MARCLAIMED

Progress Report Demo Sites

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ABSTRACT	Progress report on the deployment and implementation of the Demo Sites, showcasing the adaptability and effectiveness of MAR solutions across varied geographical, climatic, and operational contexts. The results obtained at the three Demo Sites confirm that MAR systems can significantly enhance groundwater availability and quality, optimize recharge operations, and improve resilience to climate-induced water stress.		

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EXECUTIVE SUMMARY

Managed Aquifer Recharge (MAR) with Alternative Water Resources (AWR) is emerging as one strategic adaptation measure to tackle growing water scarcity and more frequent droughts driven by climate change, particularly in semi-arid regions like Southern Europe. Optimized and successful showcase examples are essential to build confidence and support the daily operations of water utilities, as well as to inform and guide decision-makers and policy planners.

Therefore, the objectives of WP4 are: to demonstrate the efficiency of innovative MAR technological tools in practice, aiming to improve water quality, optimise infiltration rates, and increase groundwater storage (SO1); to quantify the economic and financial feasibility and performance of different MAR schemes (SO2); to engage stakeholders, beneficiaries and the CoP in MAR related decisions, increasing social perception, acceptance and trust (SO4); and to provide guidance for future MAR schemes, with lessons learnt and guidelines (SO5).

Deliverable D4.3 highlights the mid-term progress achieved at the three MARCLAIMED Demo Sites, showcasing the adaptability and effectiveness of MAR solutions across varied geographical, climatic, and operational contexts. From urban aquifers under pressure in Spain, to advanced wastewater treatment in Portugal, and agricultural water reuse on a Dutch island, each site demonstrates tailored MAR strategies that respond to local water challenges. The results obtained so far confirm that MAR systems (from infiltration ponds and SAT-MAR to ASTR configurations) can significantly enhance groundwater availability and quality, optimize recharge operations, and improve resilience to climate-induced water stress.

The initial results clearly validate the potential of MAR as a strategic water management tool, especially when combined with robust monitoring, data-driven decision-making, and site-specific adaptations. Across all three Demo Sites, improvements are observed in key-performance indicators related to aquifer recharge volumes, contaminant removal efficiencies, and operational reliability. These findings not only support the ongoing development of MARCLAIMED solutions but also provide strong, transferable evidence to guide water utilities, policy makers, and regulators in the broader adoption of MAR technologies to support sustainable water resource management in Europe and beyond.

ACRONYM GLOSSARY

ACA *- Agència Catalana de l'Aigua*
Acacia *– Acacia Water*
AgdA *– Águas Públicas do Alentejo*
APA *- Agência Portuguesa do Ambiente*
ASR *- Aquifer Storage and Recover*
ASTR *- Aquifer Storage Transfer and Recover*
AWR *- Alternative Water Resources*
Bgl *- Below ground level*
BOD *- Biochemical Oxygen Demand*
CEDEX *- Center for Studies and Experimentation of Public Works*
CECs *- Contaminants of Emerging Concern*
COD *- Chemical Oxygen Demand*
Ds *- Demo Site*
DWTP *- Drinking Water Treatment Plant*
EC *- Electrical Conductivity*
GAC *- Granular Activated Carbon*
GDE *- Groundwater-Dependent Ecosystems*
IDST *- Integrated Decision Support Tool*
IPR *- Indirect Potable Reuse*
LNEC - National Laboratory for Civil Engineering
MAR *- Managed Aquifer Recharge*
MCDA *- Multi-Criteria Decision Analysis*
ORP *- Oxidation-Reduction Potential (or Redox potential or Eh)*
PCE *- tetrachloroethylene*
PGDCFC *- Catalan River Basin Risk Management Plan*
TDW *- Tile Drainage Water*
PhC *- Pharmaceutical Compounds*
PNEC *- Predicted Non-Effect Concentration*
RMP *- Risk Management Plan*
RW *- Reclaimed Water*
SAT *- Soil-Aquifer Treatment*
SQI *- Spectral Quality Index*
SSF *- Slow Sand Filtration*
SVH *- Sant Vicenç dels Horts*
TCE *– trichloroethylene*
TDW *- Tail Drainage Water*
THM *- Trihalomethane*
TOC *- Total Organic Carbon*
TV *- Threshold Values*
TWW *- Treated Wastewater*
WHO *- World Health Organization*
WP *- Work Package*
WWTP *- Wastewater Treatment Plant*



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1 DS1: Llobregat (SP)

1.1 Introduction and objectives

The first MARCLAIMED Demo Site (DS1) is located in the Mediterranean coastal aquifer of Baix Llobregat, in the region of Barcelona, northeast Spain. This area is facing increasing water stress due to climate change and intensive land use. The site implements a Managed Aquifer Recharge (MAR) scheme using reclaimed water, aiming to enhance groundwater availability, improve water quality, and reduce dependency on conventional water sources.

