Sustainable Water Storage and Distribution in The Mediterranean

Methodology for multi-objective water management for each demo site

VERSION 1.0

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Acronyms

WP	Work Package
MED	Mediterranean
UFZ	Helmholtz Centre for Environmental Research
RSS	Remote Sensing Solutions GmbH
UPV	Universitat Politècnica de València
IDRICA	Idrica
SEMIDE	Euro-Mediterranean Information System on know-how in the Water sector
TdV	La Tour du Valat
TUC	Technical University of Crete
UNIPR	Università di Parma
UNISS	University of Sassari
UNINA	University of Naples Federico II
RSCN	Royal Society for the Conservation of Nature
LPM	Living Planet Morocco
AGRI	AgroInsider
ESIM	Higher School of Engineering of Medjez El Bab
BU	Boğaziçi University

Executive summary

The "Sustainable Water Storage and Distribution in The Mediterranean" (OurMED) project aims to design and explore innovative and sustainable storage and distribution systems tightly integrated into ecosystem management at the river basin scale. This is achieved by combining scientific and local knowledge, emerging from new and long-lasting spaces for social learning among interdependent stakeholders, society actors, and scientific researchers in eight local and one regional MED demo sites. OurMED calls for a transition from a mono-sectoral water management approach based on trade-offs to equitable multi-sectoral and integrative management that addresses all water bodies' capabilities and needs towards sustainability.

This Deliverable (D4.1) summarises the activities carried out in Task 4.1, "Development of a robust methodology using multi-objective functions," and presents the developed methodology for each demo site. It was based on established water management practices and indicators; we've adapted our approach to suit demo sites' specific conditions, stakeholder needs, and available data and tools.

Due to the complex stakeholder relationships, unique demo site challenges, and evolving OurMED project contributions, the definition of the optimisation problems is dynamic. This document is the first version of the proposed methodology, which will be updated when new findings, tools, and data are available.

1. Introduction

The “Sustainable Water Storage and Distribution in The Mediterranean” (OurMED) is an EU-funded project under Grant Agreement Number 2222. The primary goal of the OurMED project is to design and explore innovative and sustainable storage and distribution systems tightly integrated into ecosystem management at the river basin scale.

OurMED recognises the potential of integrating monitoring techniques, modelling approaches, and technological solutions to significantly enhance our ability to develop effective water management strategies, focusing on natural and artificial water storage and distribution systems. To progress towards these objectives, this document presents a robust methodology utilising multi-objective functions for water management at the demonstration sites.

The developed methodology was built upon existing multi-objective and multi-sectoral water management practices and their relevant indicators, considering the specific climatic and ecological characteristics of the demonstration sites, the needs of stakeholders, the available data, and tools.

We begin by outlining the primary concepts of multi-objective optimisation, followed by a broad overview of a multi-objective optimisation approach. Following this, we introduce a comprehensive methodology for multi-objective optimisation tailored to each demonstration site within the OurMED project. Finally, we recommend suitable algorithms.

1.1. Purpose

The aim of Task 4.1 within the OurMED project is to formulate a comprehensive methodology for sustainable and equitable water storage and distribution at the basin scale. Task 4.1 explores various options and pathways for integrated and multi-sectoral water management. Specifically, it centres on assessing existing multi-sectoral water management strategies and relevant indicators, considering the conflicting water demands for drinking, irrigation, industrial, and environmental purposes.

This document refers to deliverable D4.1 and summarises the activities undertaken in Task 4.1, "Development of a robust methodology using multi-objective functions" (Lead: UPV, Participants: All partners). It presents the resulting methodology.

Considering the complexity of the relationships between stakeholders, the unique challenges faced by each demo site, and the evolving nature of the technical contributions from OurMED products, the definition of the optimisation problems is highly dynamic. This document represents the first version of an evolving framework that will be updated as new findings, tools, and data emerge to enhance the proposed methodology.

2. Multi-objective optimisation

Optimisation methods refer to achieving outcomes that align closely with predefined objectives while disregarding worst-case scenarios. Optimisation is characterised by mathematical representations of a system's operational goals, adaptable to resolution through computer algorithms and programming languages. Typically, optimisation models aim to maximise or minimise one or more objective functions seeking the optimal or most practical solution to a given problem (Karimanzira, 2016; Loucks & van Beek, 2017; Emmerich & Deutz, 2018; Derepasko et al., 2021).

These methods find applications across diverse areas, including socioeconomic, engineering, and environmental (Nagel, 2000; Ali & Sik, 2012; Singh, 2012; Lauinger et al., 2016; Sioshansi and Conejo, 2017). Depending on the complexity of the problem, optimisation strategies may vary between single or multi-objective methods, which are the central theme of this report. Real-world challenges often present a mix of conflicting objectives, driving the use of these techniques across diverse fields, including data mining, tourism management, energy, mechanical engineering, bioinformatics, and environmental management (Liu et al., 2020; Huang et al., 2021; Tian et al., 2021. Arbolino et al., 2021; Abdallah et al., 2021; Jalili et al., 2023).

In water management, the utilisation of multi-objective optimisation stands as a well-established technique, adaptable to a variety of objective functions. These may include maximising the fairness of water distribution, ensuring equity in water use, meeting supplied demands, minimising water deficit and shortage, reducing groundwater drawdown and extraction, maximising economic benefits and revenue, minimising distribution and operational costs, reducing concentrations and discharge of pollutants, total dissolved solids, and salinity, guaranteeing environmental flow, and ensuring the overall sustainability of the system (Aalami et al., 2020; Dehghanipour et al., 2020; Farhadi et al., 2016; Nouiri et al., 2015; Qi et al., 2023; Tang et al., 2021; Tayebikhorami et al., 2019; Tian et al., 2019; Wang et al., 2022; Zeinali et al., 2020).

In every optimisation problem, alongside the objective functions, other fundamental components are invariably present, regardless of whether the problem is single or multi-objective: decision variables and constraints. The objective function typically depends on one or more decision variables, which are the parameters that can be adjusted to achieve the optimal solution. While the constraints are intended to constrain the optimisation model to adhere to physical laws or operational, socio-economic, and political requirements, i.e., they restrict the range over which the decision variables can change and thus affect the optimum solution (Jain & Singh, 2003).

An example of the definition of the optimisation problem is the study conducted by Zeinali et al. (2020), in which was highlighted that due to the seasonal nature of the Balarood River in Iran and its diminished surface water flow over six months, effective planning was essential for water allocation from both surface and groundwater sources post-dam construction. In response, they delineated two objective functions: maximising demand site coverage and minimising groundwater drawdown. The decision variables comprised the percentage of extraction from surface water resources and groundwater resources. Meanwhile, constraints centred around the total allocated water volume, maximum demands, and the total groundwater extraction volume.

The optimisation task aims to find the values of the decision variables that result in the optimal value of the objective function while adhering to imposed constraints. However, when two or more conflicting objectives exist, solutions should be sought, considering the trade-offs between the different objectives (Karimanzira, 2016). Additional techniques, such as Pareto Optimality and Nash Equilibrium, should be used in those cases.

In addition, the significance of choosing an appropriate optimisation approach from numerous available techniques cannot be overstated. It should be noted that no method can solve any optimisation problem. Still, the characteristics of each one must be evaluated, as well as the data availability and the type of solutions desired, to choose a more appropriate method. For instance, in water resources, key methods include multi-objective evolutionary algorithms like the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) and swarm-based algorithms such as Multi-Objective Particle Swarm Optimization (MOPSO).

Finally, optimisation frequently connects with simulation. Initially, a simulation can generate initial decision variables to kickstart the optimisation process. Subsequently, optimal decision variables are identified to evaluate the problem further through simulation. Therefore, identifying the most suitable tool for simulation is also an essential task. For instance, in water resources management, we found that groundwater flow and contaminant transport are commonly simulated with MODFLOW and MT3D, respectively (Yazdian et al., 2021; Far & Ashofteh, 2024). Surface water resources could be simulated employing WEAP (KhazaiPoul et al., 2019; Zeinali et al., 2020; Goorani & Shabanlou, 2021), SWAT (KhazaiPoul et al., 2019), MIKE (Dou et al., 2019) and CatchWatSD (Liu et al., 2023, and Delft3D (Abdullah et al., 2018). Additionally, several empirical models from the field of hydrology could also be used (Tarebari et al., 2018; M. Chen et al., 2019; Guan et al., 2020; Deng et al., 2022; Dong et al., 2022; Z. Wang et al., 2022). The system dynamics approach was also employed in some papers (Naghdi et al., 2021; Zhou et al., 2021). Readers can find further information in the project milestone report M4.1 titled "Literature-Based Identification of Multi-Sectoral Water Management Approaches"[1].

The components mentioned above form the foundational framework for conducting multi-objective optimisation. Figure 1 illustrates the basic workflow of a multi-objective simulation-optimisation approach. Based on this basic framework, a methodology for multi-objective optimisation was elaborated for each demo site, as presented in the next section.

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[1] OurMED M4.1 Literature-Based Identification of Multi-Sectoral Water Management Approaches (zenodo.org)

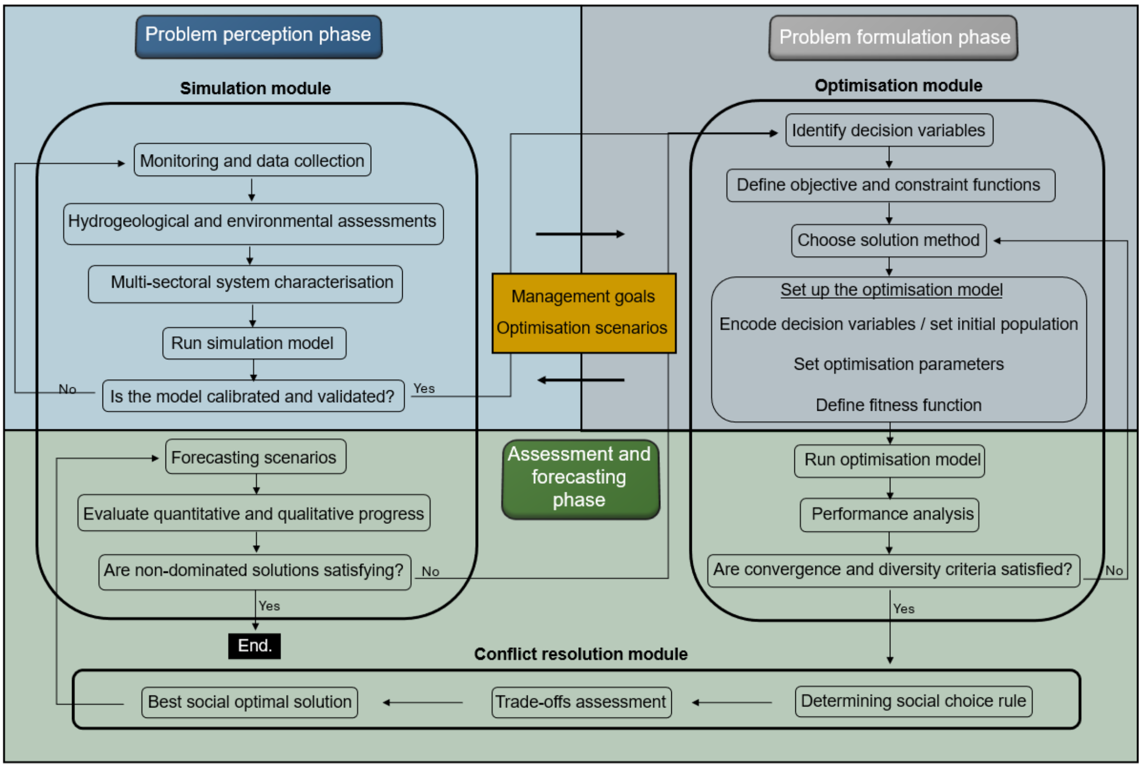

Figure 1 Basic workflow of a multi-objective optimisation method.

3. Proposed Methodology

In the upcoming subsections, we will introduce a methodology for multi-objective optimisation customised for each demonstration site within the OurMED project. This methodology has been developed by considering each demo site's unique characteristics and requirements and assessing the availability of essential data and crucial tools for the upcoming optimisation implementation.

3.1. Case Study – Bode (German)

3.1.1. Problem Contextualisation

The Bode catchment area encompasses 3300 km^2 and is in transitional zones between Germany's central uplands and northern lowlands (Figure 2). The Harz Mountains border it to the southwest and lowland plains to the northeast. Elevations within the catchment range from 1142 metres above sea level at the Brocken, the highest point in the Harz Mountains, to 70 metres above sea level in the lowland region.

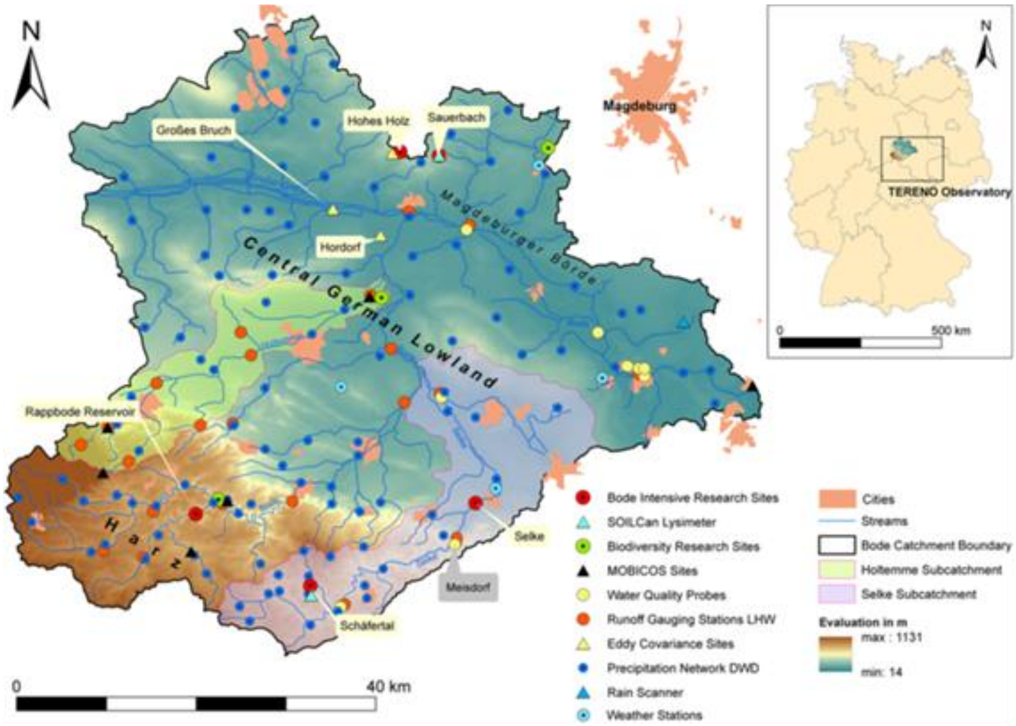

Figure 2 Bode catchment map as part of the Central German Lowland Observatory (TERENO Harz) taken from Wollschläger et al. (2017). Large red labels denote the locations of intensive research sites.

