes reader/ logger/ interface if required)	$10,000-15,000	$400-23,000	$100-3,500	$500-700	$200-400	$400-1,300

monitoring-methods_tbl1_238619241

5.2. Broader Evaluation Criteria for All Technologies

While Section 5.1 focuses on modeling inputs, other technologies evaluated across the project (e.g. IoT sensors, precision irrigation systems, nature-based solutions) require a broader set of criteria to guide their prioritization, upscaling, or integration into demonstration activities.

The criteria summarized below reflect those implicitly used in the analysis of adoption barriers, costs, and environmental performance in Section 7. These dimensions will be further refined in collaboration with Task 2.6, WP5 and WP6 to support site-specific decision-making and impact assessment.

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The following table summarizes the main evaluation dimensions relevant for comparing water and soil management technologies across diverse agro-hydro contexts. It draws from insights gathered through partner questionnaires (Section 7), methodological references (Section 3), and practices used in similar EU research projects. These criteria can support multi-criteria assessments for demonstration planning and will be further refined through collaboration with WP5 and WP6.

Table 5.2. Preliminary Evaluation Criteria for Water and Soil Technologies

Criteria Category	Description
Functionality	Main purpose of the technology (e.g., monitoring, treatment, conservation)
Technology Readiness Level (TRL)	Current maturity and deployment stage
Cost Considerations	Initial investment, operation and maintenance, training, and software costs
Environmental Benefits	Pollution reduction, biodiversity enhancement, water savings, GHG mitigation
Environmental Risks	Energy intensity, secondary pollution, dependence on local condition
Economic Benefits	
Adoption Potential	
Implementation Stage	

These criteria are intended as a practical framework to support the selection, demonstration, and eventual upscaling of technologies across Path4Med demonstration sites. The next section explores fertilizer and pesticide use data to further inform baseline input pressures and opportunities for pollution mitigation.

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6. Fertilizer and Pesticide Use Data

6.1 Introduction

Agriculture is a primary driver of water pollution, particularly through the excessive use of fertilizers and pesticides. While these chemicals help boost crop yield and protect crops from pests, their overuse poses significant risks to water quality. The leaching of fertilizers and the runoff of pesticides into water bodies lead to contamination, resulting in adverse effects on both aquatic ecosystems and human health.

To tackle these challenges, it is essential to examine current practices in fertilizer and pesticide use, explore best practices and innovations aimed at reducing their environmental impact, and highlight the relationship between these agricultural inputs and water quality and quantity.

As outlined in **Section 4**, several technologies and approaches directly contribute to reducing chemical input dependency while maintaining productivity. These include:

– Biochar application, which improves nutrient retention and reduces fertilizer runoff
– Cover crops, which stabilize soils, fix nitrogen, and reduce pesticide needs
– New-type fertilizers and slow-release formulations, which increase nutrient efficiency
– Reuse of treated sludge, offering a circular solution to nutrient recycling
– Model-based irrigation tools and soil sensors, which optimize irrigation and reduce nutrient loss through precision water management

In addition to these technologies, Nature-based Solutions (NbS), such as buffer strips and treatment wetlands, also play a significant role in capturing and filtering nutrients and agrochemicals before they reach water bodies (**Section 4.3**).

In the context of the Path4Med project, understanding fertilizer and pesticide use is critical for targeting interventions that reduce diffuse pollution. Several technologies identified by partners—such as biochar application, model-based irrigation, cover crops, and decision-support tools—specifically aim to improve nutrient efficiency and reduce chemical input use. While this section presents global patterns and best practices, site-specific input data collected through the partner Excel templates will be further analyzed

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in coordination with WP5 to establish local baselines. These data are also highly relevant for WP6, which will assess environmental improvements associated with input reduction and improved management practices.

To complement the technological overview, site-specific data on fertilizer and pesticide use have been collected via Excel templates from project partners. These data will be further analyzed in coordination with WP5 to establish input-use baselines at each demonstration site. This localized data will be crucial for identifying areas with high input loads and informing the design of site-tailored pollution reduction strategies.

Furthermore, the collected data will directly support the cost-benefit and environmental impact analysis described in Section 7. By linking input use to economic outcomes and environmental benefits—such as improved water quality or reduced runoff—WP6 can quantify expected pollution reductions, assess resource efficiency, and estimate long-term sustainability gains. These findings will contribute to the evaluation of scalable, cost-effective solutions that balance agricultural productivity with environmental protection.

By integrating qualitative insights from partners with site-specific quantitative input data, this section aims to bridge technological potential and local context—strengthening the overall project's capacity to reduce diffuse pollution while maintaining practical feasibility across Mediterranean agro-ecosystems.

6.2 Current Practices

The intensification of agricultural practices in the twentieth century led to significant increases in water pollution, primarily from the heavy use of fertilizers and pesticides. Today, pollution from pesticides and fertilizers is one of the greatest obstacles to maintaining safe water quality.

According to the Food and Agriculture Organization (FAO), nearly 4 million tons of pesticides are used worldwide each year, with China and the United States being the largest contributors, consuming approximately 1.4 million and 0.5 million tons annually, respectively. Global models indicate that agricultural insecticides may be contaminating surface waters in over 40 percent of land areas (Ippolito et al., 2015). In the United States, studies show that 90 percent of sampled water and fish from streams contain traces of

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at least one chemical pesticide (Cassou, 2018). These pesticides, including aldrin, DDT, endosulfan, and other organochlorine insecticides, are classified as persistent organic pollutants (POPs), meaning they do not degrade easily and tend to bioaccumulate in ecosystems, causing long-term ecological harm.

Fertilizers also pose a risk to water quality, especially when applied in excess of plant requirements. This issue is particularly prominent in regions with intensive agricultural activity, such as China and the Americas, where the overuse of fertilizers has led to nutrient pollution in local water bodies, especially with nitrogen and phosphorus. In the United States, the economic cost of eutrophication—an excessive nutrient load in water bodies that leads to algal blooms and oxygen depletion—is estimated at nearly USD 2.2 billion per year (Dodds et al., 2009). Further, cross-country studies have shown that an increase in nitrate levels in water can lead to a substantial rise in health issues, such as a higher rate of stunted growth in children under five and a reduction in adult earnings. This suggests that the health and economic losses from excessive fertilizer use may outweigh the benefits of increased agricultural yields (Damania et al., 2019).

Beyond synthetic pesticides and fertilizers, water quality is also compromised by pollution from livestock and aquaculture. Wastes from these systems releases antibiotics, pharmaceuticals, pathogens, and other pollutants into groundwater, rivers, and coastal waters (Mateo-Sagasta, Marjani Zadeh & Turral, 2017). Many of these substances are classified as "emerging pollutants"—synthetic or natural chemicals and microorganisms not regularly monitored but suspected to have adverse ecological and human health effects (UNESCO, n.d.). These pollutants are often toxic, carcinogenic, and can disrupt endocrine systems. The overuse of antibiotics, in particular, poses the risk of developing antibiotic-resistant microorganisms, a growing global health concern (Miranda, Godoy & Lee, 2018; Schar et al., 2021).

In the Mediterranean context, where agricultural pressures intersect with climate stress and water scarcity, understanding these input-related pollution pathways is essential. Site-specific data collected from Path4Med partners will help quantify fertilizer and pesticide use at demonstration sites and assess their link to diffuse pollution risks. This

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will inform both baseline assessments and the design of appropriate management responses in WP5 and WP6.

6.3 Best Practices and Innovations

To ensure sustainable agricultural practices while safeguarding food security and farmers' income, best practices in pesticide and fertilizer use emphasize efficiency, safety, and environmental protection. The European Commission has highlighted the importance of Integrated Pest Management (IPM) as a key strategy to reduce dependence on chemical pesticides. IPM promotes the use of natural methods wherever possible, reserving chemical control as a last resort.

In 2023, the Commission published a comprehensive IPM toolbox hosted on the JRC's DATAm platform, providing over 1300 examples of techniques and technologies aligned with eight key IPM principles. These include crop rotation, balanced fertilization, pest monitoring, targeted application, and a strong preference for non-chemical control methods. The toolbox also features 273 crop-specific guidelines developed by Member States under the Sustainable Use of pesticides Directive (SUD).

