MULTICRITERIA METHODOLOGY FOR THE SELECTION AND IMPLEMENTATION OF DECENTRALISED WATER MANAGEMENT SOLUTIONS

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Resumen

The WATERSENS project aims to address current challenges in water management by providing technological evidence on the benefits of decentralised water management (DWM) solutions. A multi-criteria methodology will be developed to help authorities and sector stakeholders in the selection, design, integration, and operation of these systems. To support this, six selected DWM technologies, (floating treatment wetlands, biofilters, photo-bioelectrochemical systems, green infrastructure, and rainwater harvesting systems), will be optimised and validated across demonstrators in four countries, chosen for their complementary capacity to respond to diverse geographical, climatic, and economic contexts. Besides, a complete parametric catalogue will be developed to apply a multi-criteria decision analysis (MCDA) for the selection of the best option, considering technical, economic, social, and environmental criteria. Furthermore, combined with GIS tools will identify suitable areas for the application of the best alternatives. These results will be integrated into a decision support system (DSS), facilitating the prioritisation of DWM solutions.

Palabras Clave: *Decentralised water management (DWM), parametric catalogue, multi-criteria decision analysis (MCDA) and decision support system (DSS).*

1 Introduction

In recent years, climate change has been intensifying the global hydrological cycle, leading to extreme events such as floods and prolonged drought periods, with significant impacts on society and the economy [1]. In this context, regions such as the Mediterranean basin and southern Africa are among the most vulnerable, with an increase in the frequency and intensity of these events projected over the coming decades [2].

At the same time, urbanisation processes are transforming population distribution, with it estimated that nearly 80% of the world's population will reside in urban environments by 2050 [3]. This trend will increase the demand for flexible and adaptive water solutions, while rural areas will face growing vulnerability due to depopulation and the progressive loss of services.

In response to these challenges, decentralised water management (DWM) solutions, such as floating treatment wetlands (FTW), biofilters, photo-bioelectrochemical systems, green walls and roofs, and rainwater harvesting systems, are emerging as sustainable alternatives capable of optimising the use of water resources. These solutions enable water to be treated and reused close to its source, making them particularly suitable in contexts where centralised systems are neither technically nor economically viable, or in cases where an increase of the water resilience is needed to face the impact of the climate change.

Furthermore, DWM promotes the development of circular economy models based on nature-based solutions (NbS), encouraging the involvement of local communities and improving quality of life through more environmentally friendly infrastructure. However, despite their advantages, the implementation of these solutions remains limited, mainly due to regulatory barriers, normative complexity, and still insufficient social acceptance [4].

2 Objective

WATERSENS project aims to provide evidence of the benefits offered by decentralised water management solutions and to develop an integrated decision-making framework that supports water authorities and stakeholders in the selection, design, integration, and operation of these decentralised solutions.

In this context, the proposed methodology consists of integrating multi-criteria decision analysis (MCDA) and a geographic information system (GIS) within a decision support system (DSS) to improve the incorporation of decentralised management technologies and their integration into the existing centralised systems. This work makes it possible to identify suitable intervention areas and to evaluate alternatives by jointly considering technical, economic, social, and environmental criteria.

3 Demonstration sites

WATERSENS will optimise six technologies for decentralised water management through validation at seven demonstration sites across four countries: Spain, Portugal, Greece and South Africa (Figure 1). These demonstration sites are:

- DEM 1.1: Floating treatment wetlands for rural wastewater treatment (Aragón, Spain).
- DEM 1.2: Compact floating treatment wetlands with microalgae for rural wastewater treatment (Cantabria, Spain).
- DEM 2: Walkable floating treatment wetlands for urban stormwater pond treatment (Cantabria, Spain).
- DEM 3: Biofilters for river water recovery (Franschhoek, South Africa).
- DEM 4: Photo-bioelectrochemical system for urban wastewater treatment at the Badajoz WWTP (Badajoz, Spain).

- DEM 5: Green walls and roofs for domestic use (Lisbon, Portugal).
- DEM 6: Traditional cisterns for stormwater collection (Naxos, Greece).