The catchment displays significant diversity in climate, land use, soil, and geology along its elevation gradient. Annual precipitation varies from 1500 mm in the Brocken to 500 mm in the lowlands, with mean potential evapotranspiration at 710 mm in the mountains and 810 mm in the lowlands. In the mountainous area, forests dominate while pasture covers 10% of the land, 8% is devoted to agriculture, and 7% is designated for urban areas and lakes. In contrast, agriculture occupies 81% of the lowland area, primarily cultivating winter wheat, winter barley, rapeseed, and sugar beet. Forests and pastureland comprise 7% and 3%, respectively, while urban areas and small lakes comprise 9%.

Consequently, the Bode catchment must address a variety of water needs crucial for human and environmental well-being. More than a million people rely on the Rappbode Reservoir for their drinking water supply. Additionally, irrigation from surface water supports approximately 10% of downstream farming land during the summer. Furthermore, downstream ecosystem services and recreational activities, such as canoeing, hinge on maintaining a minimum flow to preserve biodiversity and provide leisure opportunities.

However, extreme weather events, such as droughts and floods, have substantially influenced the Bode catchment in recent years. Over the period from 2015 to 2019, there was a notable 10% decline in annual precipitation, concurrent with a significant temperature increase of 1.46°C compared to the preceding years from 1969 to 2014. These shifts have had profound implications, notably reducing water replenishment rates and escalating evapotranspiration, amplifying water scarcity concerns within the region.

The water policy for the Bode River catchment aims to restore natural water body structures and enhance water quality by reversing past modifications, such as river straightening, removing meanders and old arms, and implementing bank-building measures. Since 2000, over 90 million euros have been invested in water structure improvements across Sachsen-Anhalt (the Bode River basin is partially located in Sachsen-Anhalt). Additionally, a sediment management concept has been active since September 2009, addressing pollutant accumulation in sediments as part of a broader Elbe-wide plan. Collaboration among government levels and stakeholders is crucial for achieving the Water Framework Directive's (WFD) goals, with public participation and economic instruments integral to the implementation process.

Although these efforts, issues related to water use persist. Among the identified impacts for the Bode demo site is severe deforestation, which adversely impacted the quantity and quality of water in the catchment area. The drought conditions have also exacerbated nutrient leaching into the drinking water reservoir and downstream river networks, causing surface water eutrophication. This is primarily due to diminished forest uptake capacity, reduced dilution capabilities, and heightened risks of soil erosion. Furthermore, in response to these conditions, farmers are likely to increasingly turn to irrigated crops, relying on both surface water and groundwater sources. This shift in agricultural practices is expected to place additional tension on already stressed water resources within the basin. In addition, the prolonged drought conditions experienced in the Bode River basin have increased water temperature and become an emerging concern for the streams and reservoir-related ecosystems. Elevated temperatures reduce oxygen levels, stress aquatic organisms, and alter species composition, decreasing biodiversity and disrupting food webs. They also speed up metabolism and chemical reactions, causing harmful algal blooms that degrade water quality and affect recreational and drinking water supplies.

To effectively address these impacts, it is crucial to implement robust water management strategies that can adapt to the changing climate landscape and meet the diverse needs of agriculture, urban development, and ecological preservation. Mitigating the impact of climatic shifts requires a collective effort to enhance storage infrastructure and ensure fair distribution of water resources across sectors.

As part of the OurMED project for the Bode demo site, we aim to enhance water distribution and quality during low-flow conditions. In pursuit of these objectives and in light of the main issues, we have identified two key challenges that could be the subject of analysis through a multi-objective optimisation approach. The first challenge is related to water quantity, and it involves evaluating the potential increase in water availability by utilising groundwater for irrigation during low-flow periods. The second challenge centres on water quality to enhance ecological conditions by implementing innovative water management strategies and controlling nitrate concentrations using nature-based solutions (NbS). In the subsequent sections, we will discuss and articulate these challenges to formulate the proposed optimisation problem.

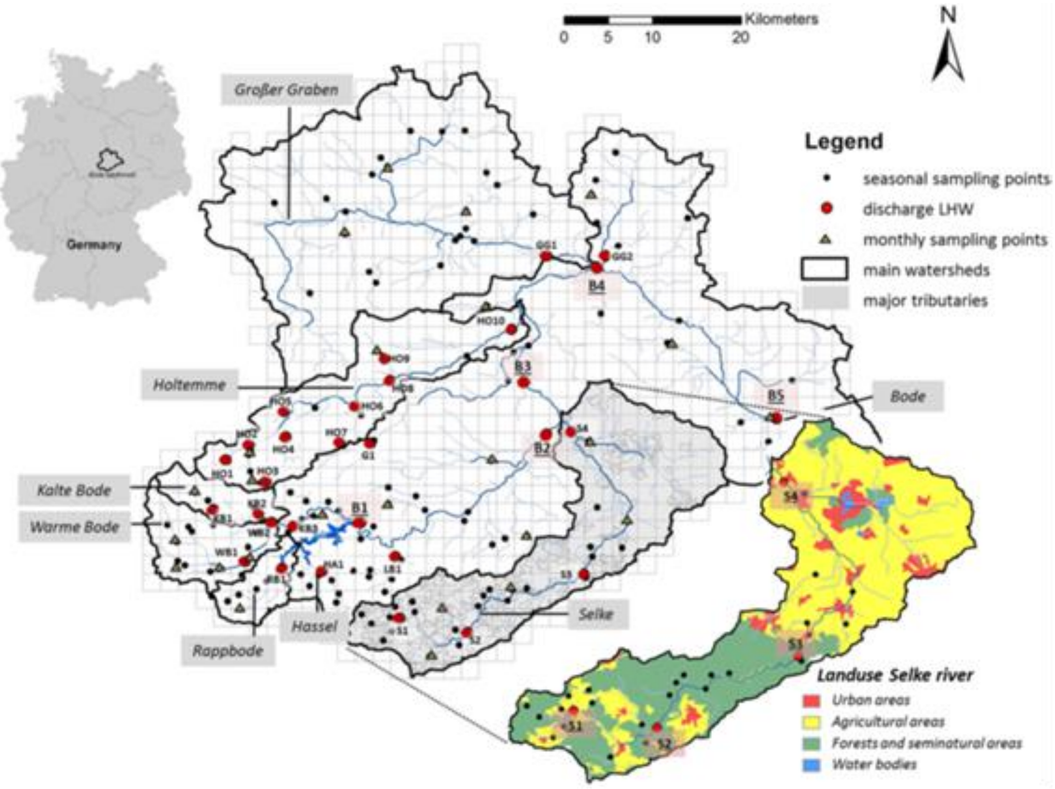

Figure 3 Location of the Bode catchment, including major sub-catchments and the spatial distribution of stream discharge gauges (Mueller, Christin et al. (2016)).

3.1.2. Definition of the Optimisation Problem

3.1.2.1. Objective functions

The multi-objective problem proposed for this demo site consists of three objective functions:

1. Minimising water deficit during low-flow periods:

It's important to note that, compared to summer, water availability is typically sufficient for all needs during winter, with no conflicts arising from quantity. The initial step involves identifying potential water sources to minimise the water deficit in summer and consequently enhance water availability. We have identified four such sources. Firstly, surplus winter water should be efficiently stored in dams or through artificial recharge into groundwater for later use during the summer months. Secondly, groundwater is a viable supplementary water source during summer, regardless of any artificial recharge efforts undertaken during winter. Third, the precipitation available in summer is also counted. Lastly, water typically discharged by reservoirs in the summer must also be considered, contributing to overall water availability.

To take into account the multi-sectorial nature of the problem, we defined the problem in terms of deficits for each sector. So, the optimisation of water availability can be quantified by measuring the deficits in each sector.

$$\min D_{\text{total\_summer}} = \sum_{sector=1}^{nj} \alpha D_{\text{sector}},$$

where $D_{\text{total\_summer}}$ represents the total deficits in water supply experienced by all sectors (it can be domestic, agricultural, recreational, ecological, or fishing) in summer, nj is the number of sectors, α is a coefficient used to prioritize sectors and D_{sector} represents the deficits for each sector in summer and can be calculated by

$$D_{\text{sector}} = (WD_{\text{sector}} - S_{\text{sector}}),$$

where D_{sector} is the deficit for each considered sector, WD is the water demand for each sector, and S_{sector} is the volume of supplied water for a sector; it is calculated as:

$$S_{\text{sector}} = P_{\text{sector}} + GW_{\text{sector}} + SW_{\text{sector}},$$

where P_{sector} represents the water from net precipitation supplied for a sector, GW_{sector} denotes the volume of groundwater supplied, and SW_{sector} is the surface water supplied. SW_{sector} and GW_{sector} are comprised of a portion of the water naturally available in summer and a portion of the winter surplus that was stored in dams, water ponds, or through artificial recharge as follows:

$$SW_{\text{sector}} = SW_{\text{sector, summer}} + SW_{\text{sector, winter}}, and$$

$$GW_{\text{sector}} = GW_{\text{sector, summer}} + GW_{\text{sector, winter}}.$$

The idea of this problem is to increase $SW_{\text{sector, winter}}$ and GW_{sector} to reduce the deficit by increasing the water availability.

2. Maximising dilution capability in summer:

The goal here is to store part of the winter surplus water in water ponds to maximise dilution capability in summer through Nature-Based Solutions (NbS) and to control nitrate concentration. We consider that the overall improvement in dilution capability in summer is a result of the efficiency of the NbS (specifically, water pounds) and the volume of water in a NbS. In this context, the objective function can be formulated as

$$max\ DC = \sum_{i=1}^{n} \epsilon_i \cdot V_{SW_i},$$

where DC is the dilution capablity, ϵ_i is the efficiency of the ith water pound, V_{SW_i} is the volume of water that can be added to the ith water pond, n is the total number of water ponds.

3. Minimising the demand for cooler water to be added to the streams:

During the summer, the water temperature typically exceeds desirable levels, necessitating the utilisation of alternative water sources to cool streams. These water sources remain consistent with those previously referenced $(P + GW + SW)$, and the integration of water for stream cooling constitutes additional water usage. The aim of this objective function lies in minimising the requirement for cooler water during the summer season. This objective function is as follows:

$$min\ WD_{\text{cooler}} = \sum_{s=1}^{n_s} WD_{\text{cooler}_s} \times \left(max(0, T_{\text{current}_s} - T_{\text{max}_s}) + max(0, T_{\text{min}_s} - T_{\text{current}_s})\right),$$

where WD_{cooler_s} represents the water demand for colling stream s, $T_{current_s}$ denotes the current temperature of stream s, ns in the number of streams, and T_{max_s} and T_{min_s} are respectively the maximum and the minimum desirable temperature for stream s.

3.1.2.2. Constraints

The two objective functions are subject to the following constraints:

1. Irrigation relies solely on groundwater sources: $SW_{\text{irrigation}} = 0$, where $SW_{\text{irrigation}}$ refers to surface water allocated for agricultural purposes.
2. The water level in the aquifer should not be less than a predefined threshold value: $h \geq h_{threshold}$, where h represents the water level of the aquifer and $h_{threshold}$ is the groundwater level threshold.
3. The cost of groundwater pumping should remains within the specified budget limit: $CP \leq CP_{max}$, where PC represents the costs of groundwater pumped and CP_{max} represents budget for pumping water.
4. The ecological flow for each day should meet or exceed a predefined threshold value: $EQ_d \geq EQ_{threshold,d}$ for all d, where EQ_d represents the ecological flow to be guaranteed at least on X consecutive days and $EQ_{threshold,d}$ represents the ecological flow threshold. To ensure that there is at least one period of X

consecutive days where the flow is above the $EQ_{threshold}$ we include the following constraint: $\sum_{i=j}^{j+X-1} x_i \geq X$ for some j, with $x_i \in \{0,1\}$ for all i, indicating binary satisfaction (1) or non-satisfaction (0) of the condition.

5. The area allocated for water ponds should not exceed a specified portion of the total available area: $A_{WP} < \%A_{total}$, where A_{WP} represents the area used for water ponds and A_{total} represents the total available area.
6. The expenses associated with constructing water ponds should not exceed the designated funds set aside for this purpose: $Cost_{wp} < Budget_{wp}$, where $Cost_{wp}$ is the total cost to build water ponds and $Budget_{wp}$, represents the funds reserved for building water ponds.
7. the nitrate concentration in the river should not exceed a predefined threshold value: $NC \leq NC_{threshold}$, where NC represents the nitrate concentrations in the river and $NC_{threshold}$ is is the nitrate concentrations threshold.
8. The desirable temperature should falls within the acceptable range defined by the minimum acceptable temperature and the maximum acceptable: $T_{\min_s} \leq T_{\text{desirable}_s} \leq T_{\max_s}$, where $T_{\min_s}$ and $T_{\max_s}$represent the minimum and the maximum acceptable temperatures for stream s, respectively. To ensure that there is at least one period of X consecutive days where the water temperature is above the $T_{\min_s}$ we include the following constraint: $\sum_{i=j}^{j+X-1} x_i \geq X$ for some j, with $x_i \in \{0,1\}$ for all i, indicating binary satisfaction (1) or non-satisfaction (0) of the condition.

3.1.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variables:

1. The volume of water pumped from the aquifers.
2. The volume of water used for artificial recharge (winter surplus).
3. The volume of water stored superficially (winter surplus) – including water ponds.
4. The area of water ponds.
5. The volume of water added to cool the streams.

3.1.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation. Table 1 summarises the available dataset and tools to be utilised at the Bode demonstration site.

Table 1 Datasets, sources, and tools for the Bode demo site.

Dataset	Source/Tool
Discharge Q	mHM-Nitrate
Nitrtate concentration	mHM-Nitrate
Groundwater level	MODFLOW
Water temperature	Conceptual model

3.2. Case Study – Jucan Basin, Albufera Natural Park (Spain)

3.2.1. Problem Contextualisation

The Albufera Natural Park is located 15 km south of Valencia along the Mediterranean coast. It is the largest natural lake on the Iberian Peninsula, covering 24 km^2 with an average depth of 1.0 m. According to the CORINE Land Cover (CLC) program, the Albufera Natural Park exhibits diverse land uses: paddy fields (65%), the lake (12%), orchards (8%), permanently irrigated land (3%), urban areas (2.5%), crops (2%), and coniferous forests (2%). The remaining land serves various agricultural, marshland, tourism, and sports activities.

This biodiverse wetland ecosystem encompasses freshwater lagoons, marshes, and forests, providing crucial habitat for migratory birds and vital *ullals* (springs) supporting diverse plant and animal life. Recognised for its environmental significance, the park holds special protection status at both the community and international levels. Designated a Special Protection Area for Birds (SPA) in April 1991 under the Birds Directive (79/409/EEC), it was listed in the RAMSAR Convention's Wetlands of International Importance in 1989. The Albufera also features habitats and species protected by the Habitats Directive (92/43/EEC). Furthermore, it is part of the Natura 2000 Network. Figure 4 shows the location of Albufera of Valencia.