A parallel study underscored that the most successful IPM adoption often coincides with broader environmental goals such as soil conservation, reduction of fertilizer use, and ecosystem services enhancement, including pollinator protection. Despite its potential, barriers such as the lack of affordable alternatives and high initial costs remain. Strategies like collective equipment purchases and contracted services, along with national and EU-level support and dissemination efforts, are considered crucial.

Importantly, the Common Agricultural Policy (CAP) provides strong financial instruments—eco-schemes, rural development funds, and innovation support via EIP-AGRI—to incentivize farmers in adopting integrated practices and reducing synthetic inputs (European Commission, 2023).

Several of the technologies submitted by Path4Med partners reflect these principles in practice, such as biochar application, precision irrigation, and cover cropping, all of which support nutrient efficiency and reduced chemical input use. These approaches

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are explored in greater detail in Section 7, which presents partner-reported technologies and their associated costs, benefits, and adoption factors.

Understanding the environmental and health risks associated with fertilizer and pesticide use underscores the need for targeted, cost-effective, and scalable solutions. Building on the global context and policy frameworks presented in this section, the next section examines how Path4Med partners are addressing these challenges through a range of technologies and practices. Section 7 presents a cost-benefit and environmental impact analysis based on partner-reported data, providing insight into the feasibility, perceived value, and adoption potential of the solutions identified across the project.

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7. Cost-Benefit and Environmental Impact Analysis

7.1 Introduction

Over the past two decades, cost-benefit analysis (CBA) has evolved significantly, particularly in its application to environmental policies and projects. While the core principles of CBA remain consistent, new methodologies have been developed to better capture the complexities of environmental decision-making (Sugden & Williams, 1978; Boardman et al., 2018), including the valuation of nonmarket benefits such as ecosystem services and pollution mitigation. These methods are essential for evaluating pollution control measures, water conservation strategies, and sustainable agricultural practices, which often involve costs and benefits that are not immediately reflected in market transactions.

These approaches are especially relevant when evaluating policies and technologies that address diffuse pollution, resource efficiency, and long-term sustainability (Pearce et al., 2006; Hanley & Barbier, 2009).

In the context of the Path4Med project, CBA is used to assess the economic and environmental performance of technologies and practices submitted by partners to address soil and water quality challenges in Mediterranean agro-hydro systems. This analysis helps identify interventions that offer not only environmental gains but also practical feasibility in terms of investment requirements, potential savings, and scalability. In addition, it supports WP5 in prioritizing solutions for demonstration, and provides inputs to WP6 for assessing expected impacts at the catchment level.

Recent advancements in environmental economics have also introduced new considerations for CBA, particularly in addressing contemporary challenges such as climate change, biodiversity loss, and diffuse pollution (Pearce et al., 2006). A key focus has been on intergenerational and intragenerational equity, ensuring that both present and future generations benefit from sustainable resource management (). Additionally, uncertainty and irreversibility in environmental decision-making have highlighted the need for a precautionary approach, favoring policies that minimize long-term risks (Loomis, 2014).

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Despite its strengths, CBA is not without criticism. Real-world applications often reveal gaps between theoretical optimal policy design and actual policy implementation (Ray, 1984; Londero, 1996). Political economy factors, including regulatory frameworks, stakeholder interests, and institutional constraints, frequently shape policy outcomes in ways that diverge from CBA recommendations (Hanley et al., 2015). Understanding these barriers to adoption and implementation is crucial for enhancing the effectiveness of technologies and innovations in water and soil management.

This deliverable applies CBA principles using structured inputs from Path4Med partners to assess technologies aimed at monitoring water and soil quality, reducing pollution, and enhancing sustainable resource management. While the findings are preliminary and based largely on qualitative assessments, they offer valuable insights to perceived benefits, adoption barriers, and potential for scaling.

7.2 Data Collection and Analysis: Economic Costs and Benefits

7.2.1 Overview of Technology Entries and Key Trends

This section presents a consolidated summary of the technologies and practices submitted by Path4Med partners through the structured questionnaire described in Section 3. A total of 29 entries were received from 13 organizations, representing technologies at various stages of maturity and implementation. These include solutions focused on water quality and quantity monitoring, irrigation optimization, nutrient and pollutant control, nature-based infrastructure, and digital tools.

Across the dataset, several consistent trends were observed:

- Initial investment costs were the most commonly cited financial challenge, followed by maintenance, training, and data/software costs.
- Expected economic benefits included improved productivity, input savings, and market competitiveness.
- Environmental advantages were reported in terms of pollution reduction, enhanced biodiversity, and improved water use efficiency

- Return on Investment (ROI) estimates varied widely: nearly half of the entries marked ROI as “unknown”, highlighting gaps in financial modeling and the early-stage nature of many solutions.

In addition to financial metrics, partners identified barriers to adoption such as lack **of technical expertise**, limited funding, stakeholder resistance, and regulatory complexity. These constraints point to the need for supportive policy environments, targeted capacity-building, and co-designed implementation pathways.

The analysis that follows presents a more detailed breakdown of these trends across categories such as technology types, cost and benefit structures, environmental risks, adoption barriers, and implementation status. While the findings are perception-based and provisional, they serve as a baseline for ongoing refinement during WP5 demonstrations and contribute to WP6’s impact assessment strategy.

7.2.2 Questionnaire: Cost-Benefit and Environmental Impact Analysis of Technologies

This section presents the results of the cost-benefit and environmental impact analysis conducted through the partner questionnaire. The analysis is structured around key dimensions assessed in the survey: (i) technology types and organizational contributions, (ii) cost structures and ROI, (iii) environmental benefits and risks, and (iv) factors influencing adoption and implementation.

The results offer insights into how partners view the feasibility and potential impact of their technologies. These findings will inform WP5 demonstration planning and contribute to baseline understanding for WP6 and Task 2.6.

7.2.2.1. Technology Type

Technologies reported by Path4Med partners were classified by function to identify prevailing approaches to addressing water and soil quality challenges in Mediterranean agro-hydro systems. Each entry could be assigned to multiple categories. This classification informs WP4 (scenario development) and WP5 (demonstration planning) by highlighting dominant solution areas and gaps.

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Table 7.2.2.1.1: Technology Type

Technology Type	No of Entries	Organizations (examples)
Water Quality Monitoring	**9**	AUA, NUBiP, AU, ISA, CU, NIBIO, GAL, MARDE
Water Quantity Monitoring	8	IPV, CU, ISA, GAL, HCMR, AU
Irrigation Management	**9**	AUA, NIBIO, CIHEAM, CU, AGTIV
Pollution Control	**12**	AUA, NIBIO, AU, CIHEAM, IPV, CU, GAL, AGTIV
Remote Sensing & GIS	**8**	AUA, NUBiP, IPV, HCMR, ISA, GAL, MARDE
Other	**13**	AUA (e.g., Nutrients management, irrigation water and nutrient sources, erosion control, fertility nutrients management, soil health monitoring DNA/RNA), NIBIO (Natural water retention measures), CIHEAM(assess the impacts of technologies and development scenarios), EXEO(physical and mechanical characteristics of the soil: strength, nature of the soil, permeability), AGTIV: Soil - Water - Plant interface indicators measurement and monitoring

Key insight: Most technologies contribute to pollution control, followed by tools for monitoring and irrigation efficiency. The "Other" category includes innovations related to soil fertility, erosion control, and system modeling, reinforcing the integrated nature of many solutions.

