



MARCLAIMED

MAR with AWR impact at municipal scales

Deliverable 1.2

**WP1: Operational efficiency and economic
sustainability in short, medium, and long-term
perspective**

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ABSTRACT	Report on the analysis of MAR with AWR impact at municipal scale		

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EXECUTIVE SUMMARY

This deliverable D1.2 reports on the analysis of MAR with AWR impact at the municipal scale using the OASIS FLOW tool. It addresses the WP1 objective to determine the current and future status of groundwater bodies forecasting the water resources availability and demands in the short-, medium- and long-term (SO1). This objective is related to RES2 (T1.2). OASIS FLOW is one of six tools in WP1. Within OASIS FLOW, the territorial water footprint is calculated and integrated with QUEEN (MAR system water footprint calculator) and AWARE (water availability indicator).

Through M15, data collection for input into the territorial water footprint and QUEEN tools has been performed for all three demo sites (DS): Llobregat, Spain (DS1); Comporta, Portugal (DS2); and Texel, The Netherlands (DS3). The results of the territorial water footprint and QUEEN have been integrated with AWARE to provide the resulting water availability factor. The factor is represented as water availability of the municipality minus the water demand (AMD). The impacts of each MAR system can be observed using a decision-support system that compares these AMD factors in a scenario without MAR systems to the present scenario with operational MAR systems.

Results indicate that the water availability in the municipality of Llobregat, Spain is greatly improved by the DS1 MAR system. The AMD factor in July, for example, is more negative without the MAR system (-0.0439) than with the MAR system (-0.0247). In the municipalities of Alcácer-do-Sal and Grândola, Portugal, the effect of the DS2 MAR system on water availability is not observable due to the large combined area of the municipalities compared to the relatively small size of the Comporta wastewater treatment plant (WWTP) MAR system. In the municipality of Texel, The Netherlands the impact of the DS3 MAR system is small, yet observable. In April, for example, the AMD factor is 0.00076 without the MAR system, which is lower than the AMD factor with the MAR system (0.00083). This effect will grow every year, as every year the Texel MAR system infiltrates more water to the growing freshwater bubble for underground storage.

During the validation and implementation phase, results from the OASIS FLOW tool will be refined and added into the integrated decision support tool (IDST) of WP2, as well as WP1 tools MARINSURE (economic performance modelling) and RECOVER (tariff setting model).

1. Introduction

1.1. *Context and background*

Water scarcity is an increasing global challenge, exacerbated by climate change, population growth, and expanding economic activities. Managed Aquifer Recharge (MAR) with Alternative Water Resources (AWR) has emerged as a strategic solution to enhance water resource sustainability at different scales. However, assessing the impact of MAR at the municipal level remains a challenge due to fragmented methodologies and a lack of integrated tools that incorporate both hydrological and socio-economic factors.

Currently, water footprint assessments in aquifers and municipalities are developed as separate frameworks, with limited integration into decision-making processes at local and regional levels. Additionally, existing water scarcity indicators rely on large-scale, macro-modeled data that do not accurately represent the reality at the municipal level. To address these gaps, OASIS FLOW has been designed as a digital tool to assess the municipal-scale water footprint performance, incorporating hydrological, economic, and social aspects into a comprehensive decision-support framework.

By integrating MAR strategies with water footprint methodologies, OASIS FLOW provides a more precise and localized assessment of water availability, demand, and economic implications. The tool will support municipalities and stakeholders in making prognoses to support informed decisions regarding sustainable water management, promoting cross-sectoral cooperation, and enhancing resilience to future water stress scenarios. When applied to the three demo sites of the MARCLAIMED project, the OASIS FLOW tool will provide a quantitative understanding of the impact of each MAR system.

1.2. *Deliverable Objectives*

The main objective of Deliverable 1.2 is to present the development and functionalities of OASIS FLOW as a digital tool designed to quantify the impact of MAR with AWR at the municipal scale. The deliverable aims to:

1. Assess water availability and demand through a municipal-scale water balance based on the water footprint method, evaluating the potential of MAR to optimize underutilized water resources.
2. Develop a comprehensive indicator framework to measure the environmental, economic, and social benefits of MAR systems, integrating key performance indicators (KPIs) such as water scarcity (KPI_2.2 "one water scarcity indicator defined for each demo site at municipal scale", KPI_6.4 "50% optimization of water

resources allocation through the municipality water scarcity indicator"). KPI_2.2 is included under SO2: To achieve economic and financial feasibility and sustainability of MAR with AWR under uncertainty while enabling recovery after unforeseeable events occur (i.e., resilience). KPI_6.4 is part of SO6: To ensure the availability and sustainability of groundwater resources with the help of AWR (i.e., contributing to achieve and preserve groundwater bodies' good quantitative and chemical status) via the MARCLAIMED IDST validation. These KPIs have a due date of July 2025, or M30 of the MARCLAIMED project.

3. Bridge the gap between hydrological and economic models, enabling the evaluation of MAR's cost-benefit implications for different sectors, including agriculture, industry, and municipal services.
4. Provide a decision-support tool that facilitates transparent and cross-sectoral reporting, empowering policymakers and local governments with actionable insights for improved water governance.
5. This deliverable will contribute to the broader objectives of the OASIS FLOW Tool (RES4) by enhancing the feasibility of MAR under diverse climatic conditions, social contexts, and economic structures.

1.3. *Scope of Work*

The scope of Deliverable 1.2 encompasses the research, development, and implementation of the OASIS FLOW tool, including:

1. Hydrological Assessment: Conducting a municipal-scale water balance analysis using water footprint methodologies, integrating data on water availability, MAR potential, and demand from different sectors.
2. Indicator Development: Defining and implementing KPIs that reflect water scarcity, resource savings, and economic benefits to enable systematic reporting and governance improvements.
3. Integration with MARINSURE and RECOVER: Ensuring compatibility and data exchange with other project components to create a comprehensive MAR evaluation framework.
4. Scenario Modelling: Simulating different MAR application scenarios based on current and projected water stress conditions to support evidence-based policy recommendations.

The results of this deliverable will contribute to advancing the understanding of MAR's role in enhancing water sustainability at the municipal level, ultimately improving decision-making and long-term water resource planning.

2. Theoretical Framework

The theoretical framework for this project is grounded in the principles of water resource management, hydrological conditions, and socio-economic assessment methodologies. The development of OASIS FLOW relies on established water footprint methodologies, institutional arrangements concerning permits, MAR theories, and decision-support frameworks to integrate hydrological, economic, and social factors into municipal-scale water resource assessments.

2.1 Key Concepts

2.1.1 MAR Principles

MAR is an essential strategy in water resource management, improving water availability through artificial recharge techniques. The theoretical foundation of MAR is based on:

- Hydrogeological Suitability: Identifying aquifer properties, infiltration rates, and storage capacity to optimize MAR applications (Alam et al., 2021; IGRAC, n.d.).
- Water Quality and Treatment: Assessing the quality of recharge water and its interaction with native groundwater to maintain sustainable use (Alam et al., 2021).
- Climate Resilience and Adaptation: MAR as a tool for mitigating climate-induced water scarcity, providing an adaptive measure for long-term resource sustainability (Dillon et al., 2020).

OASIS FLOW evaluates the potential of MAR to replenish aquifers, enhance water security, and reduce dependency on external water sources hence securing and increasing water availability.

2.1.2 Water Footprint and Water Balance Methodologies

Water footprint analysis, as proposed by Hoekstra et al. (2011), provides a comprehensive approach to assessing water use by considering direct and indirect consumption across different sectors. The water balance methodology, which evaluates the inflows, outflows, and storage of water within a given system, is crucial for understanding water availability at the municipal scale. OASIS FLOW integrates these methodologies to quantify water demand, supply, and sustainability. The theoretical underpinnings of water footprint assessment include:

- Blue water footprint: The volume of surface and groundwater consumed.

- Green water footprint: The amount of rainwater used for agricultural and natural ecosystems.
- Grey water footprint: The volume of freshwater required to assimilate pollutants to maintain water quality standards.

By incorporating these dimensions, OASIS FLOW provides a nuanced analysis of municipal water stress and the potential role of MAR in increasing local and/or regional water availability.