The DS1 includes:

1) An infiltration pond at Sant Vicenç dels Horts, where MAR is performed with reclaimed water coming from El Prat de Llobregat Wastewater Treatment Plant (WWTP).
2) A deep injection well (named Well 18) at Sant Joan Despí, where MAR is performed with surface pretreated water at Sant Joan Despí Drinking Water Treatment Plant (DWTP).

These actions contribute to aquifer water level's recovery, saltwater intrusion prevention, and long-term resilience of the water resources in the area.

DS1 also serves to validate the use of alternative water resources (AWR) and generate data to support the MARCLAIMED Integrated Decision Support Tool (IDST) for sustainable water management. This aligns with the MARCLAIMED project's overarching objective: to integrate MAR with AWR into River Basin and Drought Management Plans, enhancing the resilience and adaptability of water supply systems in the face of climate change.

1.2 Motivation for the site selection

Barcelona's Mediterranean climate makes it especially prone to water scarcity. In recent years, Barcelona has faced one of the most severe droughts in decades, meaning a decrease in water availability from both surface and groundwater resources.

The combined effect of limited precipitation and historical overexploitation of the Baix Llobregat aquifer, has caused a concerning and sustained decrease in piezometric levels between 2022 and 2024 (Figure 1.1).

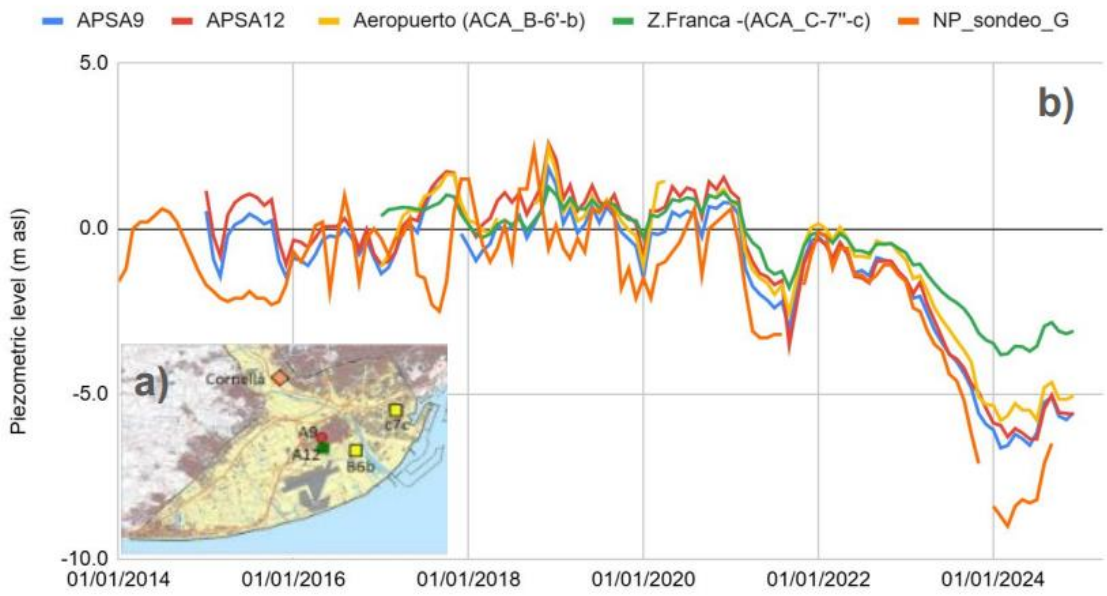


Figure 1.1 a) Piezometers located on the coastal aquifer of Baix Llobregat; b) Groundwater levels measured in the piezometers (m above sea level)

To address the water scarcity, since December 2022, a crucial strategy has been implemented, which has consisted in releasing reclaimed water from the city's main reclamation facility into the Llobregat River (Figure 1.2), in order to maintain sufficient flow for both drinking water intake and ecological needs. Before releasing the water, at the WWTP, water undergoes a basic regeneration process which consists of physico-chemical treatment and ballasted settling, followed by microfiltration and disinfection.