Table 7.2.2.1.2: Technology Name

Organization	No of Entries	Notable Technologies
AUA	12	Soil health monitoring with earth observation and ML, IoT sensors based, Precision Irrigation Management, Model based Precision Irrigation Management, Earth observation supporting water and nutrients management, Spatial explicit information services, Treated wastewater and sludge reuse in agriculture, Riparian buffer strips, New-type fertilizers, soil improver and bio-stimulant technologies,

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		Biochar application, Nutrients leaching monitoring, Cover crops, soil health monitoring with DNA and RNA markers
NUBiP	1	GIS & WQ indicators
AU	3	Micropollutants, RNA/DNA indicators, Treatment wetland for treating agricultural water runoff
GAL	**2**	automatic water monitoring stations/ **MHAS - SMART**
ISA	3	soil unsaturated zone monitoring, Ground water monitoring and Estimation of ground water withdrawals for irrigation using remote sensing
Others*	**1 each**	CIHEAM (bioeconomic tool), AGTIV (field-based monitoring, EXEO (soil geology), MARDE (organic amendments), NIBIO (Remote sensing), IPV (Automatic water monitoring), CU (Automatic water monitoring), HCMR (automatic water monitoring)

7.2.2.1.a Analysis of Technology Types (Table 7.2.2.1.1)

Based on the responses collected through the questionnaire's multiple-choice format, a total of **55** technology type entries were identified across the six categories provided. These entries reflect the multidimensional nature of many solutions, as one technology may fall under multiple categories.

- Pollution Control topped the list with **12** entries, underlining the importance of solutions aimed at reducing nutrient runoff, contaminants, and other pollutants. Technologies in this category include nature-based solutions like treatment wetlands, riparian buffer strips, and the application of biochar.
- Water Quantity Monitoring followed closely with 8 entries, emphasizing the adoption of hydrological sensors, remote sensing for groundwater monitoring, and automated station setups for real-time tracking.
- Irrigation Management also recorded **9** entries, featuring precision irrigation tools, IoT-based systems, and decision support solutions that optimize water use in agriculture.

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- Water Quality Monitoring was represented with **9** entries, reflecting the use of both traditional sensors and advanced bio-indicators (e.g., DNA/RNA tools, micropollutant detection).
- Remote Sensing & GIS Applications gathered **8** entries, suggesting their key role in mapping, monitoring, and supporting decision-making through spatial analysis.
- The "Other" category had the highest count with **13** entries, covering a diverse array of innovations including nutrient management, erosion control, soil fertility management, and modeling tools for assessing the impact of different technology adoption scenarios.

This distribution demonstrates a strong focus on pollution mitigation and integrated monitoring, while also showcasing cross-cutting innovations that support sustainable resource management in agriculture.

7.2.2.1.b Analysis of Organizational Contributions (Table 7.2.2.1.2)

The second table breaks down the contributions by each organization, providing insight into their specific technological strengths and areas of expertise.

- Agricultural University of Athens (AUA) stood out as the most prolific contributor, submitting 12 entries spanning a broad range of technologies. Their portfolio included:
  - Monitoring systems (e.g., soil health with DNA/RNA markers, IoT sensors),
  - Precision irrigation (model- and EO-based),
  - Sustainable practices (biochar application, new-type fertilizers, cover crops),
  - Water reuse and spatial decision support. This illustrates AUA's role as a central innovator across multiple domains.
- AU contributed 3 entries, focusing on advanced water quality solutions such as micropollutant detection, RNA/DNA indicators, and treatment wetlands, emphasizing expertise in environmental bio-monitoring.
- ISA submitted 3 entries, specializing in subsurface water monitoring and remote sensing-based estimation of irrigation withdrawals.

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- NUBiP, CIHEAM, CU, IPV, GAL, and HCMR each contributed 1–2 entries, generally focused on specific technologies such as GIS-based water quality monitoring, bioeconomic models, automatic monitoring stations, and geological assessments.
- EXEO provided an entry related to soil geological analysis, representing a physical measurement perspective that complements digital tools.
- AGTIV contributed a portable, in-field agronomic management solution, focusing on monitoring the soil-water-plant interface and providing real-time indicators for resource-efficient management.
- GAL Percorsi also introduced the MHAS-SMART system, a monitoring platform combining hydrological sensors and remote sensing to track multiple environmental parameters critical for sustainable agricultural practices.
- The Agricultural Research Institute offered a nature-based solution (NBS) through the application of organic amendments and slow-release fertilizers, aimed at improving soil health and nutrient management with minimal environmental risks.

This organization-level analysis underscores how different institutions specialize in distinct technology clusters, and when combined, they form a well-rounded technological landscape covering both high-tech and nature-based solutions.

7.2.2.2 Cost Factors

Understanding cost structures is essential for evaluating the feasibility and scalability of soil and water management technologies. Partners were asked to identify the main financial burdens associated with their technologies, including initial investment, operational costs, training needs, and regulatory or data-related expenditures. These insights will inform both the design of WP5 demonstrations and the cost-efficiency analysis in WP6 and Task 2.6.

Table 7.2.2.2.1: cost factors

Cost Factor	Examples of Respondents
Initial Investment	☑ AUA, NUBiP, AU, NIBIO, CIHEAM, IPV, CU, EXEO, GAL, HCMR, ISA, AGTIV, MARDE

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Maintenance & Operational Costs	☑ AUA, AU, NIBIO, IPV, CU, EXEO, ISA, GAL, MARDE
Training & Capacity Building	☑ AUA, NUBiP, AU, NIBIO, GAL, AGTIV, GAL, MARDE
Data Management & Software	☑ AUA, NUBiP, AU, IPV, CIHEAM, ISA, GAL, MARDE
Compliance with Regulations	☑ AUA, NUBiP, NIBIO, ISA
Other	☑ AUA – *data acquisition, loss of profit from non-cultivated area, sampling analysis, standard methodology is missing* ☑ IPV, GAL – *water pollution analysis*
Total No. of Respondents	29

Key Observations

- Initial investment costs were the most frequently cited financial burden, identified by all participating partners, highlighting it as a key barrier to the deployment and scaling of the assessed technologies. **Also reported by AGTIV and reaffirmed by GAL** the trend underscores that initial acquisition remains a critical challenge across the sector.
- Maintenance and operational costs also featured prominently confirming the long-term financial commitments required for sustainable implementation.
- Training and capacity building was emphasized by a subset of partners indicating that human capital development is essential, especially in contexts involving technically demanding solutions.
- Data management and software costs were reported by partners actively involved in digital and sensor-based technologies , pointing to increasing financial strain associated with digitalization and data-driven decision-making in environmental monitoring.
- Regulatory compliance, although acknowledged by several organizations, was less frequently selected compared to direct operational and technical cost categories. Nonetheless, it remains a critical consideration for ensuring that technologies meet legal and procedural standards.

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- Additional cost factors were also identified under the “Other” category. AUA reported issues such as data acquisition expenses, opportunity costs due to non-cultivated buffer areas, and costly sampling and analysis procedures, compounded by the absence of standardized methodologies. IPV and GAL highlighted the costs associated with water pollution analysis. These nuanced insights suggest that beyond the conventional categories, several indirect and often overlooked costs may significantly affect technology adoption and require careful planning in upscaling strategies

These findings highlight the importance of realistic financial modeling in the planning of demonstration activities under WP5. By identifying key cost drivers and economic benefits, the data can help partners prioritize funding needs and explore opportunities for shared infrastructure, training programs, or technical support. The insights are also valuable for policy dialogues in WP2 and WP6, as they shed light on where financial barriers intersect with regulatory and institutional constraints, potentially guiding more effective support mechanisms and enabling conditions for technology adoption.

7.2.2.3. Economic Benefits

Economic benefits play a key role in the long-term adoption and sustainability of innovations. This question aimed to capture financial incentives such as input cost savings, efficiency gains, improved market positioning, and reduced regulatory penalties. The data gathered supports the techno-economic evaluation in WP6, feeds into scenario building in WP4, and helps prioritize demonstration activities under WP5.