2.1.3 Integration with other tools and models

A critical component of OASIS FLOW outputs is the integration of socio-economic aspects and environmental factors into the assessment framework. The results of the OASIS FLOW tool can be applied for:

- Scenario-Based Modeling: Utilizing predictive simulations to assess the potential outcomes of MAR interventions under varying climatic and demand conditions.
- Cost-Benefit Analysis (CBA): Evaluating the financial feasibility of MAR implementation across different municipal sectors, including agriculture, industry, and domestic supply through the evaluation of sustainability indicators such as the water footprint.
- Key Performance Indicators (KPIs): Metrics such as defining a water scarcity indicator for each demo site at the municipal scale (KPI_2.2) and 50% optimization of water resources allocation through the municipality water scarcity indicator (KPI_6.4) to assess the impact of MAR strategies. These KPIs came from agreements made during the first General Assembly (July 2024) and are both due as milestone 2 (MS2) in July 2025.
- Stakeholder and Governance Models: Engaging policymakers, municipalities, and industries in decision-making processes through participatory governance frameworks.
- Multi-Criteria Decision Analysis (MCDA): A structured approach to evaluating alternative MAR strategies based on economic, social, and environmental trade-offs. This tool is also designed to be integrated into the decision support system (IDST) developed in **WP2 “MARCLAIMED IDST: Integrated Decision Support Tool for MAR recommendations and early warning alert system”**.

OASIS FLOW is designed to be interoperable with other tools from WP1 such as MARINSURE and RECOVER, facilitating comprehensive water management assessments at multiple scales. Therefore, OASIS FLOW not only provides hydrological assessments but

also incorporates socio-economic considerations to enhance policy development and water management strategies. The outputs of OASIS FLOW will be integrated as inputs for MARINSURE and RECOVER during the implementation and validation period.

2.2 State of the Art in the Field and MARCLAIMED

OASIS FLOW is a tool that focuses on providing an evaluation of the impact that a certain AWR (MAR for this case) has on a specific territorial unit from a sustainability point of view and not just an hydrological assessment on the state of said unit. With this information in mind we have to consider the pros and cons that this tool provides and the bottlenecks that may appear when trying to find a similar approach which serves as an anchor point from which to make a proper comparison for the actual state of these methodologies.

As it is today, there are several methodologies that may be compared individually with each one of the methodologies involved in the development of OASIS FLOW (e.g., ISO 14046) but not a general methodology that provides the same results starting from the same inputs involved in the OASIS FLOW tool (ISO, 2014).

Regarding each of the specific methodologies:

The AWARE methodology was developed in order to provide a general assessment of the availability levels that were present at a global scale. Most of the methodologies employed to fulfil the role of evaluating water availability at different levels rely on complex hydrological models in order to achieve this goal (e.g., WaterGAP2, PCR-GLOBWB 2.0 and ERA5-LAND) (ISIMP, n.d.; Sutanudjaja et al., 2018; ECMWF, n.d.). The AWARE methodology uses a dataset from which it's possible to downscale this information to a more interesting level as long as the uncertainty introduced by said process is taken into account.

To develop the territorial water footprint methodology, the Water Footprint Network (WFN) methodology was used rather than the ISO 14046 method. To further improve the quality of the results, the methodology proposed by Ferreiro-Crespo et al., 2025 was used to fine tune application of the WFN methodology how to apply the methodology for the specific case studies involved in MARCLAIMED project (Ferreiro-Crespo et al., 2025).

The QUEEN methodology was developed in the framework of an internal project by CETAQUA to evaluate the water footprint of the MAR systems. There is not any other available method as specific as the QUEEN methodology to assess these kinds of impacts in relation to MAR systems.

3. Methodology: General Approach

This study employs a comprehensive methodological approach to assess water availability and the impact of aquifer recharge at the municipal level in selected European regions. Three primary methodologies are utilized: the AWARE method for water availability assessment, the water footprint Network (WFN) approach for territorial water footprint calculations, and the QUEEN project methodology for evaluating the water footprint of MAR systems. Additionally, the OASIS FLOW tool is used to evaluate the municipal-level impact of the MAR intervention on water availability and quality.

1. Territorial water footprint Calculation Using the water footprint Network (WFN) Approach

The WFN methodology quantifies water consumption across economic sectors at the municipal level, classifying water use into blue (surface and groundwater consumption), green (rainwater stored in soil), and grey (water required for pollution assimilation) footprints. The approach involves:

- **Data Collection on Water Consumption:** Gathering detailed data on water use across sectors such as agriculture, reclaimed water, and domestic activities in each municipality.
- **Assigning water footprint Values:** Applying WFN methods to compute sectoral water footprints and their impact on municipal water balance.

2. Evaluation of MAR water footprint Using the QUEEN Project Methodology

The QUEEN methodology, developed through another project by CETAQUA, addresses the impact of the MAR systems' water footprints. This methodology assesses the impact of MAR systems on water availability through:

- **Data Collection on System Operation:** Gathering data on water infiltration rates, volumes, and water quality. Also gather information on the indirect water footprint of system operation.
- **Assigning water footprint Vales:** Applying WFN methods to compute the blue and grey water footprints of the MAR system itself.

3. Water Availability Assessment Using the WULCA AWARE Method

The AWARE (Available WAtER REmaining) method quantifies water scarcity in different regions by providing characterization factors that reflect the remaining available water

after human and ecological needs are met. The application of this method in the study regions (DS1: Llobregat, Spain; DS2: Comporta, Portugal; DS3: Texel, Netherlands) involves:

- **Identification of Hydrological Basins:** Using Geographic Information Systems (GIS) and hydrological databases to determine relevant catchment areas.
- **Obtaining AWARE Characterization Factors:** Sourcing region-specific factors from WULCA documentation to assess the potential impact of water consumption on scarcity (WULCA, 2024).
- **Calculating Water Availability:** Multiplying regional water consumption data by the respective AWARE factor to determine the relative scarcity impact.

4. Municipal Impact Assessment Using OASIS FLOW

The OASIS FLOW tool is employed to evaluate the municipal-level impact of aquifer recharge on water availability. The tool integrates water balance data, recharge rates, and local demand factors from the territorial water footprint, QUEEN tool and AWARE tool to quantify how MAR implementation affects municipal water resources. By incorporating recharge scenarios into a broader water management framework, OASIS FLOW enables the identification of optimal recharge strategies for mitigating water scarcity.

By integrating OASIS FLOW with other MARCLAIMED tools and methodologies (Figure 1), the influence of aquifer recharge on water availability at the municipal level can offer insights into sustainable water management strategies and potential policy implications. During the implementation and validation period, OASIS FLOW will use inputs from PREDMAR (water resource forecasting using AI), and the results of OASIS FLOW will be provided for use in the MARINSURE (economic performance modelling) and RECOVER (tariff setting model).

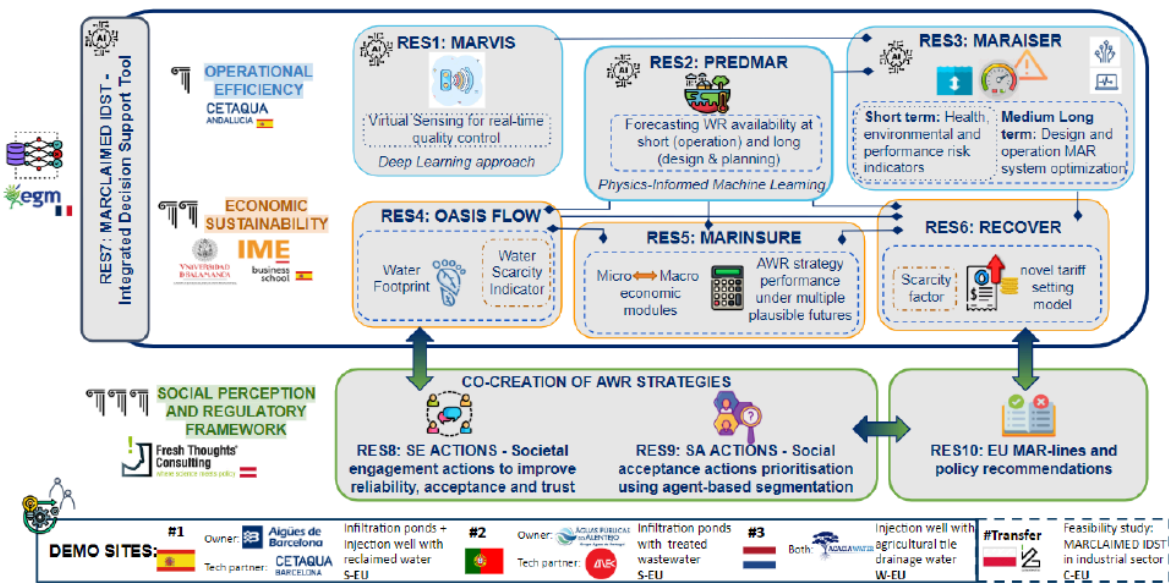


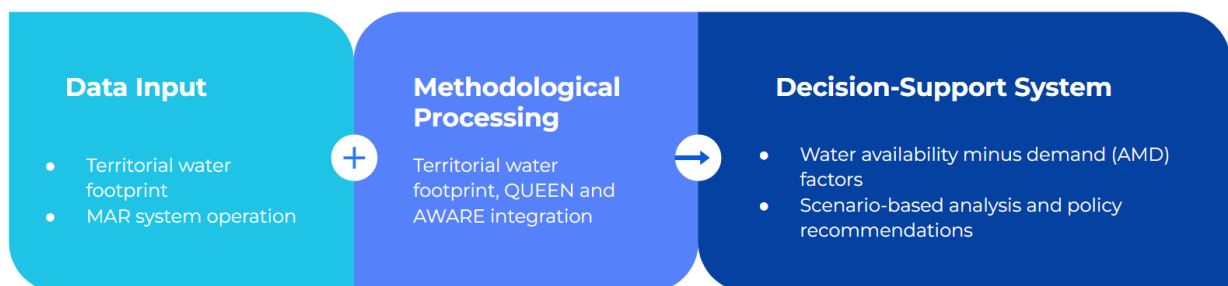
Figure 1: MARCLAIMED methodology.