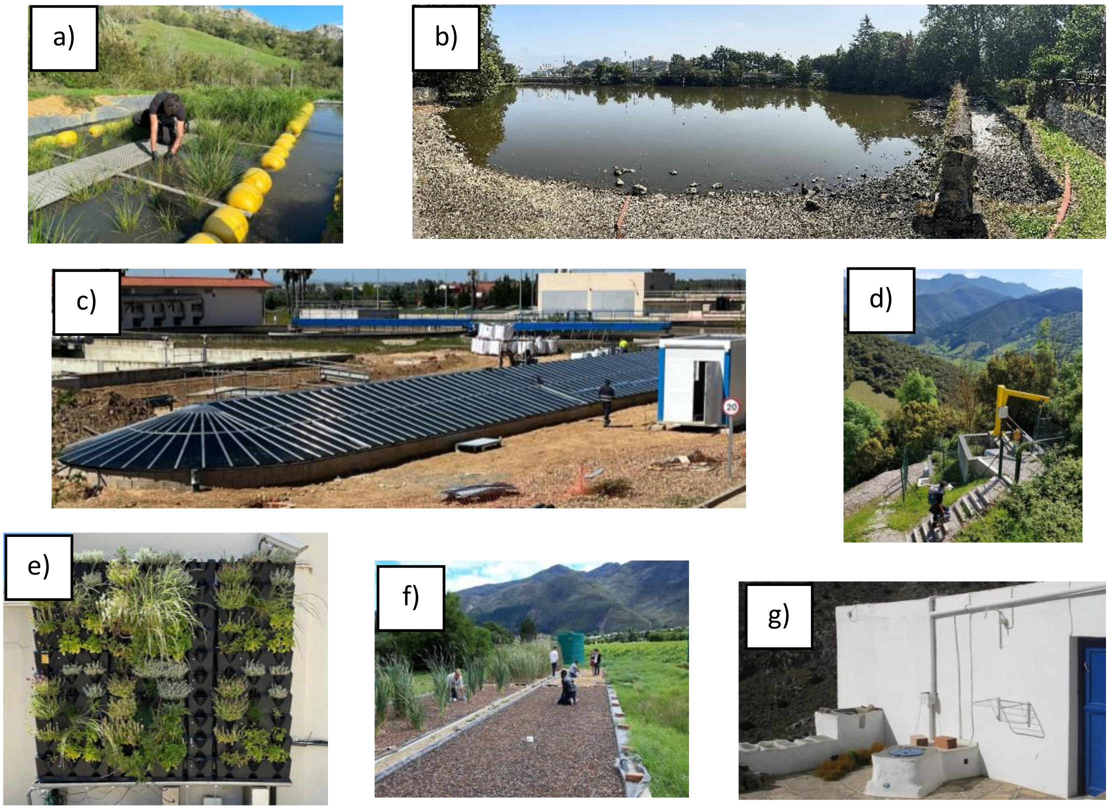

Figure 1. WATERSENS project demonstration sites a) DEM 1.1 b) DEM 2 c) DEM 4 d) DEM 1.2 e) DEM 5 f) DEM 3 g) DEM 6

3 Methodology

The workflow is structured into several sequential phases aimed at the development and implementation of a decision support system for the integration of decentralised water management solutions. These phases are described below and illustrated in Figure 2:

- Phase 1. Definition of DSS functionalities with stakeholders: identify and define potential functionalities and user requirements of the DSS through active engagement of stakeholders and project partners.

- Phase 2. Development of engineering tools to support the decision process: develop engineering and analytical tools (catalogue, MCDA, climate scenarios, GIS) to support decision-making for DWM solutions under current and future climate conditions.

- Phase 3. Design and development of DSS: design, develop, and validate the DSS architecture and components, ensuring functionality, scalability, and cybersecurity compliance.

- Phase 4. Data & modelling strategies, & data gathering for DSS demonstration: define data and modelling strategies to support DSS demonstration, ensuring data quality, consistency, and effective integration of models.

- Phase 5. DSS demonstration at demonstration sites: implement the DSS functionalities and validate its performance across the project demonstrators, covering technical, functional, and governance aspects.