Table 7.2.2.3.1: Economic Benefits

Economic Benefit	Partners Who Selected It
Cost Savings in Resource Use	AUA, NIBIO, IPV, CU, ISA, AGTIV, GAL, MARDE
Increased Productivity and Efficiency	AUA, NIBIO, IPV, CU, EXEO, GAL, HCMR, ISA, AGTIV
Reduced Regulatory Fines or Penalties	AUA, NIBIO
Improved Market Competitiveness	AUA, NIBIO, AU, CU, EXEO, ISA
Other (specified by partner)	AUA – Sustainability

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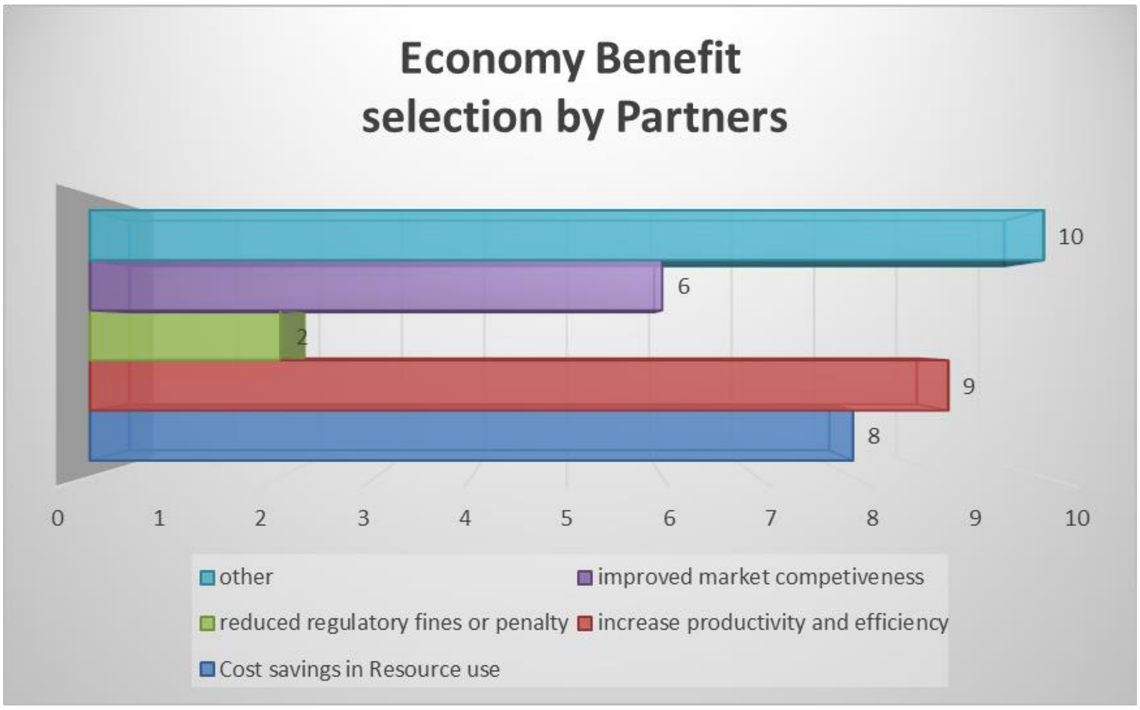
	AUA – Certification for use in incentives / Soil health improvement
	NUBiP – Better understanding of water quality (policy)
	AU – Not specifically economic, reducing pollutants
	AU – No direct gain, only status assessment
	AU – Depends on monetizing pollution reduction
	CIHEAM – Test development scenarios for policy
	IPV – Support policies for lower pollution
	EXEO – Reducing costs (eco-friendly management)
	GAL – Support policies for lower pollution

Chart 7.2.2.3.1: Economic Benefits



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Key observations:

- **Increased productivity and efficiency** was the most frequently cited economic benefit, reflecting a common expectation that these technologies improve performance and streamline agricultural or environmental monitoring operations.
- **Cost savings in resource use** (e.g., water, energy, fertilizers) was the next most cited benefit, emphasizing the importance of reducing input costs through more efficient and targeted resource management.
- **Improved market competitiveness** emerged as a strategic driver, indicating that innovation is seen as a means to differentiate offerings, enhance value, and meet sustainability or certification standards.
- **Reduced regulatory fines or penalties** was acknowledged by some partners, though it appears to be a secondary driver compared to operational or market-based benefits.
- Under the "Other" category, several nuanced and strategic benefits were mentioned. AUA highlighted contributions to sustainability, soil health improvement, and eligibility for certification schemes tied to incentives. NUBiP and IPV emphasized policy-relevant insights into water quality and pollution reduction. AU noted benefits related to pollutant reduction and status assessment, though not directly linked to financial gains. CIHEAM viewed the technology as a tool for policy scenario testing. EXEO and GAL underscored its role in supporting eco-friendly management and policies for pollution control.

Overall, while direct financial benefits remain a central motivator, many partners also emphasize strategic and policy-aligned outcomes. This highlights the multifaceted value of technology adoption across economic, environmental, and institutional domains. These insights align closely with the Path4Med objectives by demonstrating how integrated benefits support sustainable innovation uptake, foster policy coherence, and encourage resilient agricultural and environmental management in the Mediterranean region.

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7.2.2.4. What is the estimated return on investment (ROI) period?

The estimated return on investment (ROI) period provides insight into how quickly the technology delivers value relative to its costs. By identifying short-, medium-, or long-term payback periods, partners contribute to WP6's cost-benefit models, which assess investment attractiveness. The findings also help WP5 in selecting technologies suited to demonstration timeframes and stakeholder expectations.

Table 7.2.2.4.1: ROI period

ROI	Technology Name	Partner
<1 year	Spatial explicit information services, Portable and in-field agronomical management solutions	AUA, **AGTIV**
1–3 years	EO + ML soil health, model irrigation, cover crops, Nutrients leaching monitoring, automatic water monitoring stations	AUA, HCMR
3–5 years	IoT irrigation, biochar, sludge reuse, New-type fertilizers, soil improver and bio-stimulant technologies	AUA, NIBIO
>5 years	Riparian strips, DNA/RNA soil monitoring, automatic water monitoring stations	AUA, IPV
Unknow n	GIS/Remote Sensing & Water Quality Indicators, Micropollutant Analysis, DNA/RNA-based Indicators, Treatment We tland for Agricultural Runoff, Decision Support Tool: Bioeconomic Model, Automatic Water Quality Monitoring Sensors, Geological Analysis, Automatic Water Monitoring Stations, Soil Unsaturated Zone Monitoring, **MHAS – SMART,** Groundwater Monitoring, Estimation of Groundwater Withdrawals via Remote Sensing, **NBS [organic amendments] - slow-release fertilizers**	NUBiP, AU, CIHEAM, CU, EXEO, GAL, ISA, **MARDE**

Key observations:

- Return on Investment (ROI) estimations vary widely, with half of the technologies reported as having an "unknown" ROI. This reflects a major gap in cost-benefit analysis, often due to early-stage implementation or the complexity of the technologies involved.
- Among technologies with known ROI:

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- The most common ROI timeframe is 1–3 years, indicating a positive short- to medium-term economic outlook. This timeframe applied to solutions like soil health monitoring using EO + ML, model-based irrigation, cover crops, nutrient leaching monitoring, and automatic water monitoring stations.

- An ROI of 3–5 years was associated with more complex or resource-intensive solutions such as IoT-based irrigation management, biochar application, sludge reuse, and advanced fertilization techniques, suggesting viable but longer-term returns.

- Only a small number of technologies showed an ROI of less than 1 year, typically linked to low-cost, data-driven solutions such as spatially explicit information services and portable in-field agronomical tools, indicating that immediate returns are rare.

- Some technologies had an ROI exceeding 5 years, including riparian buffer strips, DNA/RNA-based soil health monitoring, and automatic monitoring stations—often due to high upfront costs or extended implementation timelines.

- Technologies with unknown ROI spanned a diverse range, including GIS/Remote Sensing, micropollutant analysis, treatment wetlands, bioeconomic decision tools, and subsurface monitoring systems. This highlights the need for better economic evaluation methodologies.

Overall, this distribution underscores the need for enhanced financial tracking, harmonized cost-benefit analysis tools, and more robust economic modeling. These improvements are vital for supporting evidence-based decision-making and accelerating the uptake of sustainable innovations in agriculture and environmental management, directly contributing to Path4Med's goal of fostering sustainable and efficient practices across the Mediterranean region.