4. Description of the Digital Tool

4.1 Conceptual scheme and main functionalities

4.1.1 Conceptual Scheme

The conceptual scheme of the digital tool follows a structured approach integrating multiple methodologies and data sources:



1. Data Input Layer

- Municipal water consumption records.
- Water quality data from wastewater treatment plants.

- Climatic and soil data for agricultural water footprint assessment.
 - Water availability data from global GIS datasets.
 - Operation data on water volumes and quality from the MAR system.
2. **Methodological Processing**
- Application of the AWARE method to derive water scarcity indicators.
 - Calculation of sector-specific water footprints using WFN principles.
 - MAR impact assessment utilizing QUEEN project methodologies.
 - Scenario modeling of water availability changes using OASIS FLOW.
3. **Decision-Support System**
- Visualization of water scarcity levels and footprint components.
 - Scenario-based analysis for scaling different MAR implementations.
 - Policy recommendations based on simulated water balance improvements.

4.1.2 Algorithms and Models Used

Water Footprint (WFN Method)

The water footprint of a region, person, company or other entity is calculated based on the sum of the direct water footprint and the indirect water footprint. The direct water footprint includes all water that is used by the entity, for example for drinking, in factory operation, for irrigation or for cleaning. The indirect water footprint includes water used for creation of goods used, for example electricity generation, or food processing and shipping. The general water footprint (WF) methodology is calculated over given period of time by:

$$WF = Blue\ WF + Green\ WF + Grey\ WF \quad \text{Equation 1}$$

Where:

- *Blue WF* = The volume of surface and groundwater consumed.
- *Green WF* = The volume of rainwater used for agricultural and natural ecosystems.
- *Grey WF* = The volume of freshwater required to assimilate pollutants to maintain water quality standards.
- If being considered, the blue, green and grey water footprint will be added for the indirect water footprint as well.

It is important to note that when the blue, green, grey or total water footprint is positive (+), that indicates the volume of water that has been consumed and is no longer available for use. This can be thought of as decreasing the water availability. When the water

footprint is negative (-), that indicates that the entity is effectively adding that volume of water to the system being considered. This can be thought of as increasing the amount of water available:

+ WF → decreases water availability

- WF → increases water availability

For the territorial water footprint methodology, only the *direct* water footprint of the municipality was included.

The water footprint of each MAR system is calculated by equation 2

$$MAR\ WF = R + Ind.\ WF + Grey\ WF \quad \text{Equation 2}$$

Where:

- $R\ [m^3]$: volume of water recharged into the ground by the MAR system. This is also the blue water footprint of the system. *In all cases, this value will be negative, because water is being added back to the system.*
- $Ind.\ WF\ [m^3]$: indirect water footprint of system operations
- $Grey\ WF\ [m^3]$: volume of water required to compensate for degrading the water quality of the aquifer. Can also be thought of as the volume of water required to dilute the mass of contaminants added to the aquifer to meet water quality levels.

Overall, the MAR water footprint should be negative, because MAR systems add water back to the system. This will be discussed further in the QUEEN methodology.

Grey water footprint Calculation Formula (WFN Method)

The grey water footprint is a measure of freshwater pollution and is defined by the water footprint Network (WFN) as the volume of water required to assimilate pollutants to meet water quality standards. The formula used in the WFN method is:

$$GWF = \frac{L}{(C_{max} - C_{nat})} \quad \text{Equation 3}$$

or

$$GWF = \frac{(V_{effl} * C_{effl})}{(C_{max} - C_{nat})} \quad \text{Equation 4}$$

where **L [mg]** represents the pollutant load (mass per unit time), **C_{max} [mg/L]** is the maximum acceptable concentration of the pollutant according to water quality standards, and **C_{nat} [mg/L]** is the natural background concentration of the pollutant in the receiving water body. **L [mg]** can also be calculated by multiplying the total volume of effluent (**V_{effl} [L]**) times the concentration of the contaminant considered (**C_{effl} [mg/L]**). This formula estimates the volume of water needed to dilute pollutants to safe levels, ensuring environmental sustainability. The grey water footprint is particularly useful in assessing industrial, agricultural, and domestic pollution impacts and guiding water management policies.

AWARE Formula for Calculating Water Availability

The first step of the AWARE Available WATER REMaining) formula is to calculate the water availability of the municipality and to add the effects of the MAR system. This is done by:

$$Avail_{net} = Avail_m - MAR WF \quad \text{Equation 5}$$

Where

- **Avail_{net} [m³/month]**: The net availability of water resources after accounting for human consumption and ecosystem requirements. It is inferred from the context of water availability calculations.
- **Avail_m [m³/month]**: Water availability of the municipality, calculated from a global water availability dataset
- **MAR WF [m³/month]**: Water footprint of the MAR system. This is a negative value when the MAR operation is adding water to the overall water availability of the area. Therefore, the MAR system *increases* the **Avail_{net}** of the municipality.

AWARE Formula for Calculating AMDs

The AWARE method is used to evaluate water scarcity impacts by determining the AMD (Availability Minus Demand) for a given region. The AMD formula is:

$$AMD = \frac{Avail_{net} - HWC - EWR\% (Avail_{delta} + Avail_{net})}{area} \quad \text{Equation 6}$$

where

- $Avail_{net}$ [m³/month]: The net availability of water resources after accounting for human consumption and ecosystem requirements. It is inferred from the context of water availability calculations.
- HWC [m³/month]: Human Water Consumption, which refers to the total volume of water consumed by human activities in a specific region. This is a critical component in calculating water scarcity as it directly impacts the availability of water resources .
- EWR [m³/month]: Ecosystem Water Requirements, which are the necessary water needs for local ecosystems to function properly. This factor is essential in determining the overall water availability in a region, as it must be considered alongside human consumption.
- $Avail_{delta}$ [m³/month]: The change or difference in water availability over time or between different regions, although this is an assumption based on the context of water scarcity assessments.
- $area$ [km²]: Area of the region being considered

By incorporating AWARE into decision-making, industries and policymakers can better assess water use efficiency and minimize impacts on vulnerable water systems.

4.2 Data Collection and Processing

4.2.1 Territorial Water Footprint

The WFN water footprint calculation method when applied to the regional scale requires water usage data from urban water supply, touristic water usage, agriculture, and livestock water footprint and includes blue, green and grey water footprints from each of these

sectors, where applicable. For the purposes of MARCLAIMED, this data was collected over one year, from January 1st 2023 through December 31st, 2023.

4.2.1.1 Urban Water Supply

The urban water supply is divided into domestic uses, communitarian uses, commercial use, industrial uses, municipal uses, and touristic demand. Domestic uses include all private household water usage such as showers, laundry and dishwashing. Communitarian and commercial water is only use by businesses such as shops and restaurants, though the distinction between communitarian and commercial uses is not made in all datasets. Industrial water is water consumed by industry such as manufacturing. Municipal uses are all other urban uses such as fire suppression water and public water access points. Touristic demand requires more complex considerations and calculations, so is described in detail in the following section of this report. It is assumed that there are no distribution losses in urban water supply. Wastewater treatment plant (WWTP) data such as the volume of water treated and the concentration of nutrients and other contaminants in influent and effluent are also included. With this data, the grey water footprint of the WWTP is considered.