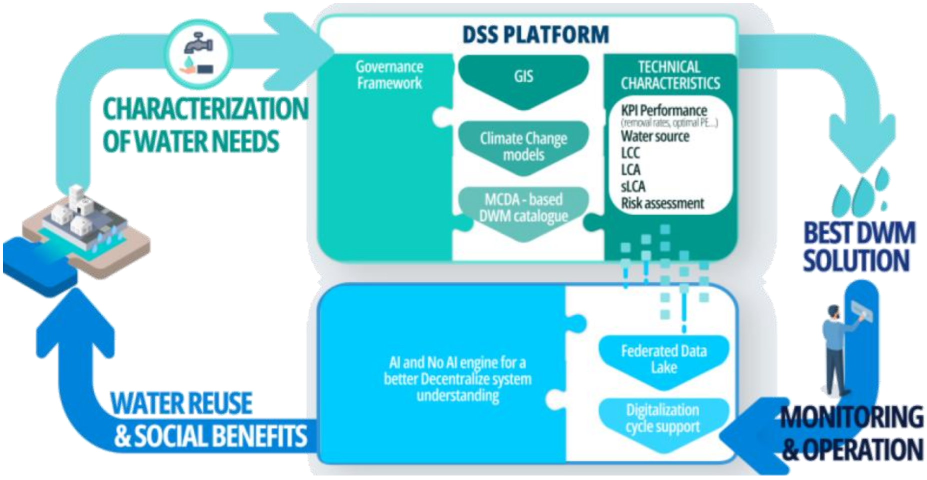

Figure 2. WATERSENS project and DSS concept

As part of Phase 2, an integrated methodological approach is proposed that combines the systematisation of existing solutions, multi-criteria analysis, the evaluation of climate change scenarios, and their subsequent integration into GIS tools. This approach enables the structuring and support of decision-making for the optimal implementation of decentralised water management solutions across different contexts.

- Step 1. Review and cataloguing of DWM solutions: in this phase, a parametric catalogue of available decentralised water management solutions is being developed. To this end, a comprehensive review of the scientific and technical literature is being carried out, including both established and innovative technologies. Based on this review, the main design and operational parameters characterising each technology will be identified, enabling the establishment of a homogeneous classification of the available alternatives. This catalogue will constitute the technical basis for the subsequent evaluation and comparison of solutions adapted to different territorial contexts and management needs.

- Step 2. Development of an MCDA-based methodology for solution selection: this phase will focus on the development of a methodology based on multi-criteria decision analysis to support the selection and prioritisation of decentralised water solutions. The methodology will integrate technical, economic, environmental, and social criteria together with resilience indicators related to maintenance, vulnerability, and response capacity to extreme events. In addition, specific weightings will be established for each criterion in order to adapt the decision-making process to different scenarios and local needs. As a result, a decision-support tool will be developed, capable of classifying and ranking different technological alternatives for their implementation within centralised water management systems.

- Step 3. Development of climate change scenarios: regional and catchment-scale scenarios will be developed to assess the impact of climate change on water resources and existing water management systems. The analysis will combine information from high-resolution regional climate models and global Earth system models, supported by machine learning techniques grounded in physical principles to generate kilometre-scale climate scenarios for the Mediterranean region and South Africa. These scenarios will subsequently be integrated with physically distributed hydrological models, enabling the assessment of potential future changes in hydrological risks and water availability under different climate conditions, initially without considering the implementation of innovative management strategies.

- Step 4. GIS integration and spatial assessment of intervention areas: this phase will consist of integrating the results obtained from the MCDA and the climate scenarios into a GIS-based decision-support tool. This tool will enable the identification of areas potentially suitable for the implementation of decentralised water solutions through the spatial evaluation of multiple variables. In addition, it will incorporate climate stress scenarios to analyse the feasibility and resilience of the proposed solutions under future climate change conditions. The result will be a planning support tool capable of facilitating the strategic integration of DWM technologies into centralised water management systems.

3 Results

At the current stage, a list of decentralised water management technologies has been developed, comprising 28 technologies classified into 6 categories. These categories have been created to group the various technologies according to their operating principles, and have been defined as constructed wetlands, photosynthetic processes, biofilm processes, suspended growth processes, green infrastructures and alternative water harvesting systems. These categories are briefly described below, providing an overview and examples of the technologies included in each category.

- Constructed wetlands: are engineered structures designed to replicate the functions of natural wetlands, enabling the transformation and removal of pollutants under controlled conditions. Constructed wetlands are versatile solutions that can be applied for wastewater treatment as well as for stormwater management and treatment. They are based on the synergistic interaction between aquatic vegetation, a porous substrate that acts as a filtration bed and support medium, and colonising microbial communities. Although the range of design variants is very broad, the technical literature distinguishes three main variants based on their hydrology: free water surface wetlands (FWS), where water flows over the substrate; subsurface flow wetlands (SSF), which are divided into horizontal and vertical systems depending on the direction of flow; and floating wetlands (FTW), which use vegetated rafts to treat water directly in ponds or channels [5, 6].