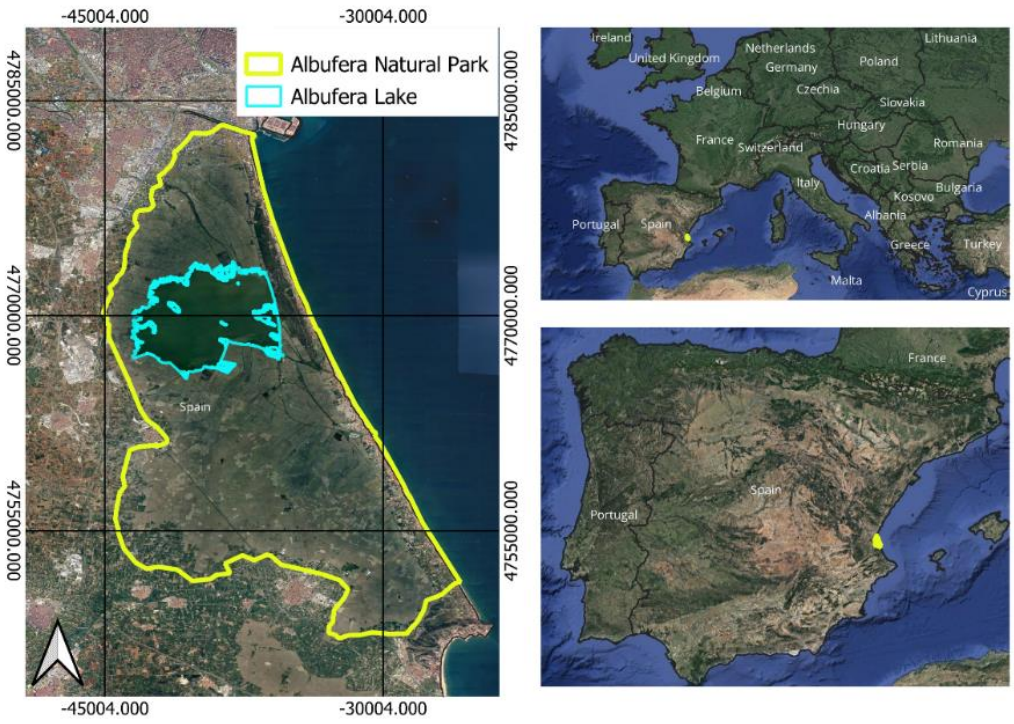

Figure 4 Location of Albufera of Valencia

Despite its ecological importance, the lake has faced challenges from urban and industrial development, serving unintentionally as a wastewater treatment plant for over 40 years. Sanitation measures were initiated in the early 1990s, with engineering techniques evolving to address the lake's deteriorating condition. Traditional hydraulic infrastructures were initially relied upon, but modern approaches now prioritise nature-based solutions. However, despite progress in sanitation efforts, untreated discharges persist, worsening water quality concerns.

Regarding water quality, the lake exhibits hypertrophic characteristics with heightened phytoplankton levels. However, recent years have shown improvement, with a maximum Chlorophyll *a* concentration decreasing to 500 µg Chl a/L and an annual average of 105 µg Chl a/L. Dissolved oxygen (DO) concentrations vary greatly, indicating a stressed aquatic ecosystem. Nutrient concentrations are low due to high recycling rates by phytoplankton, with nitrates showing variability and denitrification playing a significant role. Groundwater data collection, especially near the lake, is limited, but nitrate concentrations exceeding 250 mg/L since 2007 at a nearby spring suggest significant aquifer pressure.

In terms of water quantity, water levels in the lake are managed based on rice and environmental needs, influenced by drought and agricultural practices. Channels called *golas* connect the lake to the Mediterranean Sea, regulated by gates for field water levels. Due to rice cultivation, the hydrological cycle of Albufera is closely linked to irrigation schedules. Gate operation is crucial for water management, with gates opening from January to March for irrigation and closing during the rice growing season (May–September) to limit water flow. They reopen for harvesting in September–October and close again in November–December for *perellonà*, the winter flooding that temporarily expands the lake's surface, promoting nutrient mineralisation and fostering diverse habitats essential for birds' food, rest, and winter shelter. However, crop production remains the priority, and water is allocated to winter flooding only if reservoirs have sufficient water at the end of the irrigation campaign.

Given that our primary goal within the OurMED project is to promote the naturalisation of the Albufera Natural Park within an integrated and multisectoral management framework, we have identified two key challenges that could be the subject of analysis using a multi-objective optimisation approach. The first challenge involves enhancing water quality. The second challenge focuses on improving water availability, particularly concerning water allocation for *perellonà*. To address these challenges, we've outlined two primary strategies. One strategy involves expanding the number of constructed wetlands (CW). These wetlands serve the dual purpose of enhancing the water quality and biodiversity of Albufera Lake. Additionally, they offer a means to mitigate nutrient and suspended solids loads from urban and agricultural runoff. The second strategy revolves around enhancing water availability. This involves leveraging additional sources such as groundwater and treated wastewater from major wastewater treatment plants in the area. In the following subsections, we will mathematically explore and express these challenges to formulate the proposed optimisation problem.

3.2.2. Definition of the Optimisation Problem

3.2.2.1. Objective Functions

The multi-objective problem proposed for this demo site consists of two objective functions:

1. Maximising water quality improvement in the Albufera:

Here we consider that the overall improvement in water quality is a direct result of the presence of constructed wetlands, which have demonstrated remarkable efficiency in increasing biodiversity and diminishing nutrient loads. In this context, the objective function can be formulated as

$$max\ WQI = \sum_{i=1}^{n} \epsilon_i \times V_{CW_i} \ ,$$

where WQI is the water quality improvement, ϵ_i is the efficiency of the ith constructed wetland, V_{CW_i} is the volume of improved water from in the ith constructed wetland, and n is the total number of constructed wetlands.

2. Maximising water swap:

Clean water, that usually is designated for irrigation, could be swapped with treated water from wastewater treatment plants (WWTP), thus allowing the clean water to be redirected to the lake enhancing the dilution capability and improving the water quality. The second objective function can be formulated as

$$min\ \mathrm{WS} = \left(\frac{V_{SW}}{V_{WWTP}}\right),$$

where V_{SW} denotes the total volume of treated water swapped with clean water to be redirected to the lake, and V_{WWTP} is the total volume of treated water that is produced by the WWTP.

3. Minimise water deficit for *perellonà (*winter flooding*)*:

The idea is to identify potential water sources to increase the water availability for *perellonà*, reducing the deficit. We have identified three additional sources of water. Firstly, when irrigation is not needed during winter, treated water from WWTP could be directed to the *perellonà*. Second, water stored in CW in the summer months could be used for *perellonà* in the winter. The third and last one is the groundwater, which should only be used for Perellonà if there is insufficient water from the other three sources. In this context, the objective function can be formulated as

$$min\ D_{\text{perellonà}} = V_P - (V_{WWT_P} + V_{CW_P} + V_{GW_P})\ ,$$

where V_P is the volume of water required for the *perellonà*, V_{WWT_P} is the volume produced by WWTP and that is redirected to the *perellonà*, V_{CW_P} is the volume of water from constructed wetlands that is used in *perellonà*, and V_{GW_P} is the volume of groundwater used for *perellonà*. The groundwater could be pumped from wells or it could be stored in ponds from springs.

Constraints

The two objective functions are subject to the following constraints:

1 The area available for constructing new wetlands is constrained by the existing land availability allocated for this purpose: $A_{CW} \leq \%A_{total}$, where A_{CW} represents the area used for CW and A_{total} represents the total available area.

2 The total expenditure for constructing wetlands must not exceed the designated budget for this purpose: $Cost_{CW} \leq Budget_{CW}$, where $Budget_{CW}$ denotes the funds reserved for building CWS.

3 The total cost associated with pumping groundwater for the *perellonà* must not surpass the allocated budget for this purpose: $Cost_{GW\_P} \leq Budget_{GW\_P}$, where $Budget_{GW\_P}$ denotes the funds reserved for pumping groundwater for the *perellonà*.

4 The total groundwater pumped for the *perellonà* must not exceed the maximum allowable volume: $V_{GW\_P} \leq V_{GW\_P}, max$, where V_{GW_P}, max is the maximum volume allowed to be pumped.

3.2.2.2. Decision Variables

In the context of the stated problem, we have identified the following decision variables:

1. Area allocated for constructed wetlands.
2. Volume diverted from the wastewater treatment plant to agriculture and the *perellonà*.
3. Volume to be pumped for the *perellonà*.

3.2.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation. Table 2 summarises the available dataset and tools to be utilised at the Jucar demonstration site.

Table 2 Datasets, sources, and tools for the Jucar demo site.

Dataset	Source/Tool
Discharge	Aquatool – SIMGES/ Autonomous Community Authority
Amount of wastewater from WWTP	Public Entity for Wastewater Sanitation of the Valencian Community

Nitratate concentration	Aquatool - GESCAL
Groundwater level	MODFLOW/Water Authority
Water quality data	Water and Autonomous Community Authorities
Efficiency of the constructed wetlands	Conceptual model
Costs associated with pumping and CW	Experts
Meteorological data	State Meteorological Agency – AEMET and Valencian Meteorological Association

3.3. Case Study – Agia (Greece)

3.3.1. Problem Contextualisation

The basin of the Keritis River is one of the most important hydrological basins of the prefecture of Chania. It is in the centre of the prefecture, has an area of about 210 km^2 with an average altitude of 734 meters and lies 12 km southwest of Chania. It is located between the geographical coordinates 35 15' - 35 32' north latitude and 23 45' - 23 55' east longitude. The river delta and the reservoir of Agyia are protected areas within the NATURA 2000 network. The Therisos basin is located 3 km from the city of Chania. It has a small area of about 60 km^2. The main river of the basin area is the Kladissos. Its sources are in the White Mountains, while it flows west of Chania. Due to its tiny area, the basin area of Therisos is studied as part of the Keritis basin area, so we speak of a single Keritis-Therisos basin area.

The study area has a sub-humid Mediterranean climate with cold, humid winters and warm, dry summers, starting typically in November. Annual precipitation in Agyia’s catchment area is around 260 Mm^3, with 37% (96 Mm^3) infiltrating the ground and 20% (53 10 Mm^3) running off. Mean annual evaporation ranges from 43–58% of total precipitation. Rainfall mainly occurs in winter, with a drought period from May to October. Monthly evaporation varies from 140 mm to over 310 mm, impacting water availability due to precipitation fluctuations.

Keritis-Therisos basin area exhibits diverse land uses: natural grassland dominates (29.23%), alongside extensive olive groves (21.13%), reflecting the importance of agricultural activity. Sclerophyllous vegetation (19.21%) signifies Mediterranean flora, while fruit trees and berry plantations (9.65%) add agrarian diversity. Forests (6.90%) support varied wildlife. Other features include agricultural lands, urban areas, moors, vineyards, and more.

The Keriti-Therisou basin is renowned for its ample water resources, serving as a crucial supply for much of Chania Prefecture. Water allocation in Chania is crucially distributed across various sectors, including agriculture, domestic consumption, industrial operations, and tourism. Most of the water resources in the Keriti-Therisou basin come from the karst aquifer of Agia, which is also the primary water source in the area. This aquifer sustains numerous wells and springs across the region, supporting irrigation and general water needs. Key among these sources are the Platanos and Kolymba springs of Agia, alongside the significant Kalamionas spring. Complementing these natural sources are strategically positioned pumping wells within the watershed, strategically located above the aquifer's drainage zone.

Figure 5 shows the Keritis basin in green, in purple colour the Therisos basin; the square is the modelled area, with red dots for the well locations and blue dots for the location of Agia Lake.

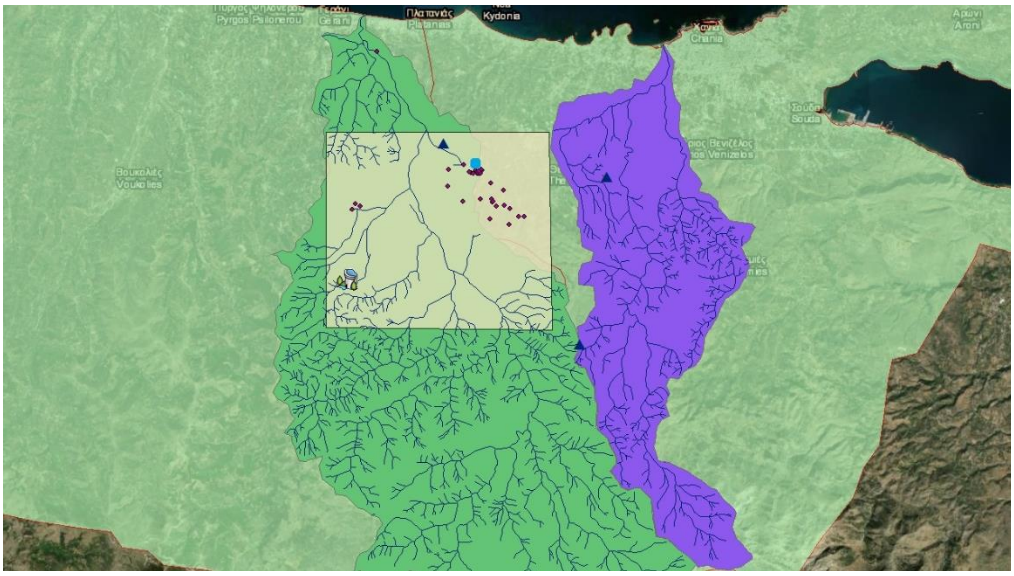

Figure 5 The Keritis basin area and the groundwater model area.

The region's ongoing initiatives involve managing water extraction from Platanos, Kolympa, and Kalamionas springs and supervised pumping wells by the Municipal Water Supply and Sewerage Companies of Chania (DEYACH), the Development Organization of Crete S.A. (OAK), and the Local Land Reclamation Organizations (TOEB). DEYACH primarily retrieves water from the Platanos spring for urban distribution in Chania, supplemented by water from pumping wells. Previously, DEYACH also utilised pumping wells owned by OAK. In the Myloniana region, OAK manages pumping wells with a 4750 m^3/hour capacity, drawing water from the same aquifer as Agyia springs. These wells operate mainly from May to November, extracting an estimated 14 Mm^3 of water primarily for irrigation. Another OAK pumping station near Patelari extracts water from Lake Agyia and Kalamionas Spring, mainly from April to November, for irrigation and water supply in the Kolymvari region. TOEB exclusively extracts water from the Kolymba spring to irrigate 12,000 hectares, operating two wells primarily from April to September, with an annual abstraction of 4 Mm^3.

In addition to those initiatives, the water management strategy in the area encompasses the management of Agyia Lake, a small water body spanning approximately 0.2 km^2 with an average depth of 4 m. At its maximum, Lake Agyia covers a surface area of 120,325 m^2 when the water level is 38 m above sea level, containing a volume of 215,138 m^3. However, at 37 m, the surface area decreases to 87,775 m^2, while the volume reduces to 104,050 m^3.

Despite the management initiatives, the significant human intervention, in particular, the excessive abstraction of water for irrigation during periods of low rainfall, has disrupted the natural balance of nutrients in the lake and contributed to the lake's increasing shallowness due to sedimentation. Consequently, the cumulative effect of these human activities has led to a deterioration in the water quality of Lake Agia.

Within the scope of the OurMED project for the Agia demonstration site, our objective is to enhance the equitable distribution of surface water and groundwater among various stakeholders, including farmers, agriculturalists, municipalities, and hotel proprietors. To achieve this, we have identified two primary challenges that lend themselves to analysis through a multi-objective optimisation methodology. The first challenge entails ensuring the preservation of Agia Lake's water levels during groundwater extraction, which can also help support biodiversity conservation and lake restoration efforts. The second challenge centres on minimising the expenses associated with groundwater extraction. We will mathematically explore these challenges in the following subsections to formulate the proposed optimisation problem.