- In **DS1 (Llobregat, Spain)** data for all types of urban uses was available for 2023. The WWTP treats water from 8 municipalities in the region. Therefore, the volume of water treated by the WWTP for DS1 was scaled by the population of the DS (34,552) compared to the total population of the region (2,550,000). This WWTP also takes in some volume of surface water and groundwater to dilute the water pre-treatment. The grey water footprint of the WWTP was calculated considering total suspended solids, total N, total P and the biochemical oxygen demand (BOD5).
- **DS2 (Comporta, Portugal)** includes two municipalities: Alcácer-do-Sal and Grândola. These municipalities are considered together because the Comporta WWTP treats water from both municipalities, and because Alcácer-do-Sal exports 1,193,721 m³ of water per year to the municipality of Grândola (ERSAR, 2022b). Urban water supply data was available for both municipalities, but for the year 2022 rather than 2023 (ERSAR, 2022a). Only one combined value for communitarian, tourism, industrial, and municipal water usage was available for each municipality. The River Basin Management Plan for the Sado River stated that in the whole Sado River basin, 17% of water abstracted from both groundwater and surface water is for industrial uses (PGRH, 2023). This estimate was used to calculate the approximate industrial water use for the DS2 municipalities. Domestic water use data was available. Total volumes treated at WWTPs servicing Alcácer-do-Sal and Grândola municipalities were summed.

- The grey water footprint of the WWTPs was calculated using water quality data from the Comporta WWTP, because only data from that WWTP was available (AgdA, 2024). There is no surface water or groundwater intake at these WWTPs. Average values of effluent concentration were used. The natural concentration of the receiving water body (C_{nat}) was not available for TSS, COD or BOD5. C_{nat} values for total N and total P were taken from 2015 and 2022, respectively, due to data availability (AgdA, 2024). The C_{max} values were based on the WWTP qualitative thresholds established in the Portugal Decree 119/2019 (Ministerio do Ambiente, 2019) and on the WWTP Permit.
- For **DS3 (Texel)**, 2023 data was available for domestic, communitarian, tourism, and industrial water use (Texel Water, 2017; Boonekamp et al., 2012; Binnenlands Bestuur, 2021; Technische Unie, 2024). Municipal water use data was not available. There is one WWTP in the municipality, which does not take in surface water or groundwater for dilution. In the winter rainy season, the WWTP effluent is poured directly into the sea, and in the summer dry season the effluent is incorporated into the municipality's surface water system. Therefore, it is assumed that half the yearly volume treated is poured directly to the sea. The concentration of nutrients and other contaminants in the treated WWTP water is data collected from 2021, as no more recent data was available. Total N was the most potent contaminant, so was used for the WWTP grey water footprint calculation.

4.2.1.2 Tourism

Touristic water use data was collected for each municipality based on the number of occupancy-nights in hotels, campgrounds, and holiday apartments (IDESCAT, 2024).

- For **DS1**, data was available from 2023 for average daily water usage based on seven different categories of accommodation: five-star hotels, four-star hotels/apartments, three-star hotels/apartments, two star hotels, one-star hotels and hostels, camping, and housing for touristic purposes (e.g. Airbnb). Water usage ranged from 115 to 594 liters per day (Congostrina & Velasco, 2024; Scherb, 1975; GFANC, n.d.; Escalera et al., 2014; Morote et al., 2018; Tirado et al., 2019; Albergue Luz de Fromista, n.d.).
- In **DS2**, there were data for three categories of accommodation available: hotels, local accommodation and rural accommodation (Instituto Nacional de Estatística (INE), 2023a; Instituto Nacional de Estatística (INE), 2023d). However, there was no data available for the daily touristic water usage for each of these types of accommodation. Instead, an approximate of 300 liters per day was used for all

accommodation types, based on EU averages (European Commission Joint Research Centre, 2017).

- In **DS3**, there is only a yearly average of touristic water usage available. This value is 779,000 m³/year (Binnenlands Bestuur, 2021; Texel Water, 2017). Most of this use takes place in the summer months, as there is a busy tourist season. Much less tourism occurs in the winter.

4.2.1.3 Agriculture (arable land)

The agricultural water footprint for arable land for each demosite was calculated using CROPWAT. CROPWAT is a software program developed by the Food and Agriculture Organization of the United Nations (FAO). It is used for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. It was designed for farmers to be able to optimize irrigation practices (Smith, 1992). Inputs for CROPWAT are monthly climate data (temperature, humidity, wind, sun hours) which is used to calculate the reference evapotranspiration (ET_o). The program uses monthly precipitation data to calculate the effective precipitation by the USDA Soil Conservation Service Method. Table 1 indicates the sources of climate data for each demosite.

Table 1: Climate data sources for CROPWAT input

Data Type	DS1	DS2	DS3
Temperature (C)	(AEMET, 2024)	(Hersbach et al., 2023)	(KNMI, 2024)
Humidity (%)	(AEMET, 2024)	(Sistema Nacional de Informação (SNIRH), 2024)	(KNMI, 2024)
Wind speed (km/day)	(AEMET, 2024)	(Hersbach et al., 2023)	(KNMI, 2024)
Sunshine (%)	(AEMET, 2024)	(Sistema Nacional de Informação (SNIRH), 2024)	(KNMI, 2024)
Rainfall (mm)	(AEMET, 2024)	(Sistema Nacional de Informação (SNIRH), 2024)	(KNMI, 2024)

The crop type and crop schedule is included based on types of crop in each demosite municipality, with the crop growth data provided by CROPWAT. The soil data of each demosite is entered into CROPWAT, including soil moisture and soil type. The program calculates the crop water requirements and the irrigation requirement per month per crop. In the OASIS FLOW tool, the annual irrigation requirement for each crop is multiplied by the number of hectares each crop is planted on in the municipality. The total required

irrigation for agricultural purposes is the agricultural blue water footprint, the total amount of precipitation used by the crops is the green water footprint, and the percentage of the land covered by each crop is used to calculate the grey water footprint from the total volume of water treated at the WWTP (SMOS, 2024). Table 2 lists the crops that were included for the CROPWAT analysis for each demosite:

Table 2: Crops used in CROPWAT inputs

DS1	DS2	DS3
Artichoke	Barley	Potatoes
Broad bean	Broad bean	Grass
Cabbage	Corn	Legumes
Celery	Lupin	Sugar Beet
Cucumber	Oats	Vegetables
Eggplant	Peas	Winter wheat
Escarole	Potato	
Lettuce	Pumpkin	
Olive	Rice	
Onion	Ryegrass	
Pumpkin and zucchini	Sorghum	
Tomato	Spring wheat	
	Sunflower	
	Tomato	
	Vegetables	
	Wheat (triticale)	

4.2.1.4 Livestock

The number of livestock in the municipality of each demosite was tallied for the year 2023. Data on the water demands of meat cows, milk cows, chickens, laying hens, pigs, sheep, goats and horses were recorded per animal. The blue water footprint (e.g. drinking water), green water footprint (rainwater) and grey water footprint (water used for cleaning animals) were considered separately for each type of livestock (Lv et al., 2018; Hena et al., 2015; Zheng et al., 2019; Zhang et al., 2022). The method of livestock rearing was also considered for water usage. This was divided into three categories: extensive, semi-intensive and intensive, where extensive farming has a higher green water footprint, and intensive farming has a higher blue and gray water footprint. The direct water footprint for food consumption by locally produced food was estimated as well as the

indirect water footprint for consumption of food produced outside the municipality. The total water footprint for all types of livestock was determined by multiplying the number of animals times the water footprint per animal.

- For **DS1**, there was data available on water usage per type of livestock and livestock rearing method. The data on the number of animals was only available from 2009 and provided by IDESCAT, and it was scaled to the estimated number of animals in 2021 using the increasing activity in the sector as well as the amount of companies involved who reported an economical activity during the subsequent years (IDECAT, 2024).
- For **DS2**, there wasn't information on the number of animals in Alcácer-do-Sal or Grândola. The total number of livestock in the Alentejo region was taken from 2023 (Instituto Nacional de Estatística (INE), 2023b). The total water footprint was scaled by the area of the two municipalities combined compared to the area of the Alentejo region. The water usage per type of animal was not available, so the same values as used in DS1 were assumed because there is not much livestock farming in this area of Portugal, so there is a small effect of livestock on the total water footprint calculated for the demosite. The percentage of livestock feed produced inside versus outside the municipality was assumed to be the same as the values provided for DS1.
- For **DS3**, livestock numbers were available in Texel for the year 2023 (StatLine, 2024). The blue, green and gray water footprints for each type of livestock were based on a 2012 report of Texel's water footprint (Boonekamp et al., 2012; Mekonnen & Hoekstra, 2010). The percentage of livestock feed produced inside versus outside the municipality was assumed to be the same as the values provided for DS1 because these data were not available for DS3.