This strategy of sending reclaimed water 16 km upstream from the WWTP has meant a clear example of the feasibility of the Indirect Potable Reuse (IPR) scheme in the region. In fact, in recent years, the use of Reclaimed Water (RW) has clearly risen, and the main use is ecological flow and IPR.

Within this strategy, also MAR was implemented, both through infiltration ponds and deep injection wells. The site selected is strategically located to contribute to the increase of groundwater reserves through MAR. Moreover, the introduction of RW in this approach supports broader water reuse efforts and helps to reduce dependency on primary water sources, particularly the Llobregat and Ter rivers.

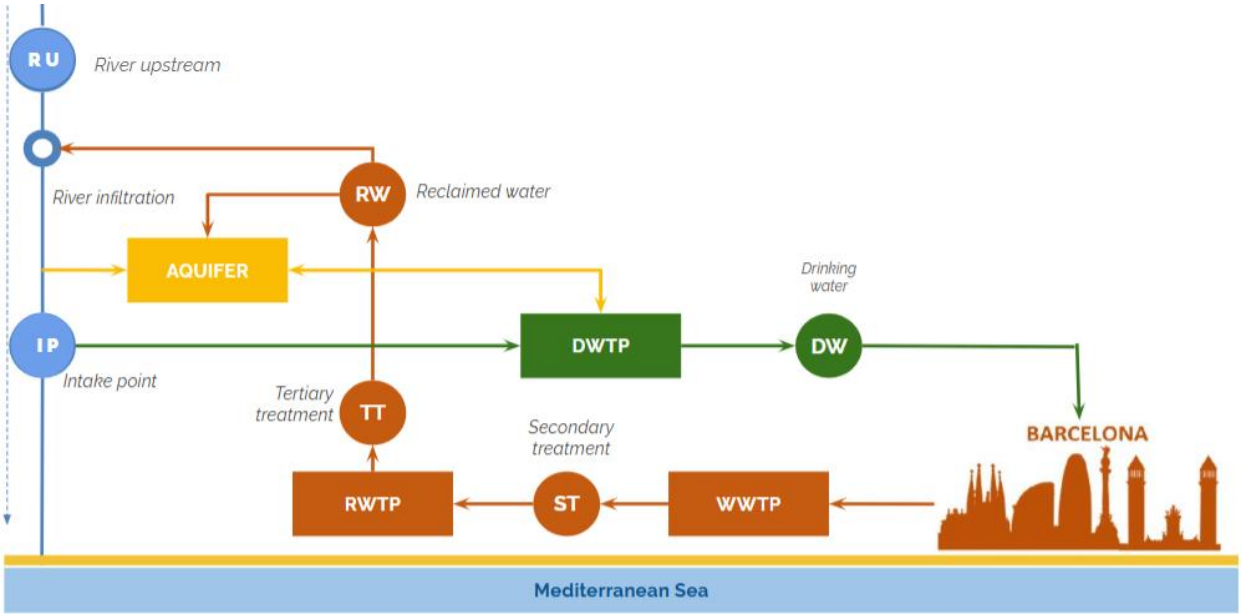


Figure 1.2 Scheme of Indirect Potable Reuse and MAR at Barcelona Metropolitan Area

The MARCLAIMED project addresses the challenge of providing more water and improving its quality, with the following expected outcomes:

1. Aquifer Recovery and Water Table Stabilization

The primary objective is to assess whether a controlled recharge system can effectively raise and stabilize the water table level. Reversing the recent decline in piezometric levels is essential to securing access to groundwater resources. MAR is expected to enhance the aquifer's storage capacity and resilience during drought periods. Furthermore, by increasing groundwater levels, the system aims to prevent saltwater intrusion in coastal zones and support Groundwater-Dependent Ecosystems (GDE).

2. Water Quality Monitoring and Risk Assessment

A thorough evaluation of the recharge water's quality will be conducted through systematic in-situ monitoring and periodic sampling campaigns. This process will include the analysis of physicochemical, microbiological, and emerging contaminants, both in the recharging water and in the aquifer. A network of strategically positioned observation points will enable the spatial and temporal tracking of water evolution. The data collected will help to identify potential impacts and support the adaptation of operational protocols, when necessary, as well as to perform risk analysis of such strategy.

3. Validation of Reclaimed Water as a Sustainable Resource

The project also seeks to promote and optimize the use of reclaimed water for sustainable aquifer recharge. The analysis of the results obtained in this demonstration site (DS1), along with findings from other demonstration sites (DS), will contribute to assessing the evolution of the aquifer since the implementation of the MAR system with AWR. These outcomes will feed into the development of the MARCLAIMED Integrated Decision Support Tool (IDST), aimed at supporting integrated water resource management.