7.2.2.5. What are the main environmental benefits of the technology?

To evaluate the environmental performance of proposed technologies, partners were asked to identify key ecological benefits, including pollution reduction, biodiversity gains, and climate mitigation. These inputs support WP3's environmental assessment and are

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essential for scenario modelling in WP4. They also inform sustainability narratives for the demonstrations under WP5.

Table 7.2.2.5.1: Environmental Benefits

Environmental Benefit Category	Technologies	Partners
Reduction of Water Pollution	Model irrigation, EO & ML soil health, EO for water/nutrient mgmt, Spatial info services, Sludge reuse, Buffer strips, Biochar, Nutrient leaching monitoring, DNA/RNA soil monitoring, GIS & RS + WQ indicators, Treatment wetland, Auto water monitoring stations, MHAS-SMART, Soil & GW monitoring, Portable and in-field agronomical management solutions, NBS [organic amendments] - slow release fertilizers	AUA, NUBiP, AU,NIBIO, IPV, CU, GAL, HCMR, ISA, AGTIV, MARDE
Reduction of Water Consumption	IoT irrigation, Model irrigation, EO for water/nutrient mgmt, Spatial info services, Sludge reuse, New-type fertilizers & biostimulants, Cover crops, Auto water monitoring stations, GW withdrawal via RS	AUA, NUBiP, NIBIO, IPV, ISA, CU, HCMR,GAL
Enhanced Biodiversity and Ecosystem Health	EO for water/nutrient mgmt, Spatial info services, Sludge reuse, Buffer strips, Biochar, DNA/RNA soil monitoring, GIS & RS + WQ indicators, Treatment wetland, Auto water monitoring stations	AUA, NUBiP, AU,NIBIO, IPV, CU, GAL, HCMR, EXEO,ISA, MARDE
Reduced GHG Emissions	EO for water/nutrient mgmt, Spatial info services, Sludge reuse, Cover crops, New-type fertilizers & biostimulants	AUA, NIBIO, CU, EXEO

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Other Benefits Circular economy, sustainability, improved monitoring capacity, soil health, risk reduction	Treated wastewater and sludge reuse in agriculture soil health monitoring with DNA and RNA markers Micropollutant analysis DNA and RNA-based indicators Geological analysis	AUA, AU, ISA

Key Observations:

- **Reduction of water pollution** and **enhancement of biodiversity and ecosystem health** were the most frequently cited environmental benefits, highlighting the technologies' roles in mitigating nutrient runoff, restoring habitats, and fostering agro-ecosystem resilience.
- A significant number of partners emphasized **reduced water consumption**, aligning with goals for resource-efficient and climate-resilient agriculture. This indicates that many technologies offer a dual benefit: environmental protection and operational sustainability.
- **Reduction of greenhouse gas (GHG) emissions** was less commonly reported, suggesting it is either a secondary benefit, context-dependent, or more difficult to measure within current implementation frameworks.
- Several technologies offered targeted environmental benefits, including support for circular economy strategies, advanced monitoring via micropollutant analysis and bio-indicators, improved soil health through DNA/RNA diagnostics, and reduced risks through data-driven decision-making.

These findings confirm that environmental sustainability is a major motivation behind technology uptake. However, the visibility, impact, and measurability of these benefits vary depending on the type of technology, its maturity level, and the specific agro-environmental context of deployment. This highlights the importance of tailored approaches within Path4Med to support the adoption of technologies best suited to diverse Mediterranean environments and sustainability goals.

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7.2.2.6. What are the main environmental risks or challenges?

Identifying environmental risks, such as energy consumption, potential for secondary pollution, or long-term uncertainties, is vital for responsible innovation planning. This information will feed into WP3's environmental risk evaluation and WP6's sustainability assessment. It also contributes to the risk mitigation strategy of WP5 demonstrations.

Table 7.2.2.6.1: Environmental Risks

ENVIRONMENTAL RISKS	TECHNOLOGIES NAME	PARTNER
POTENTIAL FOR SECONDARY POLLUTION	Treated wastewater and sludge reuse in agriculture/ New-type fertilizers, soil improver and bio-stimulant technologies, / a) automatic water monitoring stations/ b) automatic water quality monitoring sensors, / Geological analysis/ MHAS-SMART	AUA, NIBIO, CU, EXEO, GAL
ENERGY CONSUMPTION	Biochar application, / a) automatic water monitoring stations/ b) automatic water quality monitoring sensors, / Geological analysis	AUA, NIBIO,CU, EXEO
SPECIFIC ENVIRONMENTAL CONDITIONS	Treated wastewater and sludge reuse in agriculture, / Cover crops, / soil health monitoring with DNA and RNA marker, / GIS and Remote Sensing and Water quality indicators, / a) automatic water monitoring stations/ b) automatic water quality monitoring sensors, / Geological analysis/ automatic water monitoring stations/ MHAS- SMART	AUA, NUBiP, NIBIO, CU, EXEO, HCMR, GAL

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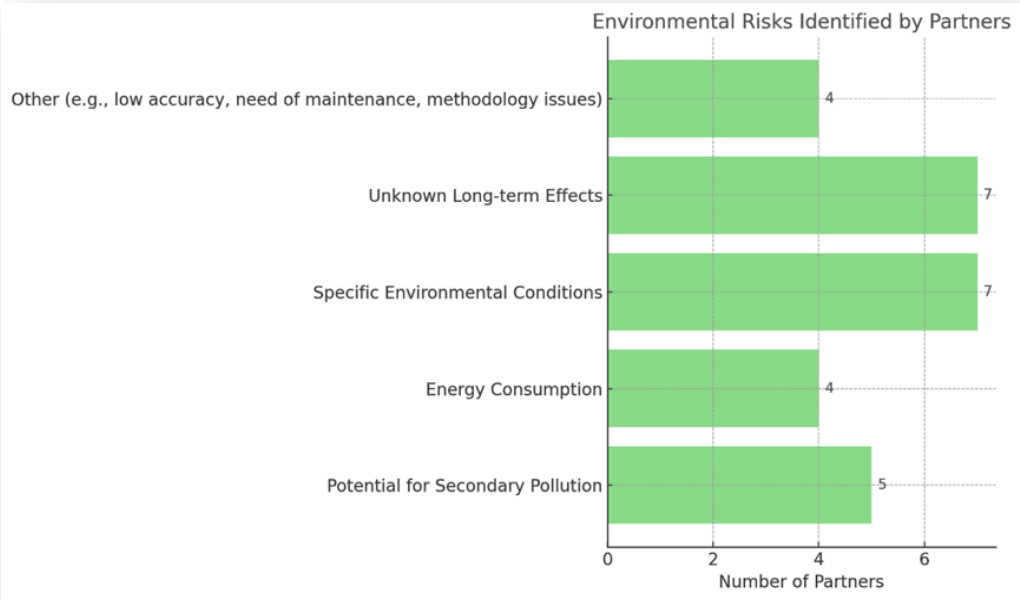
UNKNOWN LONG-TERM EFFECTS	Treated wastewater and sludge reuse in agriculture, / GIS and Remote Sensing and Water quality indicators, / a) automatic water monitoring stations/ b) automatic water quality monitoring sensors, / automatic water monitoring stations/ MHAS-SMART/ **NBS [organic amendments] - slow-release fertilizers**	AUA, NUBiP, NIBIO, CU, HCMR, GAL, MARDE
OTHER:	Soil health monitoring with earth observation and ML./ Micropollutant analysis. / DNA and RNA-based indicators/ Treatment wetland for treating agricultural water runoff/ automatic water monitoring stations/ automatic water monitoring stations	AUA, AU, IPV, GAL

Chart 7.2.2.6.1: Environmental Risks



Key Observations:

A considerable number of partners identified environmental risks categorized as **"Other,"** pointing to **context-specific and operational concerns** that extend beyond conventional risk classifications. These include:

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- **Methodological limitations**, such as unclear detection limits and unvalidated protocols for specific compounds;
- **Operational challenges**, particularly the **need for consistent maintenance** to ensure optimal system performance;
- **Knowledge and information gaps**, especially regarding **emerging technologies** where there is limited clarity on indicators and their interpretation.