The livestock and arable land agricultural water footprints are aggregated for each demosite, such that the blue, green and gray water footprints are summed to determine the total agricultural footprint.

4.2.1.5 Outputs for Integration with QUEEN and AWARE

For integration with the AWARE and QUEEN tools, the urban water supply demand, the industrial demand and the agricultural demand were used as inputs. The urban water supply demand is calculated by the domestic, communitarian, commercial, municipal and touristic demands plus the grey water footprint from the WWTP, minus the volume of water returned to the water basin from the WWTP. The industrial demand is included

separately because it is assumed to have no seasonal variation. The agricultural demand is the sum of the water use for arable land and the livestock water demand.

4.2.2 QUEEN Data calculation and methodology

The QUEEN tool within OASIS FLOW calculates the water footprint of the MAR system itself. There are four main components of the MAR system that are considered in the tool:

1. The **recharge rate** of the MAR system is the average rate that the MAR system is capable of infiltrating water into the aquifer. This value can vary by season and by month, which is accounted for in the QUEEN calculations.
2. The **system efficiency**, which accounts for water losses during infiltration.
3. The **indirect water footprint** is the water footprint incurred by the MAR system during operation and maintenance. For example, electricity uses and materials that need to be frequently replaced, such as filters, are included in the indirect water footprint.
4. The **grey water footprint** due to infiltration of water that is of poorer quality than that of the receiving waters, which is the aquifer of each demosite.

The water footprint for the system is calculated per month, and typically is a negative value because the MAR systems *add* water to the aquifer, and therefore increase water availability.

4.2.2.1 Recharge rate and system efficiency

The recharge rate in m^3/hr is multiplied by the time the system is operational per month. The following considerations were made for each DS:

- **DS1:** The recharge rate by reclaimed water from the WWTP and the pre-potable water were considered separately. Pre-potable water is taken from the Llobregat River only when the river can sustain environmental flow rates. The MAR system only uses the percentage of river water above the ecological flow rate for recharge to the system. The average recharge rate for the year was added to the water available from the river to calculate the total volume of water recharged per month, on average. Reclaimed water quality has to comply with ACA limitations (Agencia Catalana del Agua) prior to its infiltration through the MAR system and the own regulations that the infiltration permit allows.
- **DS2:** The average recharge rate over one year was used to calculate the total volume recharged by the MAR system per month.

- **DS3:** Recharge only occurs from November through April. The average recharge rate over these months was used to calculate the monthly volume infiltrated. In May through October, the volume recharged is zero.

4.2.2.2 Indirect water footprint

The result of the indirect water footprint calculations is the indirect water footprint incurred per m³ of water used for infiltration.

- For **DS1**, the indirect water footprint calculations considered chemical reagents (PAX, anionic polyelectrolyte, sodium hypochlorite, ferric chloride), electricity for air conditioning, tertiary uses and for operating the water pumps, and fine sand for filtration.
- In **DS2**, all electricity uses for the MAR system are necessary electricity uses for the Comporta WWTP because the system pumps directly to the infiltration ponds due to the proximity of a Sensitive Area that voids the possibility of discharging to a stream. Therefore, the indirect water footprint only considers sludge that is collected and re-used as fertilizer for agriculture. This produces a negative indirect water footprint for the demosite because system operation is reducing the water use required in local agricultural practice.
- For **DS3**, the only consideration for the indirect water footprint was electricity use. One value for the year of 2023 was available, which includes electricity for pumping water both into and out of the system. Materials used in the slow sand filter and granular activated carbon filter do not need to be regularly replaced, so were not included in the indirect water footprint calculations.

4.2.2.3 Grey water footprint

The grey water footprint for each demosite is calculated based on the WFN methodology. The most potent contaminant is calculated based on maximum allowable infiltration concentration of a given contaminant (C_{max}), the actual concentration of water that is infiltrated based on average concentrations in effluent (C_{effl}), the natural or background concentration of that contaminant in the aquifer (C_{nat}), and the volume infiltrated per year (V_{effl}).

- In **DS1**, nitrate (NO_3) is the most potent contaminant. Chloride (Cl), total suspended solids (TSS), and Total Nitrogen (TN) were also considered, with C_{max} values attributed to WWTP permit regulations (Aigues de Barcelona, 2024).
- In **DS2**, biological oxygen demand (BOD) is the most potent contaminant. The permit obtained by the Comporta WWTP includes discharge regulations for oil and

grease, BOD, chemical oxygen demand (COD), and total suspended solids (TSS) (AgdA, 2024).

- In **DS3**, nitrate-N ($\text{NO}_3\text{-N}$) is the most potent contaminant. The nitrate infiltrated is removed to background levels before it is recovered for use. Therefore, the concentration of nitrate in infiltrated water is assumed to be equal to that of the aquifer so that the grey water footprint calculation methodology does not erroneously overestimate the grey water footprint. Total pesticides, $\text{PO}_4\text{-P}$, and electric conductivity were also considered.

4.2.3 AWARE data from global database

The AWARE (Available Water Remaining) method calculates water scarcity by assessing the availability of renewable water resources minus human water consumption, providing a localized water scarcity indicator for specific regions. AWARE factors are primarily developed at the watershed scale, which consists of 11,050 spatial units globally, allowing for a detailed understanding of water availability and consumption patterns.

To enhance the applicability of AWARE factors, regional scale factors are introduced, which provide a more practical resolution than the watershed scale (FID), accommodating administrative regions such as states or provinces. The subnational factors are calculated using a consumption-weighted average approach, ensuring that water consumption data reflects the actual usage patterns within these regions. These factors are available on a monthly and annual basis, categorized into agricultural, non-agricultural, and unknown consumption types, allowing for tailored assessments based on specific water use contexts.

The methodology emphasizes the importance of using subnational factors over national factors due to significant variability in water scarcity indicators across different administrative regions within a country. The integration of subnational AWARE factors aims to reduce uncertainty in water footprint assessments, ultimately leading to more accurate and representative evaluations of water scarcity impacts. The AWARE methodology provides the values of the availability of water for each FID (Area Factor IDs). These FIDs are artificial spatial polygons which relate to a geopolitical region linked with a specific water basin. In many cases these polygons represent a specific region of a country.

Aiming to downscale the results of the AWARE methodology and the water availability provided for the regional scale to a municipal level, we need to use two main vectors in order to minimize uncertainty introduced. There have been several cases in which the study area is contained in several FIDs, in order to solve that problem a proportion of the

area present on each of those polygons has been used to calculate the right values provided by the FID. The main vectors used are the area of the municipality as well as the water demands for each economic sector, which are calculated in the territorial water footprint methodology for a municipal level and provided as the water footprint for each of those sectors. The sum of these values was used as the input for the total water footprint of the municipality separated in its three main components: blue water footprint, green water footprint and grey water footprint. This approach helps to mitigate the effects of the uncertainties included in the downscaling process.

4.3 Digital Tool Development

The Oasis Flow tool was developed with the goal of generating results that allow for relatively simple integration into the IDST. For the AWARE methodology and the downscaling of the global values for water availability to a regional scale, R programming language was used. The FID area was calculated using QGIS software and input into the scaling calculation in R. Calculations for the territorial water footprint and the QUEEN methodology were carried out using Excel. Resulting CSV and graphical outputs for the impact were generated.

For integration with the IDST, inputs are introduced via datasheets and a template that allows the tool to automatically provide the results. The integration will be completed in the coming months.

4.4 Technical and Implementation Requirements for the integration in the MARCLAIMED IDST

The technical and implementation requirements for the integration in the MARCLAIMED IDST are described in deep detail in the following deliverables from WP2 “MARCLAIMED IDST: Integrated Decision Support Tool for MAR recommendations and early warning alert system” development:

- D2.1 Requirements and global architecture v1 (July 2024 - submitted to the Portal).
- D2.3 Data models (January 2025 - submitted to the Portal).
- D2.4 Open interfaces (January 2025 - submitted to the Portal).
- D2.5 MARCLAIMED Integrated Decision Support Tool v1 (July 2025 - to be submitted to the Portal).

5. Application and preliminary results in Demo Sites

Preliminary results from the synthesis of the territorial water footprint, QUEEN and AWARE methodologies into the OASIS FLOW tool are presented here. Deliverables **D4.1** “MARCLAIMED in the three demo sites” (due M30), **D4.2** “Lessons learned” (due M36) and **D4.3** “Progress report demo sites” (due M30) will validate these results which will allow for further in-depth analysis.