1.3 Geological/hydrogeological setting

1.3.1 Geological/hydrogeological context

The aquifers in the metropolitan area of Barcelona, located in the Lower Llobregat River Valley and delta of the Llobregat River (Figure 1.3), cover an area of approximately 100 km² (Custodio, 2007). These aquifers are mainly composed of gravels and sands and, in the Cornellà delta, they are divided into an upper aquifer (unconfined, with slightly finer grain size) and a lower aquifer (confined, more transmissive), separated by a wedge of silts and clays that act as an aquitard (Figure 1.4). The upper aquifer thickness varies between 6 and 20 m (Gámez Torrent, 2007), while the lower aquifer thickness, formed by sands and gravels, ranges from 40 m in the valley to 10 m near the coast.

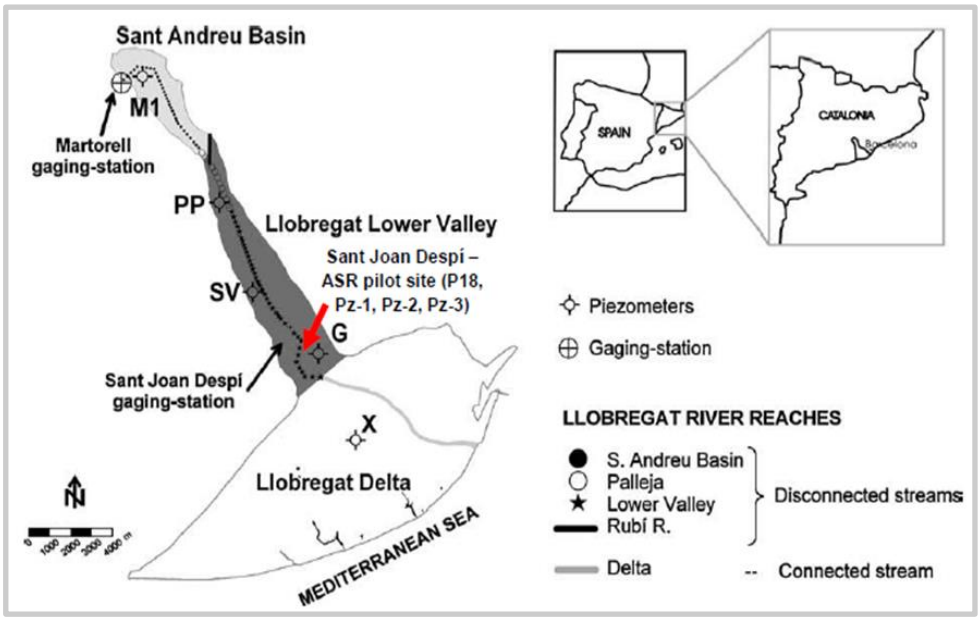


Figure 1.3 Lower Llobregat Valley and Delta; red arrow points to the Sant Joan Despí production plant involved in the Aquifer Storage and Recovery pilot system (Custodio 2007, modified)

Since the Llobregat River lies above the water table in the unconfined section of the aquifer, it contributes to groundwater recharge. This results in mixing and dilution of the recharged water before the division between the two aquifers occurs (Figure 1.4). The fact that the river and the aquifers are connected adds a particular complexity to the hydraulic functioning of the aquifer system.

The main aquifers of the Delta, which are typically composed of clean sands and gravels, generally exhibit transmissivity values ranging from 1,000 to 10,000 m²/day. The superficial aquifer shows lower transmissivity values, typically between 300 and 3,300 m²/day, with a mode of 600 m²/day and an average around 1,000 m²/day, which is consistent with its sandy composition. In the area of Sant Joan Despí – Cornellà, transmissivity values tend to be higher, particularly in Cornellà, where values around 2,000–5,000 m²/day have been reported (Queralt, 2025).