The next most frequently reported risks were **dependence on specific environmental conditions** and **energy consumption during operation**, each cited by multiple partners. These highlight important considerations:

- **Dependence on environmental conditions** raises concerns about the **sensitivity of some technologies** to local variations in climate, hydrology, or land use, which may affect performance and reliability.
- **Energy-intensive operations**, particularly in monitoring and analytical technologies, suggest potential trade-offs between **technological precision and environmental footprint**.

Although less frequently mentioned, **potential for secondary pollution** (e.g., residual chemicals, byproducts) and **unknown long-term environmental effects** were still noted by several partners. These underscore the importance of applying **precautionary principles** and designing **longitudinal studies** to assess cumulative and delayed impacts over time.

Overall, these insights affirm the importance of **comprehensive environmental risk assessment** and **adaptive planning** as part of technology deployment strategies. Transparency about limitations and uncertainties, especially in early-stage or high-tech applications, is essential for building trust and ensuring **environmentally responsible innovation**.

7.2.2.7. What are the main barriers to adopting this technology?

Understanding adoption barriers—such as financial, technical, regulatory, or social constraints—is essential for designing inclusive and actionable strategies. Partners' responses provide the foundation for WP2's analysis of adoption bottlenecks and WP3's socio-economic framing. These insights also guide WP5 in tailoring demonstration approaches to overcome real-world limitations.

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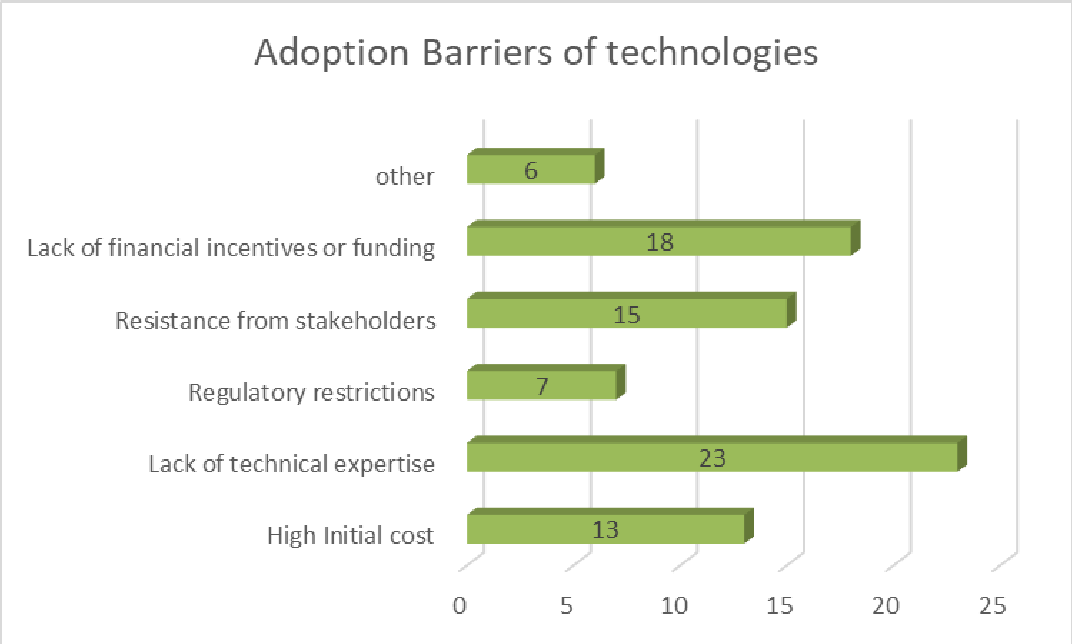
Chart 7.2.2.7.1: Adoption Barriers of technologies



Key Observations:

- **Lack of technical expertise** was the most cited barrier (23 cases), underscoring the need for user-friendly tools, targeted training, and continuous technical support.

- **Lack of funding** (18 cases) significantly hindered adoption, especially for resource-intensive solutions like precision irrigation and biochar.

- **High initial costs** (13 cases) discouraged uptake, particularly for digital and treatment technologies.

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- **Regulatory restrictions** (7 cases) impeded adoption of solutions such as treated wastewater reuse and nutrient monitoring.

- **Stakeholder resistance** (15 cases), including behavioral reluctance, institutional hesitation, and lack of awareness, affected several innovations.

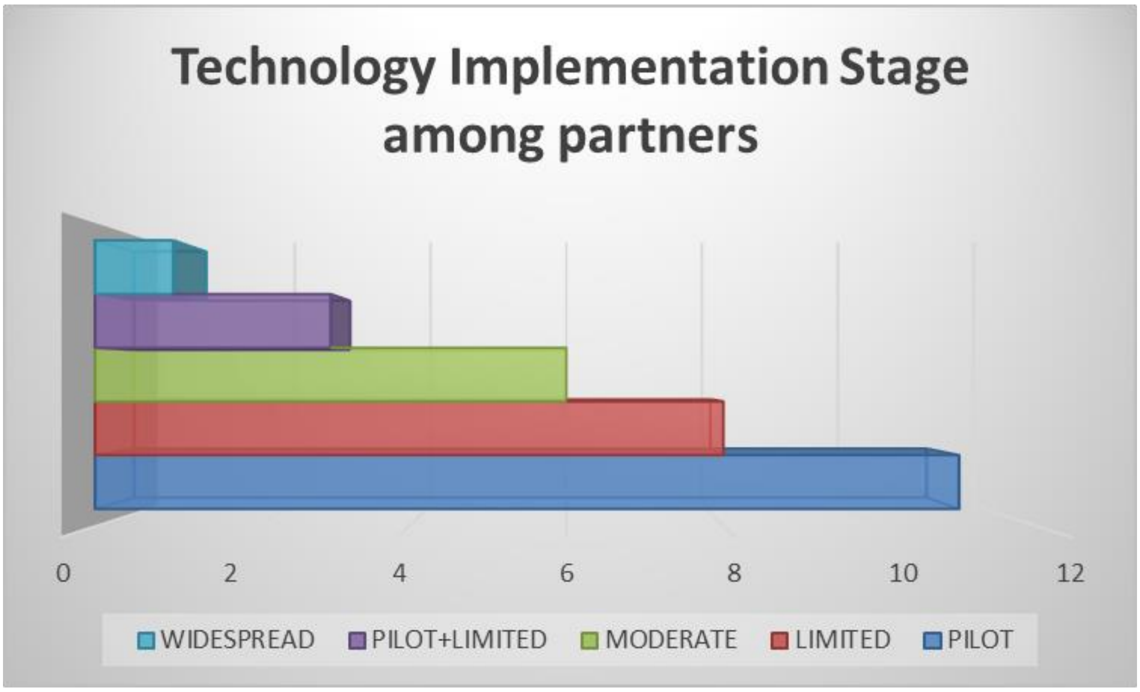
- **Other barriers** (6 cases) included infrastructure gaps, fragmented guidelines, and limited data or demo access.

These findings point to the need for a comprehensive support strategy involving investment in training and technical capacity, financial incentives and improved funding access, simplified and harmonized regulatory frameworks, improved infrastructure and data availability, and enhanced stakeholder engagement and awareness campaigns. Addressing these areas is crucial for Path4Med to foster effective uptake and scaling of innovations across Mediterranean agricultural and environmental systems.

7.2.2.8. How widely has the technology been implemented?

The reported implementation stage (e.g., pilot, limited, moderate, widespread) helps map the maturity and diffusion level of each technology. This is essential for WP2's benchmarking efforts and supports WP4 in developing realistic adoption scenarios. It also informs WP5 on readiness levels and suitability for field demonstrations.

Chart 7.2.2.8.1: Technology Implementation



Key Observations:

- **Pilot Stage (11 cases):**
  Technologies in early testing or small-scale application, such as soil health monitoring with EO and ML, biochar, treated wastewater and sludge reuse, and various water quality monitoring tools.