5.1. DS1: Llobregat, Spain

5.1.1 DS1: Territorial water footprint

The total annual territorial water footprint of Llobregat is 2,225,684 m³/ year. The following table presents the water footprint results of each sector:

Table 3: Territorial water footprint, DS1

Water footprint in the municipality of Llobregat [m ³]		Summed water footprint for input to AWARE [m ³]	
Domestic Demand	1,195,022	Municipal water supply demand	1,628,437
Communitarian Demand	19,741		
Commercial Demand	43,391		
Touristic Demand	31,494		
Municipal Demand	96		
WWTP grey water footprint	1,306,388		
Returned volume to the water basin	-967,694		
Industrial Demand	374,491	Industrial demand	374,491
Agricultural (Arable) Demand	220,210	Agricultural demand	222,756
Livestock Demand	2,546		

The returned volume to the water basin is negative because the treated outflow is returned to the water basin, not to the sea. Therefore, that volume of water is added back to the system, so is not included in the water footprint. The WWTP water footprint is only attributed to its grey water footprint.

5.1.2 DS1: QUEEN

The indirect water footprint for the DS1 MAR system was zero for months when only reclaimed water was used because all system operations are standard WWTP procedure.

In months where pre-potable water from the river was also recharged, the indirect water footprint was 353 m³/month.

The grey water footprint due to nitrate was 142,516 m³/year, which averages about 11,876 m³/month. This is about 15% of the total water recharged that must not be included in the total negative water footprint of the MAR system. The results of the grey water footprint calculations are included in **ANNEX 1**.

An average recharge rate of 108 m³/hr and system efficiency of 97.2% resulted in an average monthly MAR water footprint of -64,634 m³ accounting for both the indirect and grey water footprint of the system. This totals -775,605 m³ per year.

5.1.3 DS1: AWARE

The AWARE methodology first calculates the monthly water availability of the municipality. In Llobregat, there is a clear seasonality in which there is more water available in the winter months than the summer months (Figure 2). Without the MAR system, average monthly water availability ranges from just under 16,000 m³ in August to 130,000 m³ in February without the MAR system. When the MAR system is added into the AWARE methodology, these values increase significantly: from 16,000 m³ to nearly 82,000 m³ in August and from 130,000 to nearly 190,000 in February (Figure 2).

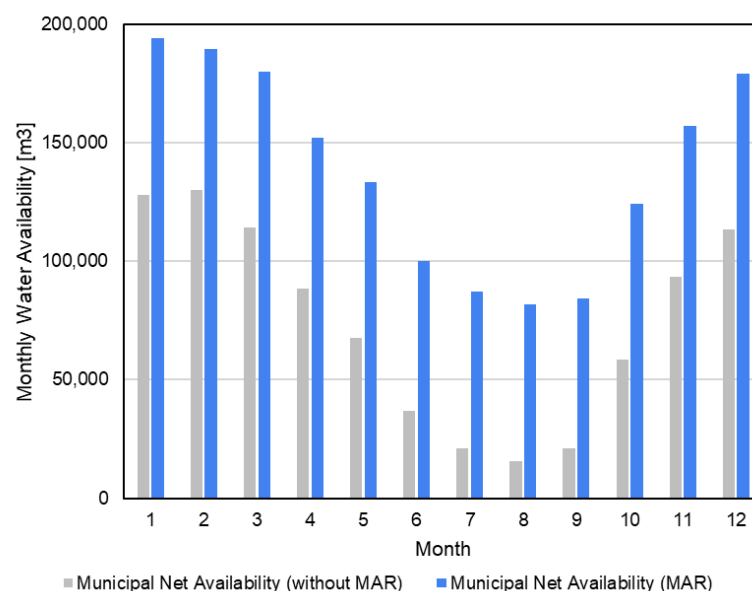


Figure 2: Monthly municipal water availability in DS1 with and without the MAR system.

When observing the water availability minus demand (AMD), even with the MAR system in place February is the only month with a water surplus in Llobregat (Figure 3).

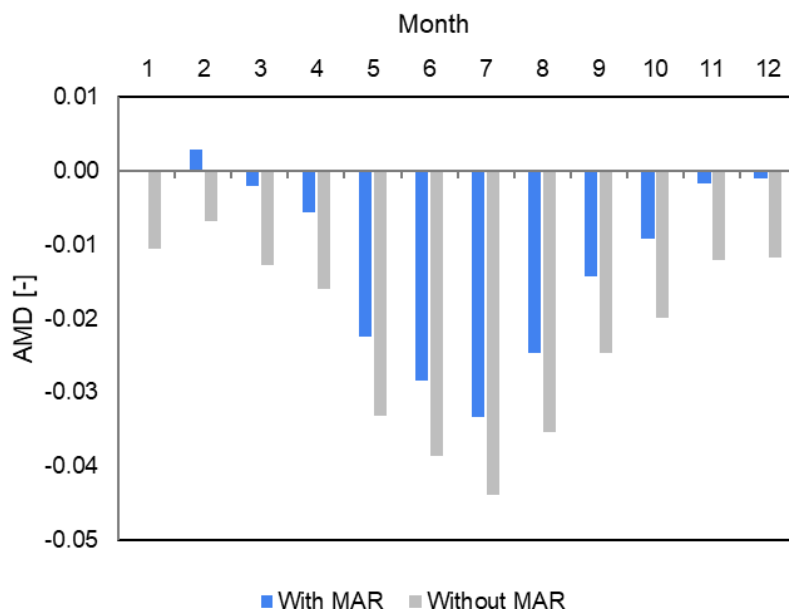


Figure 3: Monthly water availability minus demand (AMD) in DS1 with and without the MAR system.

5.2 DS2: Comporta, Portugal

5.2.1 DS2: Territorial water footprint

The total annual water footprint of the Alcácer-do-Sal and Grândola municipalities together is 130,994,530 m³. The following table presents the water footprint results of each sector:

Table 4: Territorial water footprint, DS2

Water footprint in the municipalities of Alcácer-do-Sal and Grândola [m ³]		Summed water footprint for input to AWARE [m ³]	
Domestic Demand	1,397,862	Municipal water supply demand	2,070,302
Communitarian Demand	335,020		
Commercial Demand	0		
Touristic Demand	156,312		
Municipal Demand	0		
WWTP grey water footprint	181,108		
Returned volume to the water basin	0		
Industrial Demand	68,618	Industrial demand	68,618

Agricultural (Arable) Demand	128,855,399	Agricultural demand	128,855,610
Livestock Demand	211		

5.2.2 DS2: QUEEN

The indirect water footprint for the MAR system in Comporta averages $-15.9 \text{ m}^3/\text{month}$ due to the sludge by-product used for agriculture.

The grey water footprint due to BOD was $35,054 \text{ m}^3/\text{year}$, which is an average of about $2,921 \text{ m}^3/\text{month}$. This is about 70% of the total water recharged that must not be included in the total negative water footprint of the MAR system. The results of the grey water footprint calculations are included in **ANNEX 1**.

The recharge rate of the system in Comporta is highly variable between months. Infiltration data from November 2021 through July 2024 showed peaks in summer months with an average of $6,739 \text{ m}^3$ infiltrated in August, and the smallest volume infiltrated in February with only $2,890 \text{ m}^3$. However, an average recharge rate of $5.7 \text{ m}^3/\text{hr}$ was used to acquire these preliminary results. The system has an efficiency of 99%, which results in a total of $49,932 \text{ m}^3$ infiltrated per year (AgdA, 2024). With the indirect water footprint and grey water footprint, the total annual MAR water footprint is $-14,565 \text{ m}^3$, or about $-1,214 \text{ m}^3/\text{month}$. The negative value of the MAR water footprint indicates that MAR operation is adding water back into the natural system and increasing water availability.

5.2.3 DS2: AWARE

The Comporta demosite imparts a negligible impact on the water availability of the Alcácer-do-Sal and Grândola municipalities. Monthly water availability is high even in summer months in comparison to the amount of water infiltrated monthly at DS2. In August, the average water availability without the MAR system was $303,107,000 \text{ m}^3$. In January the average water availability was more than 1.6 billion m^3 . The WWTP only infiltrates $4,161 \text{ m}^3$ of water per month on average. Therefore, the overall impact of the demosite is not seen on a municipal scale (Figure 4).