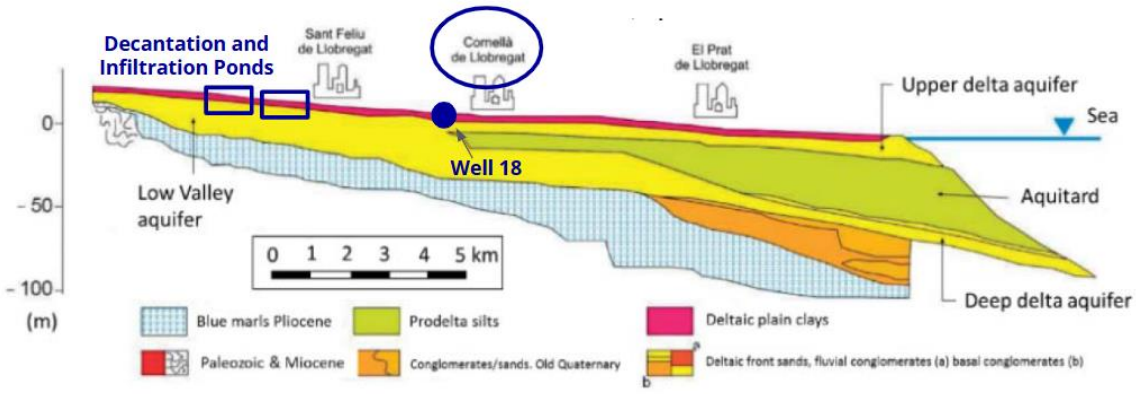


Figure 1.4 Cross-section of the Lower Valley and Delta aquifer of the Llobregat River (Queralt et al., 2020 modified). Infiltration ponds, and injection well (P18) locations are indicated

Decantation and infiltration ponds (Figure 1.4) are in the Lower Valley aquifer, at the municipality of Sant Vicenç dels Horts, northwest of Barcelona, a zone characterized by high transmissivity values.

The deep injection well (indicated as Well 18 in Figure 1.4) is located near the transition between the upper and lower aquifers, in a zone where both aquifer units are hydraulically connected, forming a permeable layer with nearly 50 m of thickness.

1.3.2 Conceptual model and pre-existing numerical models

The general flow regime in the Llobregat Delta aquifer system is governed by a natural inland-to-coast gradient, modified by decades of anthropogenic pressure.

In the unconfined aquifer, groundwater flow typically follows the topographic slope of the delta, moving from recharge zones along the Llobregat River and alluvial fans toward the Mediterranean Sea. In contrast, the confined aquifer shows more complex hydrodynamics due to historical overextraction. This has led to the development of inverted hydraulic gradients, with flow lines eventually converging from both inland and coastal margins toward heavily pumped central zones.

The aquifer, monitored by CUADLL, has been historically overexploited, with maximum extractions reaching up to 110–120 hm³/year. Withdrawals from the main aquifer have decreased to around 60 hm³/year since the 80's (Figure 1.5). As for the superficial aquifer, extraction is estimated at approximately 10 hm^3/ year, mainly due to water supply wells and agricultural use (Queralt *et al*., 2020).