3.3.2. Definition of the Optimisation Problem

3.3.2.1. Objective Functions

The Agia aquifer's groundwater management problem formulation methodology is based on previous research at the Geoenvironmental Engineering Laboratory at the Technical University of Crete, published in the Journal of Hydrology in 2007 (Karterakis et al., 2007). Herein, the methodology is extended to a multi-objective formulation focusing on maximising Agia's pumping quantity and minimising the total pumping cost.

1. Maximising the total extracted groundwater volume from n pre-selected pumping locations (production wells):

$$max \sum_{i=1}^{n} q_{i,season,}$$

where i represents a production well, q_i represents the pumping rate at each well, and $season$ represents the management period, which can be dry or wet.

2. Minimising the total costs of groundwater abstraction:

$$min \sum_{i=1}^{n} q_{i,season} C_o \left(H_i - h_{i,season}\right) T_{sp,}$$

where C_o represents the pumping cost/depth, H_i is the surface elevation of the well location i, h_i is the hydraulic head at the location i at the end of the stress period, and T_{sp} is the time length of the stress period.

These equations can be merged as follows:

$$max\ \alpha \sum_{i=1}^{n} q_{i,season} - (1-\alpha) \sum_{i=1}^{n} q_{i,season} C_o \left(H_{i,season} - h_{i,season}\right) T_{sp,}$$

where α is a coefficient within [0,1] used to prioritize between the conflictive objectives. It will be determined either manually or as a result of the Paretto front.

3.3.2.2. Constraints

The two objective functions are subject to the following constraints:

1. The surface elevation must be greater than or equal to the reference surface elevation: $h_{i,season} \geq H_{i,season_{ref}}$, where $H_{i,season_{ref}}$ represents the hydraulic head reference at each location i for the considered $season$ dry or wet.
2. The sum of the amount of water supplied by each well must not exceed the total water demand: $\sum_{i=1}^{n} q_{i,season} \leq \sum_{i=1}^{n} Q_{i,season}$, where $Q_{i,season}$ denotes the water needs to be supplied for well i and $0 \leq q_{i,season} \leq Q_{i,season}$.

3.3.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variable:

1. The pumping rates at each well.

3.3.3. Datasets and Tools

The data necessary for conducting the proposed multi-objective optimisation are linked to the impacts of groundwater pumping on the Agia aquifer. Table 3 summarises the required datasets, their respective sources, and the decision variables directly associated with them.

Table 3 Datasets, sources, and tools for the Agia demo site

Dataset	Source/Tool
Hydraulic heads	A groundwater model using the Princeton Transport Code (PTC)
Well locations	Municipal Water Supply and Sewerage Companies of Chania (DEYAX)
Pumping rates	Development Organization of Crete S.A. (OAKAE)
Costs (pumping)	Municipal Water Supply and Sewerage Companies of Chania (DEYAX)

3.4. Case Study – Arborea (Italy)

3.4.1. Problem Contextualisation

The Italian demo site is in the rural district of Arborea (about 60 km^2), central-western Sardinia (Italy). This district includes the villages of Arborea, Marrubiu and Terralba, with a population of around 18,800 and is included in the irrigation and land reclamation consortium of Oristanese, out of which approximately 36,000 hectares are served by irrigation and 15,000 hectares are irrigated (85,363 ha overall, of which some 36,000 served by irrigation and 15,000 irrigated). The region has a Mediterranean climate with an average annual temperature of 16.7°C and yearly precipitation of 575 mm, mainly from October to March. Annual reference evapotranspiration is 1164 mm, making it semi-arid. The temperature has risen, leading to more frequent heatwaves impacting agriculture, especially dairy farming. Rainfall trends aren't clear, but extreme events like dry spells and flooding are noted. The coastal area faces strong western winds and other conditions.

Dairy farming in the Arborea Plain relies on imported grains, local silage maise, and Italian ryegrass. Most of the area also grows horticultural crops, with fish farming in nearby wetlands. Previously, alfalfa was grown, but it's now imported. The sandy soil, enriched by intensive animal effluent fertilisation, faces challenges due to high nitrogen and phosphorus levels, leading to groundwater pollution. Since 2005, the area has been designated a "Nitrates Vulnerable Zone" (NVZ), requiring strict regulations, but compliance poses financial challenges and controversies. Figure 6 shows the Arborea demo site and its NVZ. Despite efforts, nitrate levels remain high, exacerbated by slow aquifer turnover. Maintaining soil fertility is crucial, but reducing organic effluent inputs raises concerns among farmers.

Overall, water availability for irrigation does not represent a challenge in this district. The Eleonora d'Arborea dam, one of the biggest in Europe, is sufficient to feed all the irrigated consortium downstream, including paddy rice (12000 m^3/ha), dairy livestock farms and horticultural farms. Groundwater is used for non-drinking purposes (washing livestock facilities, cattle watering, and industrial processes). On the other hand, several concerns related to water quality were identified in surface and groundwater.

In surface water, the Regional Agency for Environmental Protection (ARPAS) has monitored surface water quality in the NVZ since 2007, measuring various parameters. Nitrate rarely exceeds 50 mg/L, mostly below 20 mg/L, indicating low pollution. Total phosphorus levels occasionally surpass 2.0 mg/L, suggesting eutrophication is more linked to phosphorus than nitrate.

In groundwater, extensive hydrogeological studies conducted between 2010 and 2015 in the Arborea Plain revealed significant nitrate pollution. Over 350 wells associated with aquifers were examined, showing nitrate concentrations ranging from 1.58 to 406 mg/L, almost 50% exceeding WHO's recommended threshold. Pollution sources were identified within and outside the designated NVZ. In addition, an increasing trend from east to west in the direction of the main groundwater flow prevailed, highlighting an additional pollution source outside the Arborea NVZ. Agronomic studies demonstrated the challenges in reducing nitrate leaching, especially during autumn-winter. Isotopic surveys confirmed organic fertilisers as the primary nitrate source, with denitrification processes occurring in the aquifer. ARPAS has been monitoring groundwater quality since 2007, with nitrate concentrations exceeding thresholds in 18 out of 44 sampling points across the NVZ.

Figure 6 Arborea demo site and its nitrate vulnerable zone (NVZ).

As part of the OurMED project for the Arborea demo site, we aim to enhance the quality of both groundwater and wetlands. In pursuing these objectives and considering the main issues and current situation, we have identified two key challenges that could be the subject of analysis through a multi-objective optimisation approach. The first is related to controlling the source of nitrates in groundwater and wetlands by promoting changes in soil use. The second challenge centres on enhancing ecological conditions by implementing innovative water management strategies and controlling nitrate concentrations using nature-based solutions (NbS). In the subsequent sections, we will discuss and articulate these challenges to formulate the proposed optimisation problem.

3.4.2. Definition of the Optimisation Problem

3.4.2.1. Objective Functions

The multi-objective problem proposed for this demo site consists of two objective functions:

1. Minimising nitrate leaching losses:

Here, the proposal is to minimise the nitrate leaching (NL) into groundwater and wetlands by promoting changes in soil use and consolidating smaller farms into larger ones for better fertiliser management. This process has already started on the demo site, and it will have good acceptance from stakeholders.

$$\min NL\,(s, c, i, mp),$$

where s denotes soil properties, c is climatic conditions like precipitation, i represents initial conditions of nitrogen application, and mg represents management practices, including those produced by changes in the size of the farms.

2. Maximising water quality improvement:

Here, we consider that the overall improvement in water quality is a direct result of the presence of constructed wetlands, which have demonstrated remarkable efficiency in increasing biodiversity and diminishing nutrient loads in another demo site. In this context, the objective function can be formulated as

$$max\ WQI = \sum_{i=1}^{n} \epsilon_i \times V_{CW_i}\ ,$$

where WQI is the water quality improvement, ϵ_i is the efficiency of the ith constructed wetland, V_{CW_i} is the volume of improved water from in the ith constructed wetland, and n is the total number of constructed wetlands.

3.4.2.2. Constraints

The two objective functions are subject to the following constraints:

1 The area available for constructing new wetlands is constrained by the existing land availability allocated for this purpose: $A_{CW} \leq \%A_{total}$, where A_{CW} represents the area used for CW and A_{total} represents the total available area.

2 The total expenditure for constructing wetlands must not exceed the designated budget for this purpose: $Cost_{CW} \leq Budget_{CW}$, where $Budget_{CW}$ denotes the funds reserved for building CWS.

3 The total amount of nitrogen applied must not exceed the crop's nitrogen uptake capacity: $N_{\text{applied}} \leq \sum_{i=1}^{nc} N_{\text{uptake\_crop\_i}}$, where N_{applied} represents the total amount of nitrogen applied and $N_{\text{uptake\_crop\_i}}$ is the nitrogen uptake capacity for crop i.

4 The total area of each consolidated farm must falls within the allowable range: $A_{min} \leq A_j \leq A_{max}$, where A_j represents the total area of the jth consolidated farm and A_{min} and A_{max} denote the minimum and maximum allowable sizes for consolidated farms, respectively.

3.4.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variable:

1. The initial amount of fertiliser
2. The type of fertiliser
3. The area allocated for constructed wetlands
4. Cultivated Area
5. Area of each crop

3.4.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation. Table 4 summarises the possible dataset and tools to be utilised at the Arborea demonstration site.

Table 4 Datasets, sources, and tools for the Arborea demo site

Dataset	Source/Tool
Nitratate concentration	Aquatool - GESCAL
Efficiency of the constructed wetlands	Conceptual model/ bibliography
Costs associated with pumping and CW	Experts
Meteorological data	ARPAS - Regional Meteoclimate Specialist Department
Transport of water and solutes in the soil	DAISY

3.5. Case Study – Mujib (Jordan)

3.5.1. Problem Contextualisation

The Mujib River Basin (MRB) is a distinctive geographic area in Jordan, covering around 7% of the country's land. Situated at 31°16'53.76" N, 36° 4'18.54" E, it spans 6,600 km^2, mainly semi-arid to arid plateau terrain. Figure 7 shows the location of Mujib River Basin, which comprises two main catchments, W. Mujib (4,537 km^2) and W. Wala (2,056 km^2), with key tributaries like Mujib and Al-Haidan merging at a point known locally as Malaqi before reaching the Dead Sea. The Mujib Basin has a Mediterranean climate with hot, dry summers and cool, wet winters. Precipitation in the catchment ranges from 350 mm/year in the mountains to 100 mm/year near the Dead Sea. Meanwhile, potential evaporation ranges from 2450 mm/year near the Dead Sea to 3500 mm/year in the eastern sections of the catchment. More than 91% of the rainfall goes for evaporation.

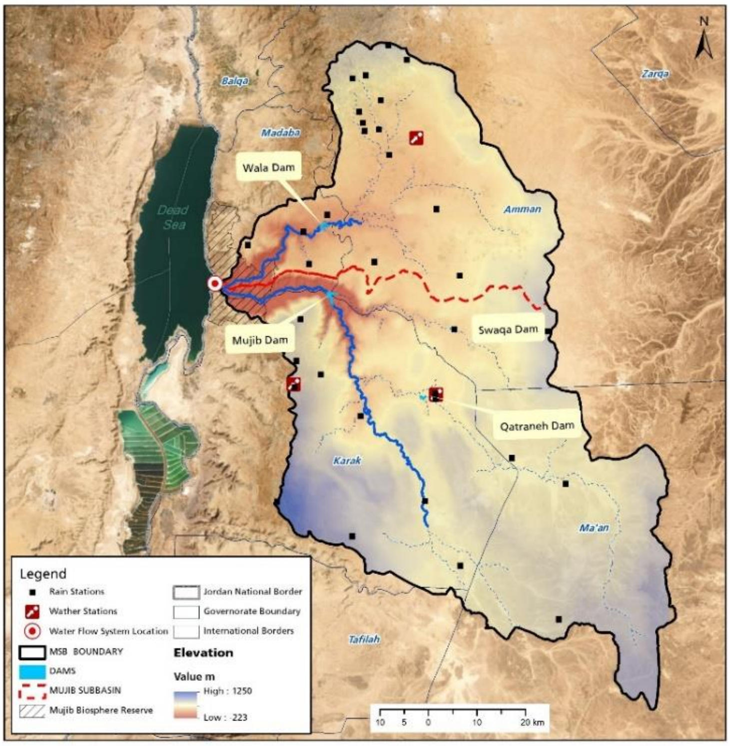

Figure 7 Location of Mujib River Basin.

The MRB encompasses various primary land uses, including bare soil, agricultural areas, tourist sites, residential and industrial zones, rangelands, and water collection structures of different sizes. Additionally, it is home to the Mujib Biosphere Reserve, the world's lowest-altitude natural reserve, at 420 meters below sea level in the western part of the basin. The reserve encompasses and is surrounded by the majority of the natural flow in the area, highlighting its crucial role in conserving the basin's ecological balance.

The MRB relies on surface water (including brackish water) and groundwater. Drinking and domestic use account for 52% of water in the MRB. Groundwater resources cover most of this use, while surface water is divided into drinking, agriculture, industry, and groundwater recharge.

The Dead Sea groundwater basin is a vital source that supplies about 8% of Jordan's groundwater. With annual pumping at 79.41 Mm^3 and a recharge rate of 39.1 Mm^3/year, the basin faces challenges due to population growth and illegal well operations, leading to a rapid decline in aquifer levels. Surface water resources in the MRB primarily comprise dams, ponds, excavations, and springs. Among these, the Mujib Dam stands out as the largest dam in the MRB, followed by the Wala and Allujon dams. These dams were constructed to provide a consistent and sustainable water supply to recharge the aquifer for drinking and agriculture purposes. In addition, local springs sustain the base flow to the Dead Sea, ranging from 20 Mm^3 to 35 Mm^3 annually during wet years. Around 5% of this flow, including springs like Ein Sarah and Al-Shababaiah, is utilised for domestic water demands.

The majority of the discharged water, including floodwater, is utilised downstream near the Dead Sea to meet various demands, such as supplying water to Amman city, Dead Sea hotels, and partially to the South Shoneh district, totalling around 20 Mm^3 per year on average according to Jordan Valley Authority (JVA) reports. In addition, the Mujib reserve, located downstream of the Mujib and Wala lower catchments near the Dead Sea, needs a continuous environmental flow from both Mujib and Wala Streams that is estimated to be nearly 5 Mm^3 where most of it is being reused after satisfying the environmental needs. Figure 8 shows a schematic of the surface water distribution system in the MRB.