- Photosynthetic processes: consists of aquatic organisms, unicellular or multicellular, equipped with pigments capable of converting solar energy into chemical energy through photosynthesis. In the field of wastewater treatment, the main groups of microorganisms are microalgae (such as green algae or chlorophytes), cyanobacteria (blue-green algae capable of nitrogen fixation), and photosynthetic sulphur bacteria (such as purple phototrophic bacteria). Their operating principle lies in the uptake of nutrients such as nitrogen and phosphorus, together with carbon dioxide, to synthesise new cellular biomass in the presence of sunlight, while producing oxygen. Usually, in wastewater treatment systems, phototrophic microorganisms coexist in symbiosis with conventional wastewater treatment bacteria. Within the spectrum of technological configurations, the main technologies include facultative and maturation lagoons, high-rate algal ponds (HRAP), and photo-bioelectrochemical systems (PBEC-PPB) [7].

- Biofilm processes: are biological systems for wastewater treatment in which the microorganisms responsible for purification are not suspended in the water but instead attached to a support matrix of inert or natural origin. The operating basis of this technology is an active biological film that metabolises soluble organic matter and nutrients in the influent as substrate for its growth and cellular maintenance. Their main variants are classified according to their operational intensity: extensive technologies such as peat filters, intermittent sand filters, and infiltration-percolation systems; or intensive technologies such as trickling filters, rotating biological contactors (RBC), and moving bed biofilm reactors (MBBR) [8].

- Suspended growth processes: are an intensive form of biological wastewater treatment in which the microbial consortium responsible for purification is maintained in a free state within the wastewater. There is a wide range of technologies, most of them derived from the well-known activated sludge process, such as extended aeration, sequential batch reactors (SBR) and membrane biological reactors (MBR) [9].
- Green infrastructures: comprises a set of strategically planned treatment technologies based on natural and semi-natural areas, designed to mitigate the impacts of urbanisation and climate change through the provision of ecosystem services. Its core basis lies in the synergistic interaction between highly porous substrates, vegetation and microbial communities, which together act as a complex ecosystem that filters and degrades contaminants through physical, chemical and biological processes. They are mainly used for urban drainage and stormwater management and treatment, and could be used for greywater treatment. This category includes technologies such as: permeable pavements, rain gardens, bioswales, green roofs and green walls [10].
- Alternative water harvesting systems: technologies for water capture and storage. This category refers to engineering infrastructures, both traditional and modern, designed to artificially collect and conserve atmospheric water from different sources for subsequent use. This is achieved by capturing water on roofs or impermeable surfaces, from which it is channelled and stored in controlled storage systems, such as artificial tanks, repurposed structures, or lined and impermeabilised artificial basins, thus ensuring its availability for later use. Within this technological spectrum, solutions such as collection cisterns, fog harvesters, and rainwater harvesting ponds can be distinguished [11].

This list provides the basis for the preparation and development of technical data sheets for each solution, taking into account the key parameters or requirements for their implementation, and will result in a parametric catalogue of decentralised water management solutions.

In a subsequent phase, a multi-criteria decision analysis will be implemented, integrating methods such as the Analytic Hierarchy Process (AHP), the Entropy Weight Method (EWM), and ranking methods (RM), enabling the evaluation and prioritisation of alternatives according to technical, economic, social, and environmental criteria [12].

In addition, these developments are complemented by the use of high-resolution data on future climate scenarios and hydrological risks, as well as by a GIS tool that enables the identification and assessment of potential locations for the implementation of decentralised systems, both under current conditions and under climate change scenarios.

4 Conclusions

The developed methodology makes it possible to advance towards a more sustainable, resilient, and integrated water management model, facilitating the incorporation of decentralised solutions across different territorial contexts.

The integration of multi-criteria decision analysis into a decision support system will provides an effective tool enabling administrations and stakeholders to evaluate and prioritise alternatives, thereby strengthening planning and decision-making in the face of future water-related challenges. The DSS will integrate advanced functionalities, including Natural Language Processing (NLP) techniques, to facilitate users' access to information on different DWM typologies, as well as their selection and prioritisation according to specific needs and local characteristics.

Furthermore, this approach helps to demonstrate the advantages of decentralised solutions, promoting circular economy strategies within the water cycle and supporting the implementation of European policies aimed at sustainability and resilience to climate change.

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