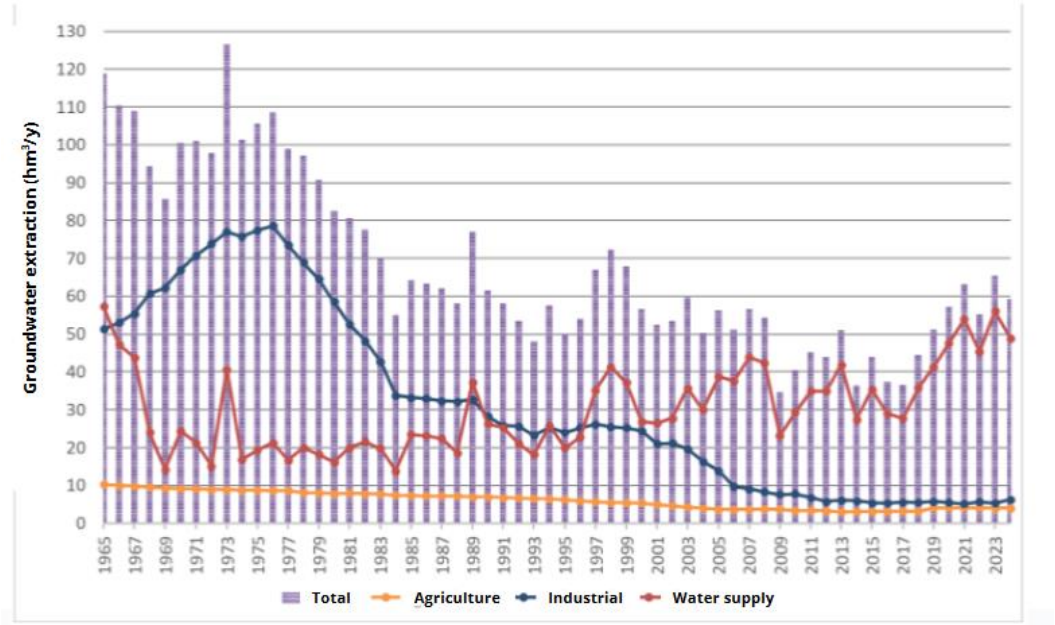


Figure 1.5 Evolution of groundwater extraction, Queralt et al., 2020

In 2003, the Polytechnic University of Catalonia (UPC) and the Catalan Water Agency (ACA) developed a numerical flow and transport model for the aquifers of the Llobregat Delta, lower Valley, and Sant Andreu basin. Now maintained and regularly updated by CUADLL, the model supports decisions for a more sustainable groundwater management.

1.3.3 Water quality considerations/issues

The Lower Llobregat River Valley aquifer exhibits a hydrochemical composition shaped by the interplay between continental recharge and marine intrusion processes. Groundwater

typically shows a transition from calcium-bicarbonate facies in the inland areas - associated with natural recharge and interaction with alluvial sediments - to sodium-chloride facies near the coast, indicative of salinization. Electrical conductivity values vary widely, reaching high levels in zones where seawater intrusion is more pronounced. Elevated concentrations of chloride and sodium are frequently observed in the deeper sections, particularly within the confined lower aquifer, suggesting limited flushing and potential upward flow of saline water. The hydrochemical signatures reflect a complex system influenced by intensive groundwater abstraction, lithological heterogeneity, and the proximity to the coastline.

According to the River Basin District Management Plan of Catalonia (PGDCFC), the Lower Llobregat River Valley and Llobregat Delta face bad qualitative status, mainly due to salinization, but also to some other contaminants such as trichloroethylene (TCE) and tetrachloroethylene (PCE). Chloride concentrations over the aquifer are shown in Figure 1.6 (Queralt, 2025).

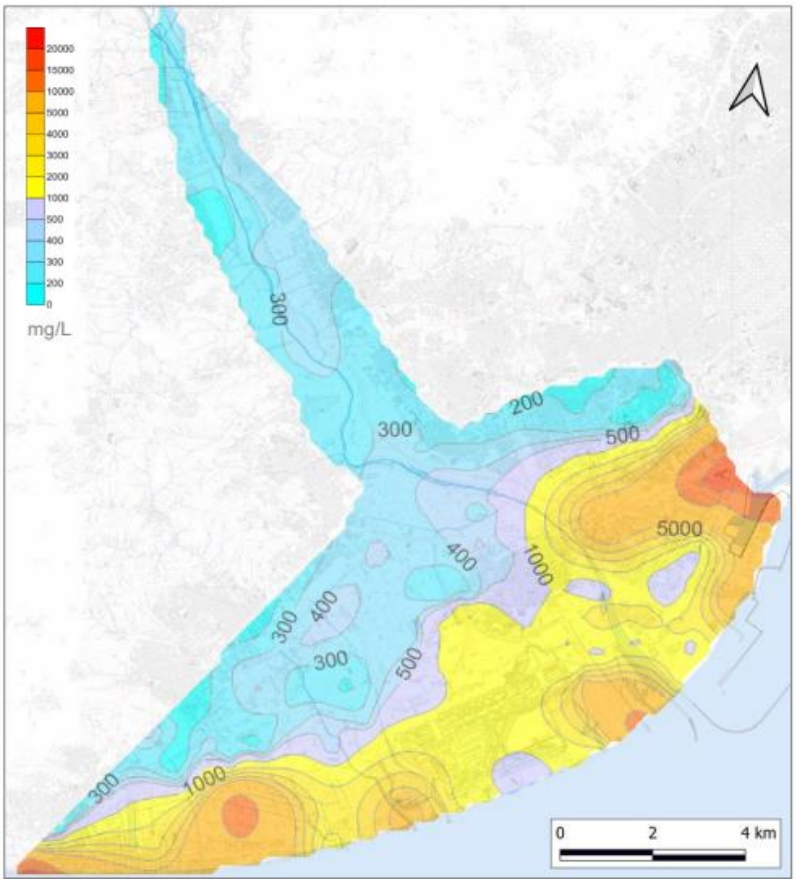


Figure 1.6 Chlorides distribution in Baix Llobregat aquifer

1.4 Existing infrastructures and MARCLAIMED contributions

1.4.1 Sant Vicenç dels Horts infiltration ponds

A scheme of Sant Vicenç dels Horts (SVH) MAR infrastructure is shown in Figure 1.7, where also the observation/sampling points are indicated.