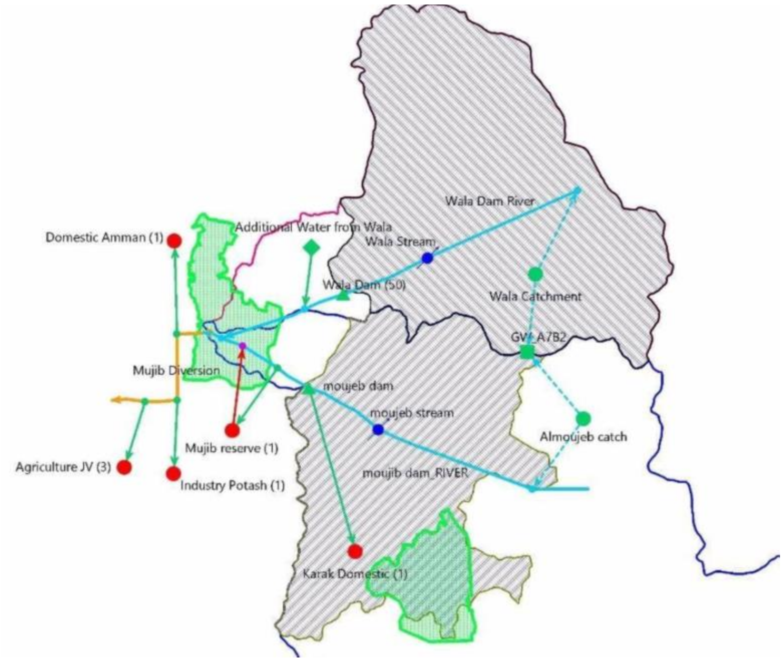

Figure 8 Schematic of the surface water distribution system in the MRB.

In 2020, amidst growing concerns over water scarcity and conflict, the International Union for Conservation of Nature (the Regional Office of West Asia) and the Royal Society for the Conservation of Nature introduced a pivotal initiative: developing a Water

Evaluation And Planning System (WEAP). This system is a crucial decision-making tool for effectively managing water resources within the MRB.

Within this initiative, a set of recommendations has been outlined for facing the complex challenges associated with water management. These include the imperative monitoring of discharge rates, comprehensive assessment of sediment levels within reservoirs, reevaluation of downstream water demands, exploration of alternative water sources, and implementation of drought and flood management strategies.

Given these recommendations and our objectives within the OurMED project to promote the integrated river basin management concept, ensuring sustainability and fostering a win-win situation for all stakeholders, we have identified two key challenges that could be the subject of analysis using a multi-objective optimisation approach. The first one involves aiding policy-making processes for sustainable management of the allocation of water resources with a particular focus on conflicts over water sharing between the agricultural and industrial sectors. At the same time, Mujib Reserve maintains its ecological flow. The second involves the evaluation of some instruments of Water Regulation acting in demand management and supply management to increase the overall water availability. The following subsections will mathematically explore and express these challenges to formulate the proposed optimisation problem.

3.5.2. Definition of the optimisation problem

3.5.2.1. Objective Functions

The multi-objective problem proposed for this demo site consists of two objective functions:

1. Minimising conflicts over water sharing:

We have assumed that the conflicts primarily arise from one sector experiencing a water deficit when the other sector utilises the water. It can be quantified by assessing the deficit in water supply following the allocation of water shares. Therefore, the objective function takes the following form:

$$min\ D_{\text{total,m}} = \sum_{sector=1}^{j} \mu_{\text{sector}} \left(\alpha_{\text{up}}\, D_{\text{sector,up,m}} + \alpha_{\text{down}}\, D_{\text{sector, down,m}}\right),$$

where $D_{\text{total,m}}$ represents the total deficits in water supply experienced by all sectors (it will be agricultural and industry) upstream and downstream per month m, α_{up} and α_{down} are coefficientsused to prioritise between upstream and downstream, respectively, and $\mu_{\text{up}}$is used to prioritise among sectors. The monthly deficits for each sector upstream can be calculated by

$$D_{\text{sector,up,m}} = \sum_{z\_up=1}^{nz\_up} \beta_{\text{zone\_up}} \left(WD_{\text{sector,up,m,z\_up}} - S_{\text{sector,up,m,z\_up}}\right),$$

while the monthly deficits for each sector downstream can be calculated by

$$D_{\text{sector,down,m}} = \sum_{z\_down=1}^{nz\_down} \beta_{\text{z\_down}} \left(WD_{\text{sector,down,m,z\_down}} - S_{\text{sector,down,m,z\_down}}\right),$$

where m is the month, D is the deficit for each considered sector, WD is the water demand, up and down are upstream and downstream, respectively, z_up and z_down represent different upstream and downstream demand zones, respectively, and $\beta_{\text{z\_up}}$ and $\beta_{\text{z\_down}}$ are used to prioritize between upstream and downstream demand zones. S_{sector} is the volume of supplied water for a sector; it is calculated upstream as:

$$S_{\text{sector,up,m,z\_up}} = P_{\text{sector,up,m,z\_up}} + GW_{\text{sector,up,m,z\_up}} + SW_{\text{sector,up,m,z\_up}},$$

and downstream as

$$S_{\text{sector,down,m,z\_down}} = P_{\text{sector,down,m,z\_down}} + GW_{\text{sector,down,m,z\_down}} + SW_{\text{sector,down,m,z\_down}},$$

where $P_{\text{sector,down,m,zone}}$ represents the monthly water from net precipitation supplied for a sector downstream in a demand zone, $GW_{\text{sector,m}}$ denotes the monthly volume of groundwater supplied, and $SW_{\text{sector,m}}$ is the monthly surface water supplied and it includes surface water naturally presents in the streams (if downstream, it includes the reuse of water after satisfying the environmental needs) and the discharged water.

2. Maximising overall groundwater sustainability:

Here, we assume that naturally, the aquifer is in equilibrium, that is, input (recharge) equals output (discharge). However, the aquifer is being altered artificially by recharge and pumping. In this case, groundwater sustainability is achieved when the volume abstracted from the aquifer by pumping is less than the volume of water resources available in the aquifers. The objective function has the form of

$$max\left(\frac{R}{\sum_{sector=1}^{j} GW_{\text{sector}}}\right),$$

where R represents the volume of total available groundwater resources (including water from artificial recharge) and GW_{sector} represents the volume abstracted by pumping for each sector j (here, we must consider all sectors that use groundwater).

3.5.2.2. Constraints

The three objective functions are subject to the following constraints:

1. Groundwater will not be used upstream for industrial uses: $\sum_{z\_up=1}^{nz\_up} GW_{\text{industry,up,m,z\_up}} = 0.$

2. Groundwater will not be used downstream for industrial uses: $\sum_{z\_up=1}^{nz\_down} GW_{\text{industry,down,m,z\_down}} = 0.$

1. The amount of water available for domestic consumption should exceed the amount of water required for domestic needs: $S_{\text{domestic}} > WD_{\text{domestic}}.$

2. The amount of water allocated for ecological purposes should surpass the minimum amount required to maintain ecological balance and preserve natural

habitats: $S_{\text{ecological}} > WD_{\text{ecological}}$, where $S_{\text{ecological}}$ is the supplied water for ecological flow and $WD_{\text{ecological}}$ denotes the demand necessary to ensure ecological flow.

3. The total water abstraction should not exceed the specified maximum allowable volume: $\sum_{sector=1}^{j} GW_{\text{sector}} < GW_{\max}$, where $GW_{\max}$ is the maximum volume allowed to be abstracted.

3.5.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variable:

1. The volume that is pumped by each sector.
2. Industrial and agricultural demands.
3. The volume used for artificial recharge.

3.5.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation.

Table 5 summarises the available dataset and tools to be utilised at the Mujib demonstration site.

Table 5 Datasets, sources, and tools for the Mujib demo site

Dataset	Source/Tool
Water uses (Domestic, Industrial, and Agriculture)	Ministry of Water and Irrigation
Water source	Ministry of Water and Irrigation
Metrological data (Monthly and daily rainfall data for 30 years from 1988 – 2023)	Ministry of Water and Irrigation
Monthly and daily rainfall data	Ministry of Water and Irrigation
Historical data that are related to dams (Storage, Water levels, Inflows, Outflows, Storage capacity)	Ministry of Water and Irrigation
Reference evaporation (ETo) (FAO Method)	Ministry of Water and Irrigation
Crop Coefficient (Kc)	Ministry of Water and Irrigation

Water allocation to different sectors	WEAP

3.6. Case Study – Sebou (Morocco)

3.6.1. Problem Contextualisation

Nestled in the heart of Morocco, the Sebou basin sprawls across an impressive expanse of 40,000 km^2, serving as a linchpin within Morocco's hydrological network. Beyond being one of the nation's largest river systems, it is a lifeline for over 6 million residents, nurturing diverse ecosystems and sustaining vital socio-economic activities. Its terrain, ranging from rugged mountains to fertile plains, harbours rich biodiversity and ecological treasures shaped by the Mediterranean climate and the varying rainfall patterns across the region.

Agriculture dominates land use in the Sebou Basin, occupying 60.01% of its territory, establishing it as a pivotal agricultural hub. Urban areas claim a modest 2.76%, while natural vegetation blankets 34.61%, highlighting the basin's ecological wealth. The Sebou River, alongside key tributaries like the Ouergha and Inaouene, weaves through diverse landscapes, fostering a vibrant tapestry of life. Notably, the basin hosts extensive wetlands, including Ramsar sites of global significance, which are crucial for biodiversity conservation, water purification, and flood regulation.

Beneath its surface lies a wealth of groundwater resources, constituting a quarter of Morocco's mobilisable potential. Stored in various aquifers like Dradère-Souière and Mamora, these resources sustain water demands and bolster the nation's water security. However, despite a substantial net groundwater contribution of 1579 Mm^3/year, factors like outflows to rivers and direct withdrawals constrain exploitable potential to 1020 Mm^3/year, resulting in an annual deficit and declining groundwater levels.

The basin's water infrastructure comprises 10 large dams and 45 smaller ones, collectively regulating 1,830 Mm^3 of water. These reservoirs drive socio-economic progress and are vital for irrigation, potable water supply, energy generation, flood control, and salinity management. Yet, alongside advancements in water management techniques, challenges persist, including water over-exploitation, pollution from agricultural and industrial sources, habitat degradation, and ageing infrastructure, exacerbated by climate change.

The Sebou Basin is committed to an integrated water management strategy, encompassing the modernisation of irrigation techniques, the adoption of cutting-edge water treatment technologies, and the implementation of rigorous conservation measures. These initiatives are designed to safeguard the basin's water resources amidst rising demand and the complexities posed by climate change. However, persistent challenges remain, including balancing water demand with conservation efforts, combating water over-exploitation, mitigating pollution from agricultural and industrial activities, addressing habitat degradation, and upgrading ageing water infrastructure. The urgency of these issues is further underscored by the exacerbating effects of climate change, emphasising the necessity for innovative, holistic water management approaches and strengthened governance measures.

Due to the huge area of the basin, the optimisation problem will be defined only for the Moyen Sebou sub-basin, specifically in the zone of Dayet Aoua Lake, due to its interesting aspects and conditions that outline conflict multi-sectoral objectives. The region has suffered from intensive agriculture impacts for some decades, mainly of apple crops requiring a large amount of irrigated water. As the surrounding groundwater is the primary or only water source for irrigation in this region, the lake started to reduce its volume in 1980 due to the intensive and continuous groundwater abstraction and climate change impacts, reaching dry conditions nowadays. Due to the cultural and economic values of the lake, Living Planet Marrocco, together with other stakeholders and authorities, suggested some strategies to restore the lake environment, such as assessing better irrigation systems to reduce the amount of water used for irrigation and encouraging farmers to plant other crops that require less irrigated water, especially in dry periods. Although only a few farmers have implemented the new irrigation system, they realized it could save up to 40% of the water used for irrigation. Figure 9 shows the sub-basin within the Sebou basin.

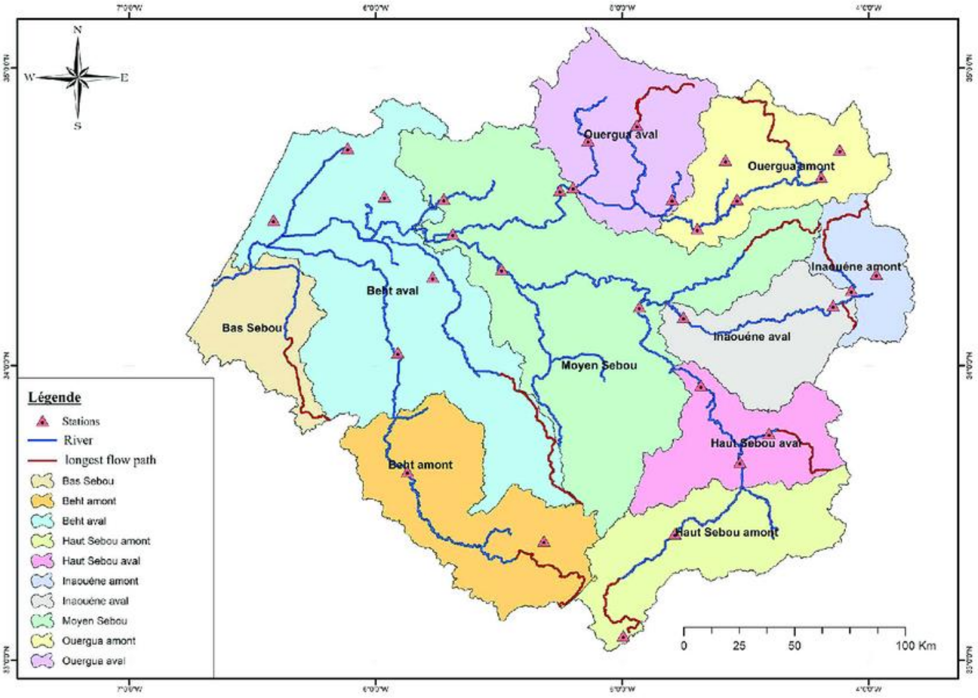

Figure 9 Location of the sub-basins within Sebou Basin (Jabri et al., 2022).

As part of the OurMED project for the Sebou demo site, our goals are to optimise water use efficiency, improve water quality, and enhance the resilience of local communities and ecosystems to climate change impacts. In pursuing these objectives and considering the main issues identified in the selected zone, we have identified two key challenges for exploration through a multi-objective optimisation approach. The first challenge involves maintaining the economic activities associated with apple orchards. The second challenge is to restore lake levels for recreational use and to serve as an ecological service provider. In the subsequent sections, we will discuss and articulate these challenges to formulate the proposed optimisation problem.

3.6.2. Definition of the Optimisation Problem

3.6.2.1. Objective Functions

The multi-objective problem proposed for this demo site consists of three objective functions:

1. Maximise apple production:

$$max\ AP = \sum_i (Y_i \cdot A_i),$$

where Y_i is the yield (production per unit area) of crop i, for apples, this would be Y_{apple} and A_i is the area allocated to crop type i.

2. Minimise the drop in levels in the aquifer:

$$min\ DropGW = GW - \sum_i (I_i \times A_i \times \epsilon_i),$$

where I_i is the irrigation requirement per unit area for crop i, and ϵ_i is the irrigation system's efficiency. The term GW represents the total groundwater pumping.

3. Recover the lake:

$$max\ Wlake = GW_{\text{in}} + S_{\text{in}} + W_l - E - W_{\text{out}},$$

where GW_{in} is the groundwater inflow to the lake, S_{in} is the surface water inflow to the lake, W_l is the water allocated to the lake as a management strategy, E is the evaporation loss from the lake, and W_{out} is the water withdrawal from the lake.