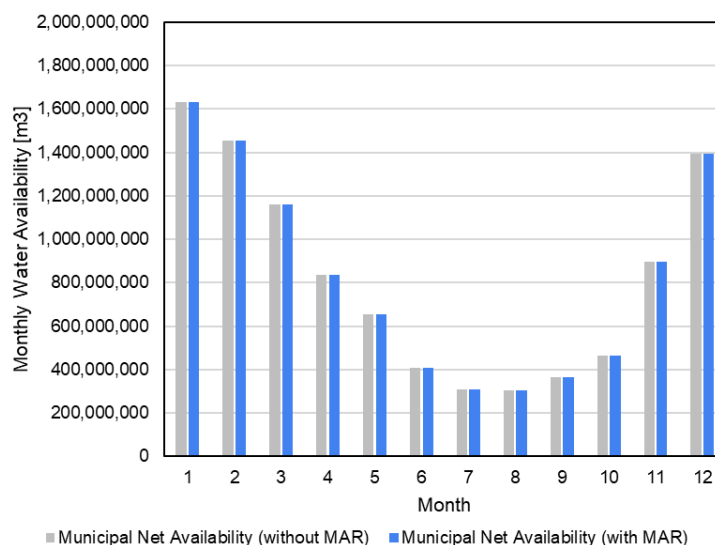


Figure 4: Monthly water availability for the municipalities of Alcácer-do-Sal and Grândola combined (DS2).

Even in the dry summer months, the water availability minus demand for the Alcácer-do-Sal and Grândola municipalities is positive (Figure 5). This indicates that there is a surplus of water throughout the year based on the OASIS FLOW methodology.

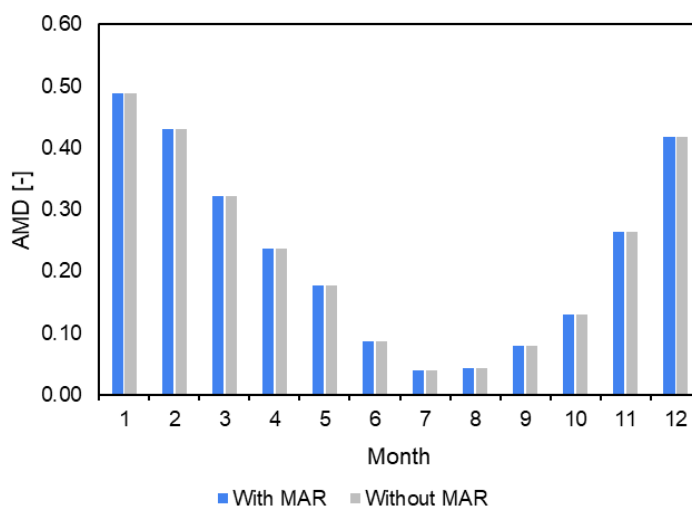


Figure 5: Monthly water availability minus demand for the municipalities of Alcácer-do-Sal and Grândola combined (DS2 - both grey WF methods return the same result because of significant figures).

5.3 DS3: Texel, The Netherlands

5.3.1 DS3: Territorial water footprint

The total territorial water footprint for the municipality of Texel is 14,961,004 m³. The following table presents the water footprint results of each sector:

Table 5: Territorial water footprint, DS3

Water footprint in the municipality of Texel [m ³]		Summed water footprint for input to AWARE [m ³]	
Domestic Demand	729,634	Municipal water supply demand	2,519,928
Communitarian Demand	783,000		
Commercial Demand	0		
Touristic Demand	779,000		
Municipal Demand	0		
WWTP grey water footprint	228,294		
Returned volume to the water basin	0		
Industrial Demand	318,633	Industrial demand	318,633
Agricultural (Arable) Demand	-3,021,015	Agricultural demand	14,961,004
Livestock Demand	15,143,458		

Note that the arable agricultural water footprint is negative because the methodology subtracts the livestock green water footprint from the green agricultural water footprint which is the amount of rain falling on fields. This ensures that the green water footprint is not double-counted for livestock feed that is grown in the area.

The value for the volume returned to the basin from the WWTP is zero because all water treated by the WWTP is released to either directly into the North Sea or ditches, which drain to the sea.

5.3.2 DS3: QUEEN

The indirect water footprint of the MAR system in Texel due to electricity use averages 8.55 m³/month during the months when the system is on (November through April). Of course, there are electricity uses for the pump during the months when water is recovered as well (May through October), but the total annual indirect water footprint was evenly dispersed over only the infiltration months so that it could be subtracted from the monthly water infiltrated to calculate the water footprint of the system.

The grey water footprint was highest for nitrate, at 913 m³/year. This averages about 152 m³/month when the system is infiltrating water. The grey water footprint is 4.7% of the total volume infiltrated per year. The results of the grey water footprint calculations are included in **ANNEX 1**.

The recharge rate of the MAR system averages 4.5 m³/hr with 100% efficiency (no water losses). This comes out to just under 20,000 m³ infiltrated per year. Including the indirect and grey water footprints of the system, the total annual water footprint of the MAR system is -18,583 m³, or about -3,100 m³/month.

5.3.3 DS3: AWARE

The AWARE methodology shows insignificant impacts of the MAR system on the water availability of the island of Texel. Without the MAR system, the average water availability of Texel is lowest in September, at 194,439 m³ and highest in January, at 982,661 m³ (Figure 6). To account for the fact that water infiltration and recovery do not occur in the same months, the cumulative volume of water infiltrated was added to the water availability of the municipality each month. By the end of the infiltration season, the water available from the MAR system is the sum of the water infiltrated in all previous months of that season. In the summer months, the water is recovered, and the availability from the MAR system decreases again (Figure 6).

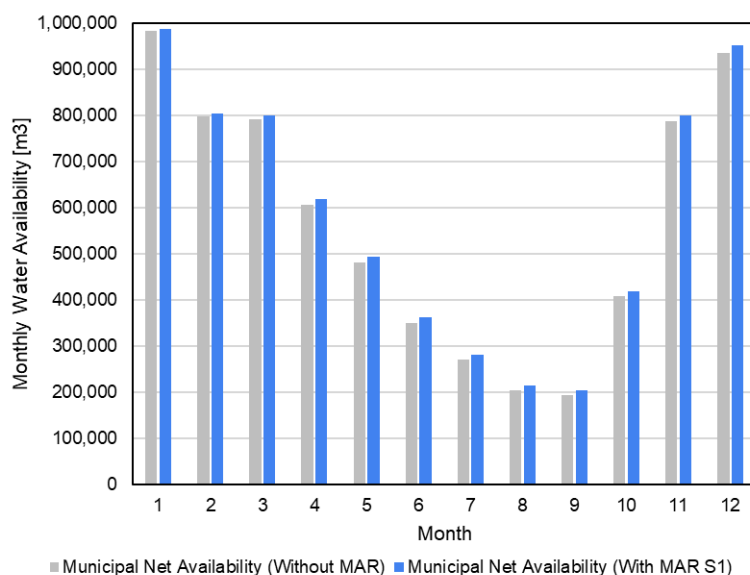


Figure 6: Monthly municipal water availability for the municipality of Texel for the first operational season, 2022-2023 (DS3).

In Texel, there is surplus water available in November through April, and a water deficit in May through September (Figure 7). Note that this also corresponds roughly with infiltration and recovery seasons of the MAR system.

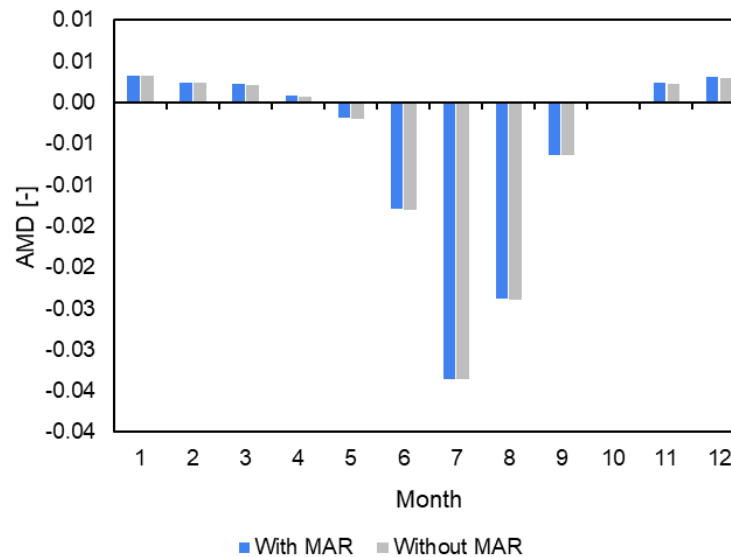


Figure 7: Monthly water availability minus demand for the municipality of Texel (DS3).

6. Discussion

6.1 Implications for MAR Impact at a Municipal Scale

The goal of the OASIS FLOW tool within WP1 and SO2 “To achieve economic and financial feasibility and sustainability of MAR with AWR under uncertainty while enabling recovery after unforeseeable events occur (i.e., resilience)” is to measure the observable impact of each MAR system in its respective municipalities and therefore provide implications for MAR as a reliable form of AWR management.