Both the decantation and infiltration ponds were constructed in 2010 as part of the ENSAT project under the LIFE Program. Previously, aquifer recharge was carried out using surface water from the Llobregat River.

Reclaimed water (RW) reaches the decantation pond by a bulkhead operated manually by CUADLL. Reclaimed water, pumped from the reclamation facility first enters the 4.000 m² decantation pond and then flows through the channel into the 5.600 m² infiltration pond. The decantation and infiltration ponds are connected by a channel controlled also by a bulkhead. Finally, there is a drainage chamber at the end of the infiltration pond.

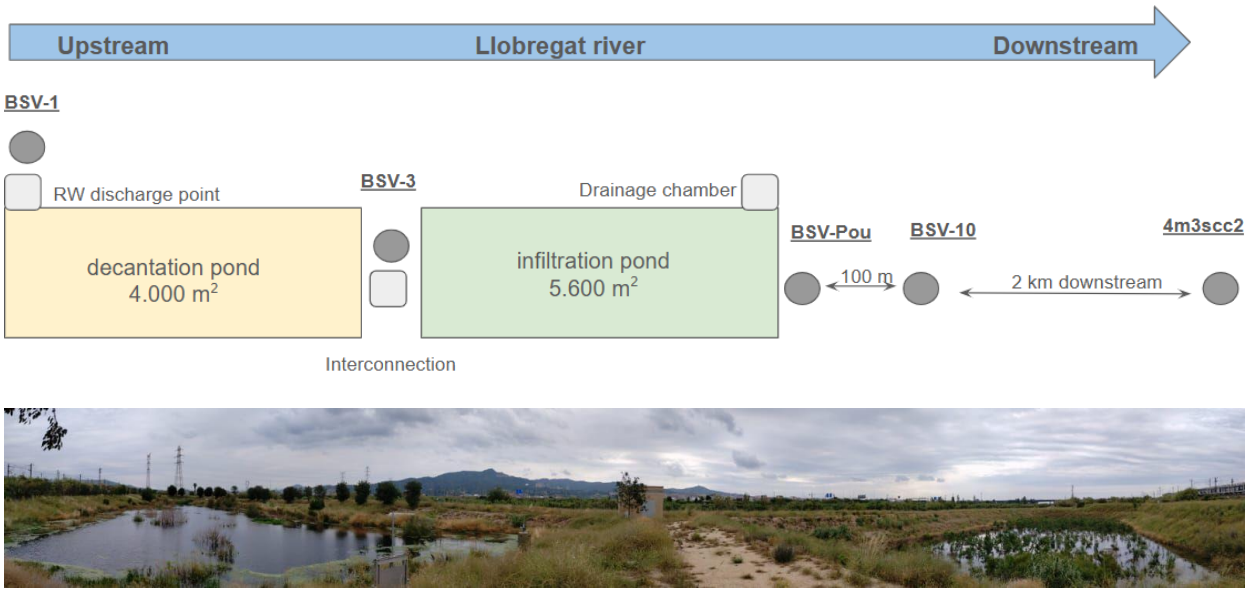


Figure 1.7 Sant Vicenç dels Horts infiltration ponds infrastructure scheme

Note: Picture shows, from left to right, the decantation pond, the interconnection and the infiltration pond. The interconnection between the ponds is 8–10 m. Wells BSV-1, BSV-3, and BSV-Pou are located just beside the ponds (less than 5 meters) as shown in the figure. Wells BSV-10 and 4msecc2 are located 100 m and 2 km downstream, respectively, from the infiltration pond

The devices installed to monitor the ponds are summarized in Table 1.1, Table 1.2, Figure 1.8 and Figure 1.9. To be noticed that the same piezometers (BSV-1, BSV-3, BSV-Pou, BSV-

10, 4M3SCC2) where CTD sensors are installed are the ones where the water quality sampling campaigns are performed. Groundwater flow direction is parallel to that of the Llobregat river, that is, from BSV-1 (upstream discharge point) towards 4M3SCC2 (more than 2 km downstream).