3.6.2.2. Constraints

The three objective functions are subject to the following constraints:

3. The volume of groundwater supplied is limited to a maximum allowable value to ensure sustainable use of the aquifer: $GW \leq GW_{max}$
4. The cultivated area of each crop must be less than the available land resources: $0 \leq A_i \leq A_{max}$
5. The irrigation system's efficiency should remain within a feasible range: $0 \leq \epsilon_i \leq 1$
6. The water allocated to the lake must be less than the available amount of water based on management strategies or environmental: $0 \leq W_l \leq W_{l_{max}}$
7. The amount of water withdrawn from the lake should be less than maximum values: $0 \leq W_{\text{out}} \leq W_{\text{out}\,t_{max}}$
8. The water level in the aquifer should not be less than a predefined threshold value: $h \geq h_{threshold}$, where h represents the water level of the aquifer and $h_{threshold}$ is the groundwater level threshold.

9. The total apple production should meets a certain target: $Apple \geq Apple_{target}$, where $Apple_{target}$ represents the production target.

3.6.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variable:

1. The volume of groundwater supplied.
2. The cultivated area of each crop.
3. Water allocated to the lake.
4. The irrigation system's efficiency.
5. Water withdrawal from the lake.

3.6.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation. Table 6 Table 6 Datasets, sources, and tools for the Sebou demo sitesummarises the possible available dataset and tools to be utilised at the Sebou demonstration site.

Table 6 Datasets, sources, and tools for the Sebou demo site

Dataset	Source/Tool
Cropping patterns	Agronomic model Aquacrop/CropSyst
Data allocation to different sectors	WEAP
Groundwater level	MODFLOW

3.7. Case Study – Medjerda (Tunisia)

3.7.1. Problem Contextualisation

The Medjerda basin, covering 23,700 km² across Northern Tunisia and Northeastern Algeria, spans from 35°14 to 37°12N and 07°17 to 10°16E. Originating from the Tebessa and Aures mountains, this transboundary river flows 500 km before reaching the Mediterranean near Ghar el Melah in Tunisia. In addition, the basin hosts three Ramsar sites: Ghar El Melah lagoon, Ain Dhiab caves, and Reserve Naturelle Djebel Saddine.

The Medjerda basin is Tunisia's largest catchment, providing over half of its cereal yield, 40% of surface freshwater, and 25% of total freshwater. Its water supply system relies on hydraulic structures, including 10 large dams (with capacities exceeding 5 Mm^3), numerous small dams (with capacities over 500,000 m^3), and small hill dams. The large areas are interconnected for water transfer within the region and North Tunisia. Water serves agricultural, drinking, and industrial needs, distributed via gravity or pumping.

Field crops, including cereal crops and fodder, dominate 50% of the basin, while fruit trees, forests, and matorral cover 29.2%, primarily in the northwest and along the Medjerda wadi axis. Bare soils, such as urban areas and uncovered soil, comprise 25.1%, mainly in the southwest. Primarily used for irrigation (75%) and drinking/industrial purposes (25%), the basin faces challenges due to increased demand and decreased water flow. The historical flow of the Medjerda at Sidi Salem was 640 Mm^3, but it dropped to around 400 Mm^3 in the last decade due to severe droughts. This trend is evident across all dams, with recent flows averaging less than 40% of the historical average in the previous eight years. The decision to allocate water from Medjerda dams for agriculture negatively impacted groundwater use where available.

Here, only two distinct sub-catchments within the Medjerda basin will be detailed: one on the northern side, named Bouhertma, characterised by a more humid climate, and the other on the southern side, named Siliana, which experiences semi-arid conditions with a high siltation rate. Figure 10 shows the location of the sub-catchments within the catchment. The selected sub-catchments are as follows:

Bouhertma Sub-catchment

The Bouhertma River, a significant subwatershed in Tunisia, was dammed in 1976 along with one of its tributaries, the Beni Metir dam, which was constructed in 1954. Initially, Bouhertma's storage capacity was 117 Mm^3 and Beni Metir's was 61.6 Mm^3. Bouhertma's capacity was later increased to 133 Mm^3. The primary purposes of Bouhertma are to supply drinking water regionally, support irrigation, and prevent flooding in Jerusalem City, while Beni Metir primarily supplies drinking water to the capital, Tunis. Hydroelectric power plants were also installed at both dams (H. Liu et al., 2013). A pipeline was established to transfer water from the Barbar dam to Bouhertma, and gravity facilitates water transfer from Beni Metir to Bouhertma through Wadi Ellil. Siltation rates for both dams remain below 7%. The Medjerda River, upstream of the Sidi Salem dam, gathers flows from the Mellegue and Bouhertma dams, supplying irrigation to approximately

25,000 hectares of land in Jendouba and Bousalem, reinforced by dams like Mellila and Zouitina (Chahed et al., 2014).

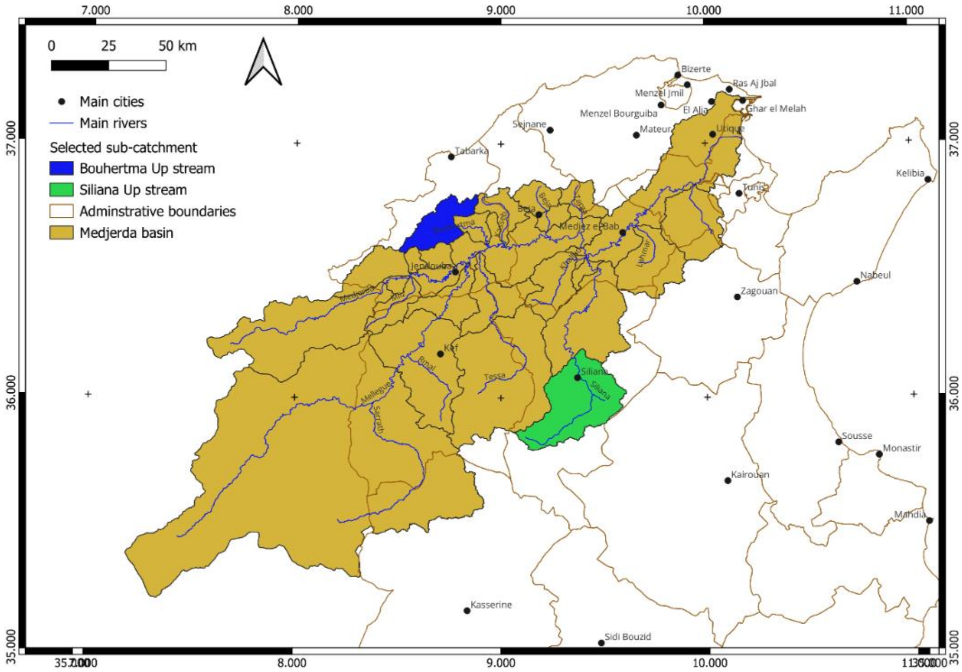

Figure 10 Location of the selected sub-catchments within Medjerda Basin.

Bouhertma's irrigated area is divided into upstream and downstream sectors. Water transferred from the Barbara dam irrigates the upstream area, with the remaining volume flowing into the Bouhertma dam. Water released downstream is used for drinking water in nearby cities, serving around 200,000 inhabitants. The planned irrigation volume, including Medjerda flow and Mellegue dam release, is approximately 70 Mm^3/year for a downstream area of 25,000 hectares. Land use has shifted from sugar beet and cereals to crops like tomatoes, peppers, potatoes, cereals, fodder, and fruit trees, with irrigation efficiency below 60% despite drip irrigation methods.

Siliana Sub-catchment

The Siliana River was dammed in 1987, while its tributary, the Lakhmess River, had a dam constructed in 1966. Both dams were primarily designed for irrigation and flood control in the Medjerda Lower Valley, situated in a semiarid region with annual precipitation below 600 mm. Initially, the Siliana dam had a capacity of 70 Mm^3, while Lakhmess's capacity was 8.2 Mm^3. Water released from these dams supports downstream irrigated areas.

Siltation levels in the Lakhmess dam are around 15%, attributed to forested areas as the main land use. However, the Siliana Dam faces significant siltation, with levels at 56%, greatly impacting reservoir functionality and water availability for irrigation. Severe and frequent droughts, coupled with decreased storage capacity, have heavily impacted the irrigated areas served by the Siliana Dam in recent years.

Both dams are utilised for irrigation, benefiting areas upstream and downstream. Groundwater from aquifers such as Ras El Ma, Siliana underflow, and Soualem supplements irrigation efforts, particularly during droughts. The Lakhmess Dam supports an area of 1,250 hectares, while the Siliana Dam irrigates the Siliana Valley and Laaroussa Plain, covering around 5,000 hectares. Farmers in the Siliana Valley often rely on a mix of dam resources and groundwater, especially during drought.

Cropping systems include cereals, fodder, summer gardening, and fruit trees like olive trees. Despite using drip irrigation, network efficiency remains below 60%. Table 7 summarises the characteristics of the selected sub-catchments.

Table 7 Characteristics of Bouhertma and Siliana sub-catchments

Characteristic	Bouhertma	Siliana
Climate	Sub humid	Semi-arid
Area (km^2)	390	1040
Precipitation (mm/yr)	700-1400	370-600
Inflow average (Mm^3)	Buhertma: 120	Siliana: 49
	Beni Metir: 41	Lakhmess: 11
Main land use	Woodland and field crop	Field crops and sparse forest
Initial hydraulic structure capacity (Mm^3)	Bouherma Dam: 117	Siliana Dam: 70
	Beni Metir dam: 61.6	Lakhmass dam: 8.22
Initial hydraulic structure capacity (Mm^3)	[2]Bouherma dam: 111.5	[3]Siliana Dam: 30.9
	Beni Metir dam: 60.39	Lakhmass Dam: 6.92
Average erosion rate (t/ha/yr)	7	16
Water transfer in	5.5	4
Water transfer out	From the dams of Barbara and Beni Metir	From Lakhmess dam
Main water use	To Sidi Salem,	-
Hydrological modelling	Drinking water and irrigation	Irrigation

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[2] In 2024, the storage capacity was increased to 133×106 m3 by the heightening of the dam.

[3] Another dam is planned upstream since the Siliana dam siltation is too high.

Although water management for the Medjerda River in Tunisia has progressed significantly since the 1970s through infrastructure development, efficiency measures, and pollution control, conflicts and issues related to water use persist. These conflicts include disputes between upstream and downstream farmers/water users over the available surface water, tensions between conservation-ecological issues and agricultural production, and conflicts between neighbouring districts, one focused on ecological flows, hydrosystem protection, and small-scale farming, and the other serving as the agricultural production hub of the basin, which diverts water that could otherwise benefit nearby communities. Additionally, siltation is a key issue in the basin, reducing reservoirs's storage volumes.

In response to these challenges, Tunisia's Water Vision for 2050 aims to achieve hydraulic balance through administrative reforms. Key objectives include enhancing climate resilience, ensuring drinking water supply, improving infrastructure efficiency, promoting unconventional water use, supporting rain-fed agriculture, controlling pollution, and adopting a holistic approach to water, food, energy, and ecology.

As part of the OurMED project for the Medjerda demo site, we aim to contribute to the achievement of the key objectives by creating guidelines for water resource allocation, encompassing local use, transfers (in and out), drinking water provision, and ecological flow maintenance, despite the limited data available. Given these objectives and the main issues faced, we've identified two major challenges that could be the subject of analysis using a multi-objective optimisation approach in the selected sub-catchments. The first challenge involves assessing surface water allocation and use efficiency to enhance water supply and to develop guidelines for land use and land cover (LULC). The second challenge focuses on supporting policy-making processes for sustainable management of surface water resources within the study area, focusing on conflicts over water sharing between upstream and downstream users.

The following subsections will mathematically explore and express the two challenges to formulate the proposed optimisation problem.

3.7.2. Definition of the Optimisation Problem

3.7.2.1. Objective Functions

The multi-objective problem proposed for this demo site consists of three objective functions:

1. Minimising conflicts on water transfer between and within sub-catchments under water shortage:

Enhancing water supply and reducing vulnerability is imperative to minimise conflicts related to water transfer between and within catchments during water shortages. This involves effectively and efficiently moving water from one dam to another to meet demands and reduce water shortage risk. This could enhance water resource management within the integrated framework and mitigate conflicts among water users.

It could encompass various aspects, including minimising losses, maximising transferred water volume per unit of energy or cost, extending demand coverage, and ensuring timely delivery to the designated destination. However, given the absence of comprehensive data, we've simplified our approach to focus primarily on minimising vulnerability, expressed here simply as the deficit in the water supply. Therefore, the objective function takes the following form:

$$min\ D_{\mathrm{total,m}} = \omega_{catchA} D_{\mathrm{catchA,m}} + \omega_{catchB} D_{\mathrm{catchB,m}},$$

where D_{total} represents the total deficits in water supply experienced by all sectors (it can be domestic, agricultural, ecological) in the two considered sub-catchments A and B, ω_{catchA} and ω_{catchB} are coefficients used to prioritize sub-cathcments, if necessary, and D_{catchA} and D_{catchB} are the total defict in catchments A and B, respectively. $D_{\mathrm{catchA}}$is calculated as

$$D_{\mathrm{catchA,m}} = \sum_{sector=1}^{nj} \mu_{\mathrm{sectorA}} \left(\alpha D_{\mathrm{sectorA,upA,m}} + \beta D_{\mathrm{sectorA,\ downA,m}} \right),$$

where μ_{sector} is used to prioritize sectors (for example, in wet and dry seasons), α and β are used to prioritize upstream and downstream uses, respectively, $D_{\mathrm{sectorA,upA,m}}$ denotes the deficits for each sector upstream for the sub-catchment A and it is calculated as

$$D_{\mathrm{sectorA,upA,m}} = \sum_{z_{upA}=1}^{z} \beta_{\mathrm{z\_upA}} \left(WD_{\mathrm{sectorA,upA,m,z\_upA}} - S_{\mathrm{sectorA,upA,m,z\_upA}} \right)$$

while the monthly deficits for each sector downstream can be calculated by

$$D_{\mathrm{sectorA,downA,m}} = \sum_{z\_downA=1}^{z1} \beta_{\mathrm{z\_downA}} \left(WD_{\mathrm{sectorA,downA,m,z\_downA}} - S_{\mathrm{sectorA,downA,m,z\_downA}} \right).$$

Simmilarly, D_{catchB} is calculated as

$$D_{\mathrm{catchB,m}} = \sum_{sector=1}^{j} \mu_{\mathrm{sectorB}} \left(\alpha D_{\mathrm{sectorB,upB,m}} + \beta D_{\mathrm{sectorB,\ downB,m}} \right),$$

$D_{\mathrm{sectorB,upB,m}}$ denotes the deficits for each sector upstream for the sub-catchment B and it is calculated as

$$D_{\mathrm{sectorB,upB,m}} = \sum_{zone\_upB=1}^{z} \beta_{\mathrm{zone\_upB}} \left(WD_{\mathrm{sectorB,upB,m,zone\_upB}} - S_{\mathrm{sectorB,upB,m,zone\_upB}} \right)$$

while the monthly deficits for each sector downstream can be calculated by

$$D_{\mathrm{sectorB,downB,m}} = \sum_{zone\_downB=1}^{z1} \beta_{\mathrm{zone\_downB}} \left(WD_{\mathrm{sectorB,downB,m,zone\_downB}} - S_{\mathrm{sectorB,downB,m,zone\_downB}} \right),$$

where m is the month, D is the deficit for each considered sector, WD is the water demand, up and down are upstream and downstream, respectively, $\mathrm{z\_up}$ and $\mathrm{z\_down}$ represent different upstream and downstream demand zones, respectively, and $\beta_{\mathrm{zone\_up}}$ and $\beta_{\mathrm{zone\_down}}$ are used to prioritize between upstream and downstream demand zones for the correspond sub-catchment A or B. S_{sector} is the volume of supplied water for a sector; it is calculated upstream for sub-catchment A as:

$$S_{\text{sectorA,upA,m,z\_upA}} = P_{\text{sectorA,upA,m,z\_upA}} + GW_{\text{sectorA,upA,m,z\_upA}} + SW_{\text{sectorA,upA,m,z\_upA,}}$$

and downstream as

$$S_{\text{sectorB,downB,m,z\_downB}} = P_{\text{sectorB,downB,m,z\_downB}} + GW_{\text{sectorB,downB,m,z\_downB}} + SW_{\text{sectorB,downB,m,z\_downB,}}$$

And for the for sub-catchment B as

$$S_{\text{sectorB,upB,m,z\_upB}} = P_{\text{sectorB,upB,m,z\_upB}} + GW_{\text{sectorB,upB,m,z\_upB}} + SW_{\text{sectorB,upB,m,z\_upB,}}$$

and downstream as

$$S_{\text{sectorB,downB,m,z\_downB}} = P_{\text{sectorB,downB,m,z\_downB}} + GW_{\text{sectorB,downB,m,z\_downB}} + SW_{\text{sectorB,downB,m,z\_downB,}}$$

where $P_{\text{sector,down,m,zone}}$ represents the monthly water from net precipitation supplied for a sector downstream in a demand zone, $GW_{\text{sector,m}}$ denotes the monthly volume of groundwater supplied, and $SW_{\text{sector,m}}$ is the monthly surface water supplied and it includes surface water naturally presents in the streams/lake/reservoirs in a demand zone plus the transferred water inter and intra basin.