- **Limited Adoption (8 cases):**
  Technologies used in specific regions or cases but not yet widely applied, including IoT-based precision irrigation, riparian buffer strips, EO tools for water/nutrient management, and DNA/RNA-based indicators.

- **Moderate Adoption (6 cases):**
  Technologies gaining broader use across regions and settings, such as new-type fertilizers, GIS/Remote Sensing, cover crops, and automatic water monitoring stations.

- **Pilot & Limited (3 cases):**
  Technologies reported in both pilot and limited stages, showing early signs of progress but still lacking widespread deployment.

- **Widespread Adoption (1 case):**
  Groundwater monitoring technologies, including remote sensing for groundwater withdrawal estimation, have been adopted widely and are integrated across regions.

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Overall, most innovations remain in pilot or limited stages, particularly in water and soil management. Moderate adoption is emerging for certain solutions, while widespread uptake is currently limited to specific technologies. Continued R&D and targeted scaling strategies will be essential for broader implementation, aligning with Path4Med's goal to accelerate the deployment of sustainable innovations across the Mediterranean.

7.2.2.9. Additional Comments

The additional qualitative contributions from CIHEAM, ISA, and NIBIO offer valuable perspectives on the practical dimensions of technology deployment in diverse agro-environmental settings:

- **CIHEAM** illustrates the integration of **systems-thinking** through the development of a **bioeconomic modeling framework**. This approach is designed to assess the long-term impacts of agricultural development scenarios and technological interventions on water and soil resources. It exemplifies how **evidence-based scenario planning** can bridge research, innovation, and policy agendas.
- **ISA** presents two pragmatic advancements:
    - The **installation of groundwater sensors** to address deficiencies in national monitoring systems reflects the role of project-based actions in **enhancing institutional data infrastructures**.
    - The development and testing of a **novel methodology for estimating irrigation withdrawals** in wells lacking metering demonstrates how **context-adapted innovations** can improve data accuracy and support better resource management in data-scarce environments.
- **NIBIO** contributes a socio-economic and behavioral lens, emphasizing that:
    - The effectiveness of **Nature-Based Solutions and Water Resource Management (NSWRM)** technologies is significantly influenced by **financial incentives** and the degree of **stakeholder collaboration**.
    - **Economies of scale** enhance the economic viability of such interventions, underlining the importance of **broad implementation strategies**.
    - **Social acceptance**, informed by education, past experiences, and **trust in policy frameworks**, is a determining factor in successful adoption, reinforcing the importance of **institutional credibility** and **community engagement**.

These insights collectively stress the necessity of aligning **technological innovation** with **economic modeling**, **robust monitoring systems**, and **socio-institutional dynamics**. For successful uptake, replication, and scalability of water and soil management

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technologies, a **multidimensional strategy** is essential—one that fosters **cross-sectoral collaboration**, **builds trust**, and ensures **strategic financial support** alongside the deployment of technical solutions.

7.3 Summary of Findings from the Questionnaire-Based Assessment

The baseline assessment reveals a dynamic but uneven landscape of technology deployment among partners. While numerous innovative tools are in use or planned, their levels of maturity, adoption, and demonstrable impacts vary considerably. Encouragingly, the technologies under review generally align with core sustainability objectives, offering benefits such as reduced water pollution, improved biodiversity, and enhanced resource efficiency.

However, the uncertainty around ROI—especially with nearly half of the partners unable to provide estimates—and the prevalence of context-specific environmental risks highlight the importance of strategic planning and capacity-building. The most commonly anticipated ROI period is within 1–3 years, yet the "unknown" responses point to the need for enhanced economic evaluation tools and monitoring frameworks.

Environmental benefits remain a key driver for adoption, but challenges such as energy demands, the need for validated methodologies, and concerns over long-term impacts must be proactively addressed. The technology's implementation is primarily in pilot and limited adoption stages, with a few partners having achieved moderate adoption. This suggests that while the technology holds promise, broader implementation is still in the early stages. More support and validation will be necessary to move from pilot testing to widespread deployment.

Further qualitative contributions from CIHEAM, ISA, and NIBIO shed light on the practical dimensions of technology deployment. CIHEAM's bioeconomic modeling framework highlights the need for evidence-based scenario planning, while ISA's groundwater sensor installation and novel irrigation withdrawal estimation methodologies demonstrate context-specific innovations. NIBIO's focus on financial incentives, stakeholder collaboration, and social acceptance reinforces the importance of socio-economic and behavioral factors in successful adoption.

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These insights collectively stress the necessity of aligning technological innovation with robust economic modeling, monitoring systems, and socio-institutional dynamics. For successful uptake, replication, and scalability of water and soil management technologies, a multi-dimensional strategy is essential—one that fosters cross-sectoral collaboration, builds trust, and ensures strategic financial support alongside the deployment of technical solutions.

7.4 Preliminary Financial Analysis of Technologies

This preliminary financial analysis draws upon self-reported data collected from 13 partners across 29 completed questionnaires. While the responses offer indicative insights into investment expectations and potential economic returns, it is important to note that most technologies are still in early stages of implementation. As such, the financial dimension presented here should be considered **provisional**, with a **comprehensive cost-benefit evaluation to be finalized following pilot deployment** within the designated catchment areas, where real-life operational and contextual variables will be measured.

Across the dataset, reported **Return on Investment (ROI)** timeframes vary significantly. Approximately half of the respondents estimated an ROI of **1–3 years**, indicating a promising short-term economic potential for a number of the proposed technologies. However, **45% of responses marked ROI as "unknown"**, reflecting either the novelty of the technologies or insufficient economic modeling at this stage. This highlights the need for further data collection and financial monitoring during demonstration phases.

In terms of **investment costs**, responses indicate that **initial capital expenditures (CAPEX)** for several water and soil technologies—such as precision irrigation systems, digital monitoring platforms, and biosensors—are perceived as relatively high, particularly for smallholders. **Operational expenditures (OPEX)** were generally expected to be moderate or low, especially for technologies with minimal maintenance needs or that are embedded in existing farm management practices.

The most frequently cited financial barriers included:

- **High upfront investment requirements** (10+ partners),

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- **Lack of targeted funding schemes or subsidies** (13 partners),
- **Unclear long-term savings or revenue generation potential**,
- **Limited capacity for economic planning among end-users**, particularly in small-scale operations.

Despite these constraints, several partners associated the adoption of specific technologies with **cost savings through reduced input use (e.g., water, fertilizers), improved crop yields, and compliance with environmental regulations**—suggesting positive financial externalities that warrant further quantification.

Given the current lack of complete cost data, partners have agreed to **validate and refine financial performance indicators during the pilot implementation** in the respective catchment areas. This phase will involve:

- Tracking **actual investment and operational costs**,
- Recording **measurable benefits such as water savings, reduced pollution penalties, or yield improvements**,
- Calculating **ROI, payback periods, and cost-efficiency ratios** in real-world conditions.

These outcomes will feed into a final economic assessment in upcoming deliverables, enabling more accurate financial modeling and evidence-based decision-making for broader replication and scaling. The results will also inform business model development and funding strategies under WP5 and policy dialogues in WP2/WP6, strengthening the enabling environment for wider technology uptake across Mediterranean agro-hyro-ecosystems.

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8. Environmental Impact of Diffuse Pollution Reduction Technologies

Diffuse pollution remains a significant global environmental challenge, affecting water quality, soil health, and ecosystem stability. Unlike point-source pollution, which originates from identifiable locations such as industrial or wastewater treatment plants, diffuse pollution arises from widespread activities, including agricultural runoff, urban stormwater, and industrial processes. It enters water bodies through precipitation, infiltration, and surface runoff, carrying nutrients, pesticides, heavy metals, and other contaminants that degrade both surface and groundwater quality (Fletcher, Andrieu, & Hamel, 2013).