6.1.1 DS1: Llobregat, Spain

In DS1, the impact of the MAR system on water availability in the municipality is seen in all months. The annual water footprint, or water volume recharged considering the indirect and grey water footprint of the MAR system (775,605 m³) is 35% of the total annual territorial water footprint of the municipality (2,225,684 m³). The grey water footprint is minimized because of high legal contaminant concentrations in recharged water compared to that of DS2 and DS3. The AMD factor for DS1 is more negative in the driest

month (July) without the MAR system (-0.0439) than with the MAR system (-0.0247), emphasizing the impact of the MAR system on municipal water availability. Therefore, the OASIS FLOW tool provides a reasonable result and achieves the deliverable objectives of WP1 and SO2 of determining that the operational efficiency of the MAR system is acceptable.

6.1.2 DS2: Comporta, Portugal

In DS2, the impacts of the MAR system are not seen at the municipal scale. The annual volume of water infiltrated ($49,932 \text{ m}^3$) is only 0.04% of the territorial water footprint of Alcácer-do-Sal and Grândola ($130,994,530 \text{ m}^3$). Including the indirect water footprint and grey water footprint, the impacts of the system are diminished further: The MAR water footprint is $-14,565 \text{ m}^3$, only 0.01% of the territorial water footprint. The AMD factors without the MAR system and with the MAR system are the same every month. As expected, the MAR system does not make an impact at the scale of the two municipalities because of the comparably immense water footprint of Alcácer-do-Sal and Grândola. While the OASIS FLOW tool has been successfully applied to DS2, thus meeting the WP1 and SO4 goal of applying a model-based tool to determine the operational efficiency of the MAR system, the results are not conclusive due to the small scale of the system. During the validation period, this result will be considered so that more conclusive results can be drawn from the tool.

6.1.3 DS3: Texel, The Netherlands

In DS3, the impacts of the MAR system are only seen on a small scale. The annual water footprint, or water volume recharged considering the indirect and grey water footprint of the MAR system ($18,583 \text{ m}^3$) is 0.1% of the annual territorial water footprint for Texel ($14,961,000 \text{ m}^3$). The AMD factor at the end of the infiltration season (April) is lower without the MAR system (0.00076) than with the MAR system (0.00083). However, every year, the MAR system grows the fresh water “bubble”, effectively increasing the amount of water made available due to AWR. The OASIS FLOW tool is not designed to calculate water availability accumulation, but simple modifications can be made to add this capability. The OASIS FLOW tool applied to DS3 meets the WP1 and SO4 goal of assessing the operational efficiency of the MAR system. Further work will be done during the validation process and the reporting in deliverable **D4.2 “Lessons Learned”** to improve our understanding of the effects of groundwater accumulation on system efficiency.

6.3 Challenges

Challenges that arose in development and application of the OASIS FLOW tool to the three demosite include:

1. **Data unavailability:** For results to be comparable, the same data should be used for each demosite. However, there were some cases where data from 2023 was not available. Assumptions had to be made in some cases due to unavailability of data; for example an estimation of the municipal livestock numbers for DS3 was made based on regional data.
2. **Scaling to demosite:** Scaling in the AWARE tool may result in uncertainties when going from the global water availability database to the municipal scale. This was done using the fraction of the area covered by the municipality within the FID and the municipal level demands. Of course, the water availability within the FID is not even spatially. For example, if there is a large river on one part of the FID, the water availability is higher there and would increase the average water availability across the FID. With smaller municipalities, this effect is exacerbated. Additionally, it is not clear how to treat the FID area that is over an ocean. If there is an urban center within the municipality, the water supplying that area may not be from within the municipality itself. Therefore, the effects of the MAR systems on municipal water availability is an oversimplification.
3. **Grey water footprint calculations:** The grey water footprint methodology for the MAR system has some drawbacks. In the case of DS3, the result from the grey water footprint is large compared to the volume of water infiltrated. With OASIS FLOW, this suggests that a large portion of the water infiltrated cannot be “counted” in the water footprint. The grey water footprint is also based on legislative concentration limits for water infiltration. In the case of DS3, these legislative limits are for drinking water, which is not the effective end-use of the water being infiltrated and are not (yet) enforced in the MAR system. With no other legislative limits available, the grey water footprint methodology is likely over-estimating the impact of the MAR systems on water quality degradation.

7. Conclusions and Next Steps

The implementation of the assessment tool across the three demo sites has demonstrated its effectiveness in evaluating the impact of aquifer recharge on water availability. In Llobregat (DS1) and Texel (DS3), the tool successfully provided meaningful insights into water availability changes based on the water footprint methodology. However, in the Comporta (DS2) demo site, the large scale of the municipality compared to the small scale

of the MAR system impedes the OASIS FLOW method from determining a measurable impact in water availability.

Further implementation efforts will focus on collecting more real-time data on water quality post-infiltration. As additional data becomes available, it will be used to refine the assessment and improve the tool's ability to capture changes in availability. Continuous monitoring and validation will be essential to better understand how water quality evolves over time and whether adjustments to the methodology are necessary to account for sites with high grey water footprints.

Future validation efforts will include:

- Regular collection and analysis of water quality data after infiltration, ensuring a more accurate representation of recharge impacts.
- Exploration of potential methodological refinements to better account for sites with substantial grey water footprints.
- Collaboration with stakeholders to integrate additional water management strategies that could enhance the observed benefits of aquifer recharge.
- Validation and consideration to adopt modifications to improve the understanding of the effects of groundwater accumulation on system efficiency.
- Integration of Oasis Flow WFP calculation methods into the MARCLAIMED integrated decision support tool (IDST).

By following this approach, the tool's applicability across different MAR systems purposes can be strengthened, ensuring its robustness as a decision-support system for aquifer recharge management.

Stakeholder engagement surrounding the OASIS FLOW tool will further inform the future application and scenario modelling for each demosite. Scenarios such as scaling the MAR systems by making systems larger versus by implementing more systems of the same scale across the municipality can be explored. Such stakeholders and their roles in AWR are described in **D3.2** "Co-creation report v1".

Further data validation and scenario modelling with the OASIS FLOW tool will be conducted in **WP4** "CoPs-based implementation and validation at the demo sites" and presented in **D4.2** "Lessons Learned".

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9. Annexes

ANNEX 1: Grey Water Footprint

DS1: Llobregat, Spain

Reclaimed water	Chloride (mg Cl/l)	TSS (mg/l)	NT (mg/l)	NO3 (mg NO3/l)
V abtr	1,412,060	1,412,060	1,412,060	1,412,060
C act (river or similar)	415.0	100.0	18.9	18.9
C max	800	35	10	25
C nat (aquifer)	0.0	0.0	0.0	0.0
C effl	522.0	4.3	11.2	32.0
V effl	946,080	946,080	946,080	946,080
Grey waterfootprint	-115,189	-3,918,764	-1,606,819	142,516
142,516				

Recharged water [m3]	946,080	Grey water footprint [m3]	142,516	15%	Factor	0.151
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DS2: Comporta, Portugal

	Oil and Grease [mg/L]	BOD [mg/L]	COD [mg/L]	TSS [mg/L]
C max	15	25	125	35
C nat (aquifer)	0.0	6.63	7.34	0.13
C effl	1.7	12.9	63.2	13.8
V effl	49,932	49,932	49,932	49,932
Grey waterfootprint effluent	5,659	35,054	26,819	19,759
35,054				

Recharged water [m3]	49,932	Grey water footprint	35,054	70%	Factor	0.702
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DS3: Texel, The Netherlands

	Total Pesticides [ug/L]	NO3-N [mg/L]	PO4-P [mg/L]	EC[mS/cm]
C max	0.5	11.2	0.400	1.6
C nat (aquifer)	0.0	0.5	1.2	22.0
C effl	0.0	0.5	0.9	1.4
V effl	19,548	19,548	19,548	19,548
Grey waterfootprint	0	913	-22,830	-1,342
913				

Recharged water [m3]	19,548	Grey water footprint [m3]	913	4.67%	Factor	0.047
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MARCLAIMED will support decision makers to integrate Managed Aquifer Recharge (MAR) with Alternative Water Resources (AWR) in River Basin and Drought Management Plans supporting the adaptation and resilience of structural supply systems in the context of climate change. The main outcome will be the MARCLAIMED Integrated Decision Support Tool (IDST) that will provide solutions to tackle existing and emerging threats and support decision making and adaptation policies.



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