Adjusting the demands for each sector and zone and modifying the volume of water pumped and transferred will be essential to minimise the deficits.

2. Maximising water use efficiency in irrigation:

The aim is to maximise the total water use efficiency (WUE) in irrigation. To achieve this objective, it's imperative to have flexibility in accommodating various crop types and adjusting the balance between rain-fed and irrigated areas.

This approach aids in formulating guidelines for land utilisation and conservation. Moreover, adopting best management practices facilitates crop rotation, mitigating the risks associated with monoculture farming, such as elevated soil erosion rates. The objective function can be defined as follows:

$$min \sum_{c} WUE^{c}_{\text{irrigated}} = \sum_{c} \frac{Y^{c}_{\text{irrigated}}}{ET^{c}_{\text{irrigated}}}$$

Where $Y^{c}_{\text{irrigated}}$ is the crop yield for crop c and $ET^{c}_{\text{irrigated}}$ is the evapotranspiration, of the irrigated crops calculated as:

$$ET^{c}_{\text{irrigated}} = I + P - R - D \pm SW,$$

where I is irrigation, P is precipitation, R is surface runoff, D (mm) is downward flux below the crop root zone, and SW is the change in stored soil water (0–200 cm) between two specific stages of the soil profile.

3. Minimising Siliana dams' siltation:

There are a lot of measures that can be taken to minimise dam siltation, such as implementing sediment trapping systems upstream, conserving soil through reforestation, establishing vegetative buffer strips, enforcing land use regulations to limit development, periodically flushing sediment from the reservoir, managing the reservoir effectively, and conduct regular monitoring and maintenance activities. Here, the focus will be on the maximisation of the sediment discharge. Therefore, the objective function takes the following form:

$$min\ Q_{os}$$

where Q_{os} is the sediment discharge, and it can be obtained by using any available model that estimates the sediment quantity evacuated from reservoirs, for example, the Tsinghua equation as following:

$$Q_{os} = \Psi \frac{Q_t^{1.6} S^{1\cdot 2}}{W^{0.6}},$$

where Q_t are releases from the reservoir, S is the longitudinal energy slope during flushing, W represents the width of the eroded channel, and Ψ is the erodibility coefficient.

3.7.2.2. Constraints

The three objective functions are subject to the following constraints:

1 The total water transferred to all sectors in month m cannot exceed the maximum monthly volume of water that can be transferred according to the reservoirs' operation rules: $\sum_{sector=1}^{j} T_{\text{sector,m,}} \leq T_{max,\text{m}}$, where$T_{\text{sector,m}}$ represents the monthly water transferred to supply the demands of a sector and $T_{max,\text{m}}$ is the maximum monthly allowable volume of water that can be transferred according to the reservoirs (Barabra to Bouhertma) operation rules.

2 The supplied drinking water for the Jendouba region in month m must meet or exceed the drinking water demand for that month: $S_{\text{drinking,m,Jendouba}} \geq WD_{\text{drinking,m,Jendouba}}$.

3 The total energy cost for water transfer must not exceed the maximum budget allocated for energy expenses: $C_{\text{energy}} \leq C_{\text{energy,}\ max}$,where C_{energy} is is the total energy cost for water transfer, and $C_{\text{energy,}\ max}$is the maximum budget allocated for energy expenses.

4 The total water supplied to fruit trees must meet or exceed the minimum amount required for their survival during severe and long droughts: $S_{\text{fruit trees,m}} \geq WD_{\text{fruit trees,}\ min}$, where $S_{\text{fruit trees}}$ is the water supplied to fruit trees, and $WD_{\text{fruit trees,m}\ min}$, is the minimum water demand necessary to guarantee the survival of fruit trees during severe and long droughts.

5 The volume of groundwater pumped cannot exceed the maximum allowable volume: $V_{GW} \leq V_{\text{GW\_P},\ max}$, where $V_{\text{GW\_P},\ max}$ is the maximum volume allowed to be pumped.

6 The supplied water for domestic uses must meet or exceed the domestic demand: $S_{\text{domestic}} \geq WD_{\text{domestic}}$, where S_{domestic} is supplied water for domestic uses including drinking and WD_{domestic} denotes the domestic demand.

7 The supplied water for ecological flow must meet or exceed the demand necessary to ensure ecological flow: $S_{\text{ecological}} \geq WD_{\text{ecological}}$, where $S_{\text{ecological}}$ is the supplied water for ecological flow and $WD_{\text{ecological}}$ denotes the demand necessary to ensure ecological flow.

3.7.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variable:

1. The amount of water used for irrigation.
2. The demands for each sector.
3. The transferred water inter and intra basin.
4. The volume of water released from the Siliana reservoir.
5. The volume of groundwater supplied.
6. The cultivated area of each crop.
7. The energy costs.

3.7.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation. Table 8 summarises the available dataset and tools to be utilised at the Medjerda demonstration site.

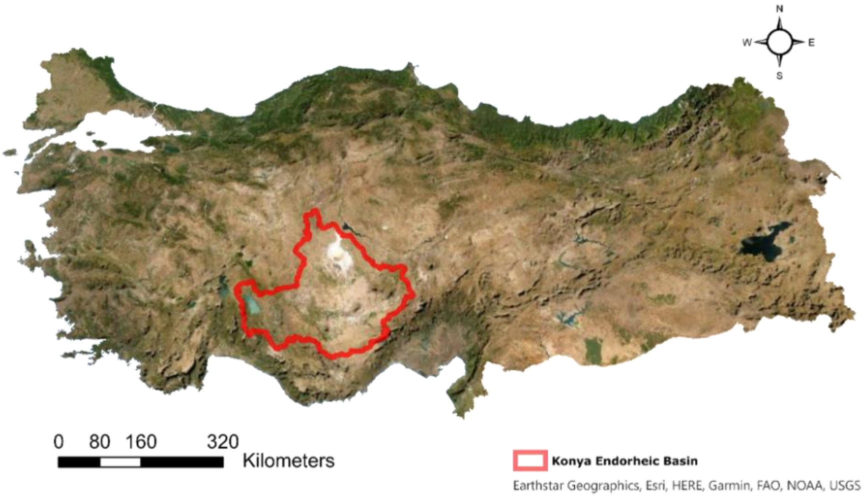
Table 8 Datasets, sources, and tools for the Medjerda demo site

Dataset	Source/Tool
Runoff	HYPE/SWAT
Soil moisture	Sensor/EO
Water release from dams	DGBETH & SECANORD
LULC	EO, technical services MARHP

3.8. Case Study – Konya (Turkey)

3.8.1. Problem Contextualisation

The Konya Closed Basin (KCB), situated in Central Anatolia, is the largest endorheic basin in Turkey, encompassing a total area of 49,963 km^2. The basin occupies 6.4% of the country's land area. KCB is geographically located between 31° 7' 29.01'' E - 35° 3' 28.94'' E and 36° 53' 45.17'' N - 39° 29' 10.33'' N (Figure 11). There are two main water bodies in the basin, one of them on the west side (Lake Beysehir) and the other in the north of the basin (Lake Tuz) (Figure 12). The optimisation problem considers the zone of Lake Beysehir, a freshwater lake that is a major contributor to the water transfers to the KCB. The basin is characterised by a semi-arid climate with an average annual precipitation of about 380 mm/year, resulting in water scarcity issues.



Earthstar Geographics, Esri, HERE, Garmin, FAO, NOAA, USGS

Figure 11 Location of Konya Basin in Turkey.

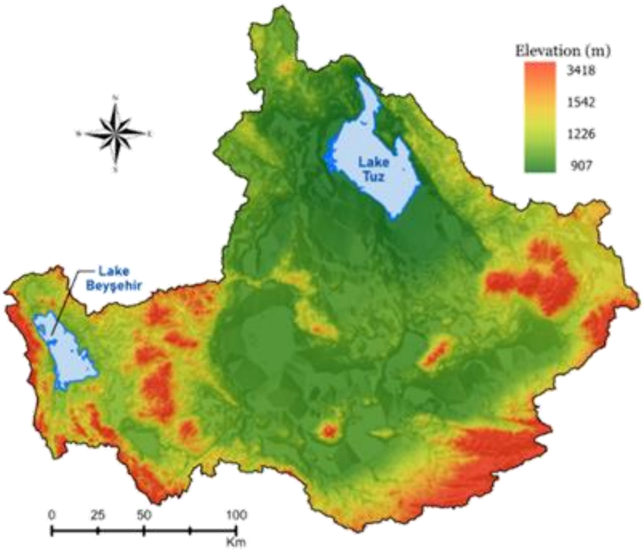


Figure 12 Digital elevation map of Konya Basin, including the water bodies of the basin.

The KCB is rich in diverse ecosystems, including freshwater and saline lakes. The Beyşehir Lake, Turkey's largest freshwater lake, is vital for ecological balance, water system regulation, and biodiversity conservation. There are thirty-two islets in the lake, all of varying sizes. However, the significant amount of water used for irrigation from this source led to the formation of a muddy area in 1990. Since 1991, the Turkish Ministry of Culture has granted this lake 1st-degree Natural Protection Status. Despite having legal protection, the lake faces difficulties such as fluctuations in water levels brought on by insufficient regulations, excessive vegetation growth, fishing activities, urban development, and water contamination (Dursun, 2010).

Surface water resources are crucial for various sectors in the basin, with overall consumption rising alongside population growth. Irrigation dominates water demand, accounting for about 90% of total usage, while drinking water and environmental usage represent around 4% each. Industrial and energy sectors contribute modestly, with 1% and 0.14%, respectively.

The agricultural sector's water demand in the basin surpasses national and global averages, exacerbated by crop patterns requiring excessive water. Inefficient irrigation practices worsen the situation, hindering efforts to optimise water use. The Basin faces a significant water deficit, with consumption exceeding the annual water budget by approximately 2 billion m^3. Excessive groundwater extraction to compensate for this deficit has led to the alarming depletion of underground water sources, prompting concerns about sustainability. As a result, both surface and groundwater resources are severely stressed, posing significant environmental challenges.

Inter-basin water transfer projects have been implemented to transport and distribute water from Lake Beyşehir to the Konya basin for use in agricultural and domestic demand sites to alleviate this stress. Approximately 90% of the water potential in all sub-basins is used in the agricultural sector. Again, according to the action plan of the General Directorate of Water Management (SYGM), despite this very high allocation rate reserved for the agricultural sector, it is predicted that the rate of meeting the water demand will further decrease significantly in today's conditions and especially in severe and very severe drought scenarios. Even in sub-basins such as Beyşehir and Konya Çumra, where important surface water resources are located or transferred, it is stated that the rate of meeting agricultural water demand in severe and very severe drought scenarios will decrease from around 90% under normal conditions to around 75%.

Figure 13 illustrates the surface water distribution system in the Turkish demo site, where priority is given to meeting domestic water demands before addressing irrigation needs. Any surplus water is allocated for ecological services, such as restoring dried wetlands. The operational framework of this system is outlined as follows:

1. The primary component of this project is the Beyşehir-Sugla-Apa (BSA) channel feeding the Sugla storage, which has a capacity of 277.5 million m^3 of storage and an area of 4000 hectares.
2. The BSA channel provides water to most agricultural regions in the Beyşehir and Konya- Çumra subbasins.

3. The second part of the BSA channel connects to the Apa dam. This dam is used for agricultural regions in the Çumra district, in the centre of the basin.
4. The Apa-Hotamis Iletim (AHI) channel also connects BSA to the Hotamis storage area (dried wetland), another water storage in the basin that is currently dry.
5. Another dam south of the basin is the Bagbasi on the Goksu River, which is connected to the BSA channel by the Blue (Mavi) tunnel. Bagbasi Dam collects water in the south of the basin from the Afsar and Bozkir dams using the Hadimi tunnel.

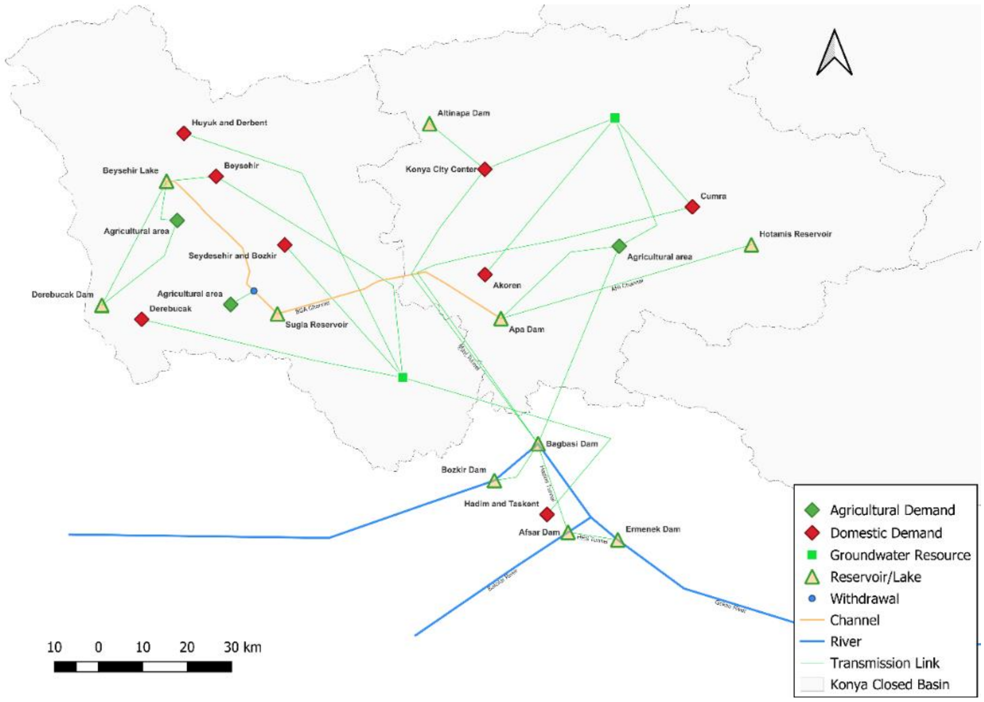


Figure 13 Schematic of the surface water distribution system

Given that one of our goals within the OurMED project is to promote the sustainable management of water resources and the balance between upstream and downstream users in the zone of Lake Beysehir, we have identified two key challenges that could be the subject of analysis using a multi-objective optimisation approach. The first challenge involves assessing surface water allocation and supplementary groundwater pumping requirements, which can also indirectly contribute to biodiversity and wetland restoration. The second challenge focuses on aiding policy-making processes for sustainable management of surface water resources within the basin, focusing on conflicts over water sharing between upstream and downstream users. In the following subsections, we will mathematically explore and express these challenges to formulate the proposed optimisation.