In the context of the Path4Med project, understanding and reducing diffuse pollution is central to achieving Mission Soil objectives and improving the sustainability of Mediterranean agro-hydro-ecosystems. The technologies identified and analyzed across the project contribute to this goal through various mechanisms, grouped into five impact areas:

Monitoring and Assessment

Monitoring technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS) help track land cover changes, forecast hazards, and assess erosion risks, enhancing catchment resilience. Artificial Intelligence (AI) improves water metering, leak detection, and predictive analytics, ensuring efficient resource management, while DNA/RNA monitoring indices provide molecular insights into biodiversity, pollution levels, and pathogen detection. Hydrological and water quality monitoring, along with hydrometeorological data collection, support informed decision-making and sustainable water resource management.

Water Conservation

Conservation technologies like drip irrigation, irrigation management apps, and rainwater catchment systems optimize water use, reducing waste and preventing excessive runoff,

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contributing to the sustainable use of limited water resources in agriculture and urban settings.

Treatment and Filtration

Advanced treatment solutions such as nanotechnology-based filters and reverse osmosis (RO) desalination offer effective removal of pollutants from water sources. Additionally, biofilters made from sand, woodchips, or other organic materials serve as cost-effective options for filtering runoff before it enters natural waterways. These technologies ensure cleaner discharge, reduce health risks, and protect aquatic ecosystems.

Nature-based Solutions

Nature-based solutions (NbS) such as riparian buffer strips, constructed wetlands, and green infrastructure promote natural water infiltration, absorb pollutants, and enhance soil stability. By mimicking natural processes, NbS provides multiple co-benefits — including flood mitigation, biodiversity enhancement, and erosion control — while requiring minimal energy input.

Digital and AI-Driven Innovations

Digital tools powered by AI, including gamified in water metering apps and GIS-based climate adaptation tools, drive behavioral change and enhance resilience to climate variability. By integrating these technologies, pollution reduction efforts contribute to cleaner water, healthier ecosystems, and long-term environmental sustainability.

The integration of advanced monitoring, conservation, treatment, and nature-based technologies significantly reduces the environmental impact of diffuse pollution. By improving water quality, conserving resources, and fostering climate resilience, these solutions play a crucial role in sustainable water and soil management. The combination of AI and a variety of digital tools enhances effectiveness, demonstrating the need for a multi-faceted approach. International collaboration and continued research are essential to further refine these technologies and maximize their environmental benefits.

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The integration of Geographic Information Systems (GIS), particularly QGIS, and Artificial Intelligence (AI) has significantly advanced the precision and scalability of cost-benefit and environmental impact analyses in water and soil management. QGIS enables spatially explicit modeling by mapping land use, topography, hydrological patterns, and pollutant sources, facilitating a detailed spatial understanding of environmental risks and intervention outcomes. When combined with AI algorithms - such as machine learning for pattern recognition, anomaly detection, and predictive analytics - these tools can assess large datasets from remote sensing, sensor networks, and climate models. This integration supports the simulation of multiple scenarios, optimization of intervention strategies, and dynamic assessment of ecosystem services. Consequently, QGIS and AI empower stakeholders to evaluate both economic and environmental trade-offs with higher accuracy, identify cost-effective and environmentally sustainable solutions, and prioritize actions in data-scarce or complex catchment areas.

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9. Conclusions

This report provides a baseline assessment of the technologies, practices, and environmental and economic dynamics shaping sustainable water and soil management in Mediterranean agro-hydro systems. Based on an extensive literature review, partner input, and questionnaire-based analysis, the findings present a multidimensional baseline of existing capabilities, challenges, and opportunities in different regional contexts.

The technologies reviewed-including precision irrigation, biosensors, IoT monitoring systems, nature-based solutions, and remote sensing tools-demonstrate strong alignment with sustainability goals, particularly reducing water pollution, conserving resources, and improving agro-ecosystem resilience. However, their current level of adoption remains uneven, with most technologies still at the pilot or limited implementation stage. Only a few, such as groundwater monitoring systems, have reached widespread use.

Economic analysis revealed a fragmented understanding of return on investment (ROI), with nearly half of the partners unable to estimate financial outcomes. While many technologies report ROI within 1-3 years, indicating promising economic potential, the lack of systematic financial modeling remains a barrier to scaling. Initial investment costs, lack of technical expertise, regulatory complexity, and stakeholder resistance were cited as major barriers to broader adoption.

Environmentally, most technologies contribute to pollution reduction and biodiversity enhancement, although concerns about energy requirements, context-dependent performance, and unknown long-term impacts underscore the need for ongoing monitoring and adaptive safeguards.

Importantly, these baseline insights directly inform the planning and prioritization of demonstration activities under WP5, as outlined in Deliverable 5.1. The identified environmental benefits and barriers will help shape co-design decisions, sustainability strategies, and participatory monitoring protocols for the Living Labs. Moreover, this

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deliverable supports WP2 and WP6 by identifying technology clusters with high policy relevance, potential for upscaling, and measurable environmental outcomes.

Taken together, these findings highlight the need for a holistic, cross-sectoral strategy that integrates technical, economic, environmental, and social considerations to accelerate the adoption of sustainable technologies.

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ANNEX I: Partner Expertise and Role Distribution Template

PARTNERS	COUNTRY	EXPERTISE CATEGORY	SUBTEAM	SPECIFIC ROLE/ CONTRIBUTION	TYPE OF ORGANIZATION	RELEVANT TECHNOLOGIES/ METHODS	SOLUTIONS	DESCRIPTION	APPLICATION AREA	TRL	PROJECT/ SOURCE	OUTCOMES/ RESULTS	CHALLENGES

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Annex II: Questionnaire – Cost-Benefit and Environmental Impact Analysis of Technologies

1. General Information

1.1 Organization Name:

(Text field)

1.2 Contact Person & Email:

(Text field)

1.3 Technology Name:

(Text field)

1.4 Technology Type: *(Select all that apply)*

☐ Water quality monitoring (e.g., sensors, DNA/RNA-based)

☐ Water quantity monitoring (e.g., hydrological sensors)

☐ Irrigation management (e.g., precision irrigation, mobile apps)

☐ Pollution control (e.g., nanotechnology, nature-based solutions)

☐ Remote sensing and GIS applications

☐ Other (please specify):

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2. Economic Costs and Benefits

2.1 What are the main cost factors associated with the technology? *(Select all that apply)*

☐ Initial investment (e.g., equipment, installation)

☐ Maintenance and operational costs

☐ Training and capacity building

☐ Data management and software costs

☐ Compliance with regulations

☐ Other (please specify):

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2.2 What are the main economic benefits of implementing this technology? *(Select all that apply)*

☐ Cost savings in resource use (e.g., water, energy, fertilizers)

☐ Increased productivity and efficiency

☐ Reduced regulatory fines or penalties

☐ Improved market competitiveness

☐ Other (please specify):

2.3 What is the estimated return on investment (ROI) period? *(Select one)*

☐ <1 year

☐ 1–3 years

☐ 3–5 years

☐ >5 years

☐ Unknown

---

3. Environmental Impact

3.1 What are the main environmental benefits of the technology? *(Select all that apply)*

☐ Reduction of water pollution (e.g., nutrient runoff control)

☐ Reduction of water consumption

☐ Enhanced biodiversity and ecosystem health

☐ Reduced greenhouse gas emissions

☐ Other (please specify):

3.2 What are the main environmental risks or challenges? *(Select all that apply)*

☐ Potential for secondary pollution (e.g., chemical residues, waste production)

☐ Energy consumption during operation

☐ Dependence on specific environmental conditions

☐ Unknown long-term effects

☐ Other (please specify):

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4. Adoption and Implementation

4.1 What are the main barriers to adopting this technology? *(Select all that apply)*

☐ High initial cost

☐ Lack of technical expertise

☐ Regulatory restrictions

☐ Resistance from stakeholders

☐ Lack of financial incentives or funding

☐ Other (please specify):

4.2 How widely has the technology been implemented? *(Select one)*

☐ Pilot stage (small-scale testing)

☐ Limited adoption (used in specific cases)

☐ Moderate adoption (used in multiple locations)

☐ Widespread adoption (implemented across regions)

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5. Additional Comments

(Open text field for any additional information)

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