3.8.2. Definition of the Optimisation Problem

3.8.2.1. Objective Functions

The multi-objective problem proposed for this demo site consists of three objective functions:

3. Minimising upstream adverse impacts resulting from water transfer:

Here, adverse impacts can be defined as the alterations in water availability upstream resulting from water transfer, thereby affecting accessible surface water resources upstream. These alterations have social and economic ramifications for users, often leading to conflicts. We can quantify these impacts by measuring the deficits in water supply upstream and downstream after the transference of water. So, the objective function has the form of

$$min\, D_{\text{total,m}} = \sum_{sector=1}^{nj} \left(\alpha_{\text{up}}\, D_{\text{sector,up,m}} + \alpha_{\text{down}}\, D_{\text{sector, down,m}}\right),$$

where $D_{\text{total,m}}$ represents the total deficits in water supply experienced by all sectors j (it will be domestic, agricultural, and ecological purposes) upstream and downstream per month m, nj is the number of sectors to be considered, and α_{up} and α_{down} are used to prioritize between upstream and downstream, respectively.

Given that the water authority has stipulated that water will primarily be allocated to fulfill the needs of domestic sectors (both upstream and downstream), with agriculture receiving priority thereafter, and any surplus water being allocated to ecological purposes, the monthly deficits for the domestic sector upstream can be computed as follows:

$$D_{\text{d,up,m}} = \sum_{z\_up=1}^{nz\_up} \beta_{\text{z\_up}} \left(WD_{\text{d,up,m,z\_up}} - S_{\text{d,up,m,z\_up}}\right),$$

while the monthly deficits for each sector downstream can be calculated by

$$D_{\text{d,down,m}} = \sum_{z\_down=1}^{nz\_down} \beta_{\text{z\_down}} \left(WD_{\text{d,down,m,z\_down}} - S_{\text{d,down,m,z\_down}}\right),$$

where d denotes domestic sector, m is the month, D is the deficit, WD is the water demand, up and down are upstream and downstream, respectively, z_up and z_down represent different upstream and downstream demand zones, respectively, nz_up and , nz_down are the number of zones upstream and downstream, respectively, and $\beta_{\text{z\_up}}$ and $\beta_{\text{z\_down}}$ are coefficients used to prioritize between upstream and downstream demand zones. S_{d} represents the volume of supplied water for domestic uses; it is calculated upstream as:

$$S_{\text{d,up,m,z\_up}} = P_{\text{d,up,m,z\_up}} + GW_{\text{d,up,m,z\_up}} + SW_{\text{d,up,m,z\_up}},$$

and downstream as

$$S_{\mathrm{d,down,m,z\_down}} = P_{\mathrm{d,down,m,z\_down}} + GW_{\mathrm{d,down,m,z\_down}} + SW_{\mathrm{d,down,m,z\_down}},$$

where P represents the water from net precipitation, GW denotes the volume of groundwater supplied, and $SW$is the surface water supplied, and it includes surface water naturally presents in the streams/lake/reservoirs plus the transferred water.

The monthly deficits for the agricultural sector upstream can be calculated by

$$D_{\mathrm{a,up,m}} = \sum_{z\_up=1}^{nz\_up} \beta_{\mathrm{z\_up}} \left(WD_{\mathrm{a,up,m,z\_up}} - S_{\mathrm{a,up,m,z\_up}} \times I_{\mathrm{d}\,,m}\right),$$

and the monthly deficits for the agricultural sector downstream can be calculated by

$$D_{\mathrm{a,down,m}} = \sum_{z\_down=1}^{nz\_down} \beta_{\mathrm{z\_down}} \left(WD_{\mathrm{a,down,m,z\_down}} - S_{\mathrm{a,down,m,z\_down}} \times I_{\mathrm{d}\,,m}\right),$$

where a represents the agricultural sector and $I_{\mathrm{d}\,,m}$ is an indicator operator. It's employed to fulfill agricultural demands when domestic demands are fully satisfied. This operator takes the value 1 when domestic demands are met entirely, and 0 otherwise.

Following the same rationale, the monthly deficits for ecological purposes upstream can be calculated by

$$D_{e,\mathrm{up,m}} = \sum_{z\_up=1}^{nz\_up} \beta_{\mathrm{z\_up}} \left(WD_{e,\mathrm{up,m,z\_up}} - S_{e,\mathrm{up,m,z\_up}} \times I_{\mathrm{a}\,,m}\right),$$

and the monthly deficits for the ecological purposes downstream can be calculated by

$$D_{\mathrm{e,down,m}} = \sum_{z\_down=1}^{nz\_down} \beta_{\mathrm{z\_down}} \left(WD_{\mathrm{e,down,m,z\_down}} - S_{e,\mathrm{down,m,z\_down}} \times I_{\mathrm{a}\,,m}\right),$$

where e represents the ecological sector and $I_{\mathrm{d}\,,m}$ is an indicator operator. It's employed to fulfill ecological demands when agricultural demands are fully satisfied. This operator takes the value 1 when agricultural demands are met entirely, and 0 otherwise.

4. Minimizing total supplementary groundwater pumping requirements to meet crop demand for the irrigated areas:

Here, we first assume that each crop c is first irrigated by using surface water, and groundwater is only used if surface water is not enough. The objective function has the form of

$$min\ \ SGW_{\mathrm{total,m}} = \sum_{c=1}^{nc} SGW_{c,\mathrm{m}},$$

where $SGW_{c,m}$is the supplementary groundwater pumped for a crop c in month m, , and nc denotes the total crops.

5. Maximizing economic returns.

Here the idea is to maximize economic returns while considering the reduction of money spent on groundwater extraction and maximizing production by prioritizing crops that use less water with higher selling prices. The objective function has the form of

$$max \quad R_{\text{total,m}} = \sum_{c=1}^{nc} R_{c,\text{m}} = Sales_{c,\text{m}} - Costs_{c,\text{m}},$$

where $Sales_c$ is are calculated as

$$Sales_{c\,c,\text{m}} = Y_{c,\text{m}}(\mathrm{S}_{c,\text{m}}) \times A_{c,\text{m}} \times \text{ Selling Price }_{c,\text{m}}$$

and $Costs_c$ as

$$Costs_{c,\text{m}} = \text{ GW Cost }_{c,\text{m}} \times \text{ Water Used }_{gwc,c,\text{m}},$$

where Y_c represents the yield of crop c, S_c is the total supplied water for crop c, A_c is the total area used for cultivating crop c, Selling Price $_c$ is the selling price of crop c per mass unit, GW Cost $_c$ is the cost of pumping supplementary water for irrigate crop c, Water Used $_{gwc,c}$ represents the groundwater used for crop c and m represent the month.

3.8.2.2. Constraints

The three objective functions are subject to the following constraints:

10. Groundwater will not be used upstream for domestic uses: $\sum_{z\_up=1}^{nz\_up} GW_{\text{d,up,m,z\_up}} = 0$.
11. Groundwater will not be used downstream for domestic uses: $\sum_{z\_up=1}^{nz\_down} GW_{\text{d,down,m,z\_down}} = 0$.
12. Groundwater will not be used upstream for ecological uses: $\sum_{z\_up=1}^{nz\_up} GW_{\text{e,up,m,z\_up}} = 0$.
13. Groundwater will not be used donwstream for ecological uses: $\sum_{z\_up=1}^{nz\_down} GW_{\text{e,down,m,z\_down}} = 0$.
14. The water provided for domestic uses must meet or exceed the demand for domestic water: $S_{\mathrm{d}} \geq WD_{\mathrm{d}}$, where S_{d} is supplied water for domestic uses including drinking and WD_{domestic} denotes the domestic demand.
15. The supplied water for agricultural uses must meet or exceed the demand necessary to ensure agricultural uses: $S_{\mathrm{a}} \geq WD_{\mathrm{a}}$, where S_{a} is the supplied water for agricultural uses and WD_{a} denotes the demand necessary to ensure agricultural uses.
16. The total monthly volume of water transferred to the basin from all sectors must not exceed the maximum allowable volume of water transfer set by the water authority: $0 \leq \sum_{sector=1}^{j} T_{\text{sector,m,}} \leq T_{\mathrm{max,m}}$, where $T_{\mathrm{max,m}}$ is the maximum monthly allowable volume of water that can be transferred to the basin according to the water authority.

17. The total cost of pumping groundwater for all crops must not exceed the budget allocated for pumping water: $\sum_{c=1}^{n} P_c \leq P_{max}$, where P_c represents the costs of groundwater pumped for crop c and P_{max} represents the maximum allowable cost to spend on pumping water.
18. The water level of the lake must not fall below the minimum threshold level: $L \leq L_{threshold}$, where L represents the water level of the lake and $L_{threshold}$ is the minimum water level to be guaranteed in the lake.
19. The area used for cultivating sugar beets must not exceed the maximum allowable total area allocated for cultivating sugar beets: $A_{Sbeets} \leq A_{Sbeets,max}$, where A_{Sbeets} is the used for cultivating sugar beets and $A_{Sbeets,max}$ is the maximum total area allowed to be used for cultivating sugar

3.8.2.3. Decision Variables

In the context of the stated problem, we have identified the following decision variables:

1. Cultivated Area *
2. Area of each crop *
3. Areas of Irrigation vs Rain-fed cultivation *
4. Groundwater Extraction*
5. Water transfer for domestic and irrigation (this variable would depend on precipitation and lake levels. At the end of the wet season each year, the water authority decides how much surface water will be transferred to the basin)

* Farmers are the decision-makers

3.8.3. Datasets and Tools

Data and tools are required to conduct the proposed multi-objective optimisation. Table 9 summarises the available dataset and tools to be utilised at the KCB demonstration site.

Table 9 Datasets, sources and tools for the Konya demo site

Dataset	Source/Tool
Cropping patterns	Turkish Statistical Institute
Water allocation to different sectors	WEAP
Meteorological data	Turkish State Meteorological Service (TSMS).
Ground elevation	DEM (Digital Elevation Model) by the General Directorate of Mapping (HGM)
Crop evapotranspiration	(TAGEM & DSİ, 2017)

4. Recommended Algorithms

In this report, no specific suggestions will be provided regarding the models to be utilised in the simulation. The rationale behind this decision is to leverage the available tools and expertise present at each demonstration site.

Regarding the optimisation algorithms, while no one-size-fits-all method can solve every optimisation problem, evaluating each method's characteristics, data availability, and the desired type of solution is crucial to selecting the most suitable approach. In this section, we aim to suggest several algorithms to be considered for applying multi-objective optimisation at each demo site. It's important to note that the suitability of an algorithm should be assessed throughout the process, and if needed, multiple algorithms should be used to compare preliminary results.

In the identified problems within the demo sites of the OurMED project, all optimisation tasks share a similar level of complexity, with none featuring more than three objective functions. Moreover, none of the problems entails high complexity, high dimensional functions, or intricate, complex multimodal or disconnected functions. As such, employing methods designed for higher complexity, such as NSGA-III, MOEA/D, or Hype, is unnecessary. These methods yield comparable or inferior results if compared to the proposed methods when handling problems with up to three objective functions. Therefore, we recommend three methods to tackle the optimisation problems:

1. NSGA-II: For all Demo Sites that do not need or wish to consider user/decision-maker preferences. The reasons for this are:
   - The most used algorithm in the optimisation of water management problems.
   - It is a fast-converging and efficient method for multi-objective optimisation problems with up to three objective functions.
   - It does not require manipulating several parameters to guide the search process or to formulate the problem.
   - Encoding the problem into binary format will not be difficult, as the problems are not very complex, have few decision variables, and these variables are often discrete. Thus, the size of each string (individual) and the population size will likely be reasonable.
2. SMS-EMOA: This method is suggested primarily for problems that want to implicitly consider user/decision-maker preferences in the optimisation process. SMS-EMOA is efficient for multi-objective optimisation with few dimensions and a small population of search agents.

3. Linear Programming combined with Scalarization Techniques: These techniques would be particularly interesting for those who lack the knowledge and tools to use evolutionary algorithms but already have the software capable of using linear programming (LP) and want to consider different weights for the objective functions.

Table 10 presents a comprehensive overview of the recommended methods and their respective advantages and disadvantages.

Finally, after identifying non-dominated solutions for each demonstration site through previously suggested methods, it's advisable to employ a conflict resolution approach such as Nash bargaining (Nash, 1950) to address stakeholder conflicts regarding solution selection. This method enhances the Pareto front by integrating stakeholders' preferences, resulting in mutually beneficial solutions. Furthermore, it facilitates equitable agreement on Pareto front solutions while evaluating their stability and resilience.

Table 10 Recommended optimisation methods for demo sites

Multi-objective Optimization Approaches			**Pros**	**Cons**
Multi-objective Evolutionary Algorithms (MOEA)	Indicator-based	SMS-EMOA	1) It works well in finding well-distributed solutions; 2) It is ideal for Pareto sets with few population elements.	1) The estimation time increases exponentially as the solution dimension grows; it may be inefficient regarding computational complexity.
	Dominance-based	NSGA-II	1) It can achieve near-optimal solutions well distributed across the Pareto front in a reasonable time; 2) It often has a good performance when compared to other methods; 3) It is unnecessary to input weight vectors to guide search procedures.	1) Poor performance may happen under more than three objectives, although there are variants that can solve many objectives problems; 2) It is required to know how to encode the characteristics of the problem and define specific parameters.
	Observations		1) Penalty functions may be necessary to handle constraints; 2) Each of these methods has its way to measure performance and to select the fittest solutions; 3) Dominance-based methods follow a straightforward design principle, requiring only a few parameters in its framework, and it can easily solve up to three objective functions; 4) Indicator-based methods allow implicit inclusion of user preferences in the optimisation process, and they are mainly used to assess the convergence behaviour of an algorithm;	
Classical Methods + Scalarization Techniques	Linear Programming		1) Flexibility and ability to adjust and solve large-scale problems; 2) It achieves the global optimum values; 3) Many computational packages ready to use; 4) Efficient to find solutions to very large optimisation problems containing many variables and constraints.	1) Solving highly complex problems regarding nonlinear, nonconvex, multimodal, and discontinuous characteristics may be complicated or impossible.
	Observations		1) Although scalarisation techniques allow classical methods to solve more than one objective, it may be very hard or even impossible to solve high dimensional problems with many variables and objective functions, nonlinear and multimodal or discontinuous characteristics.	

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