Table 1.1 Devices installed at Sant Vicenç dels Horts ponds

Location	Device Installed	Parameter	Frequency
RW discharge point	OTT	Water level	Hourly
Interconnection (inflow channel)	ISCO 2150 Duratracker OTT	Flow, level (batteries) Flow, level (solar energy) Level	Every 5 min Every 5 min Hourly
Drainage chamber	OTT	Water level	Hourly
Infiltration and decantation pond	Limnometric scales	Water level	Manual reading

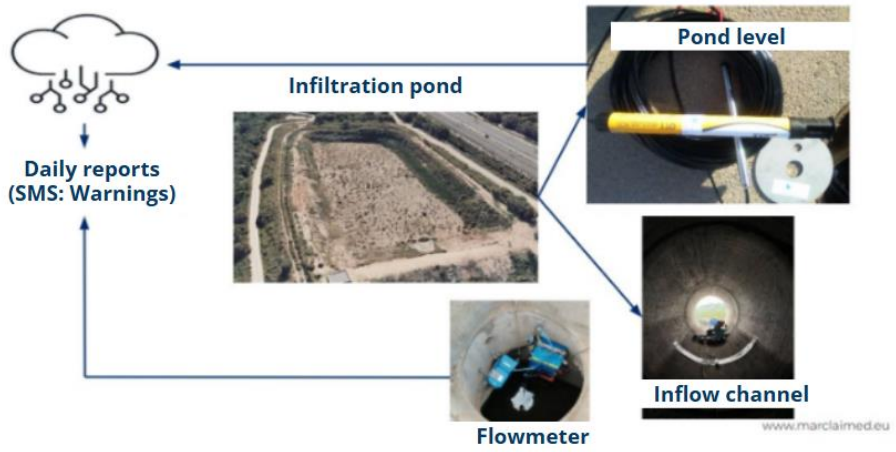


Figure 1.8 Devices installed to continuously measure flow and levels at the ponds

Table 1.2 Sensors installed at Sant Vicenç dels Horts ponds

	BSV-1	BSV-3	BSV-Pou	BSV-10	4m3scc2
Location	Upstream decantation pond	Upstream infiltration pond	Downstream decantation pond	Downstream 100m from decantation pond	Downstream 2 km from decantation pond
Installed device	CTD	OTT/CTD	CTD	CTD/barometer	CTD 2x
Measured parameters	Water level, pressure, temperature and conductivity	Water level, total dissolved solids, conductivity, salinity and temperature	Water level, pressure, temperature and conductivity	Water level, pressure, temperature and conductivity, atmospheric pressure	Water level, total dissolved solids, conductivity, salinity and temperature

All piezometers in SVH infiltration ponds site have total depths ranging from 20 to 26 meters.



Figure 1.9 Devices installed, in order from left to right: CTD, CT2X, Barometer and the ecoLog 1000

1.4.2 Deep injection at Well 18

Deep aquifer injection is conducted at the Sant Joan Despí drinking water treatment plant, through the Well 18 (Pou 18). Before the injection, the water passes through several treatment steps: i) a pre-oxidation process with chlorine dioxide; ii) coagulation/flocculation process by polyaluminum chloride; iii) sedimentation/decantation pond and iv) rapid sand filtration (Figure 1.10).

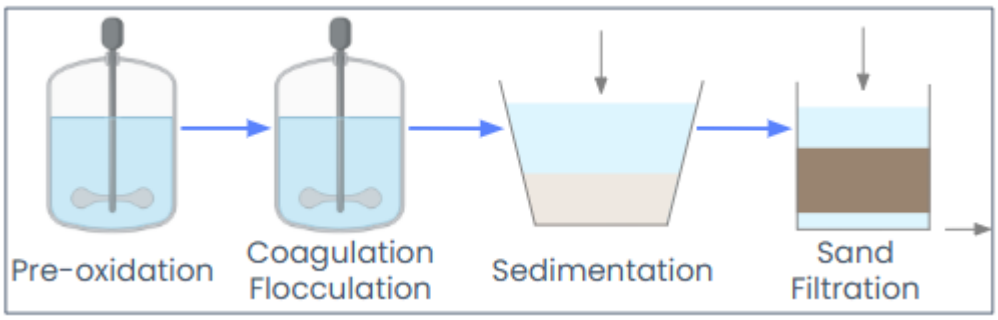


Figure 1.10 Treatment steps before water injection in Well 18

The configuration of the deep injection MAR systems is described as follows: three piezometers (PZ1, PZ2, and PZ3) are located at the distances of 4, 8 and 15 m from Well 18 (Aquifer Storage and Recover (ASR) well, P18 in Figure 1.11). Groundwater recharge Well 18 was equipped with these nearby piezometers as part of a previous research project (DESSIN, 2015). Nonetheless, due to diameter constraints, only PZ2 is included in the sampling campaigns within MARCLAIMED Project.

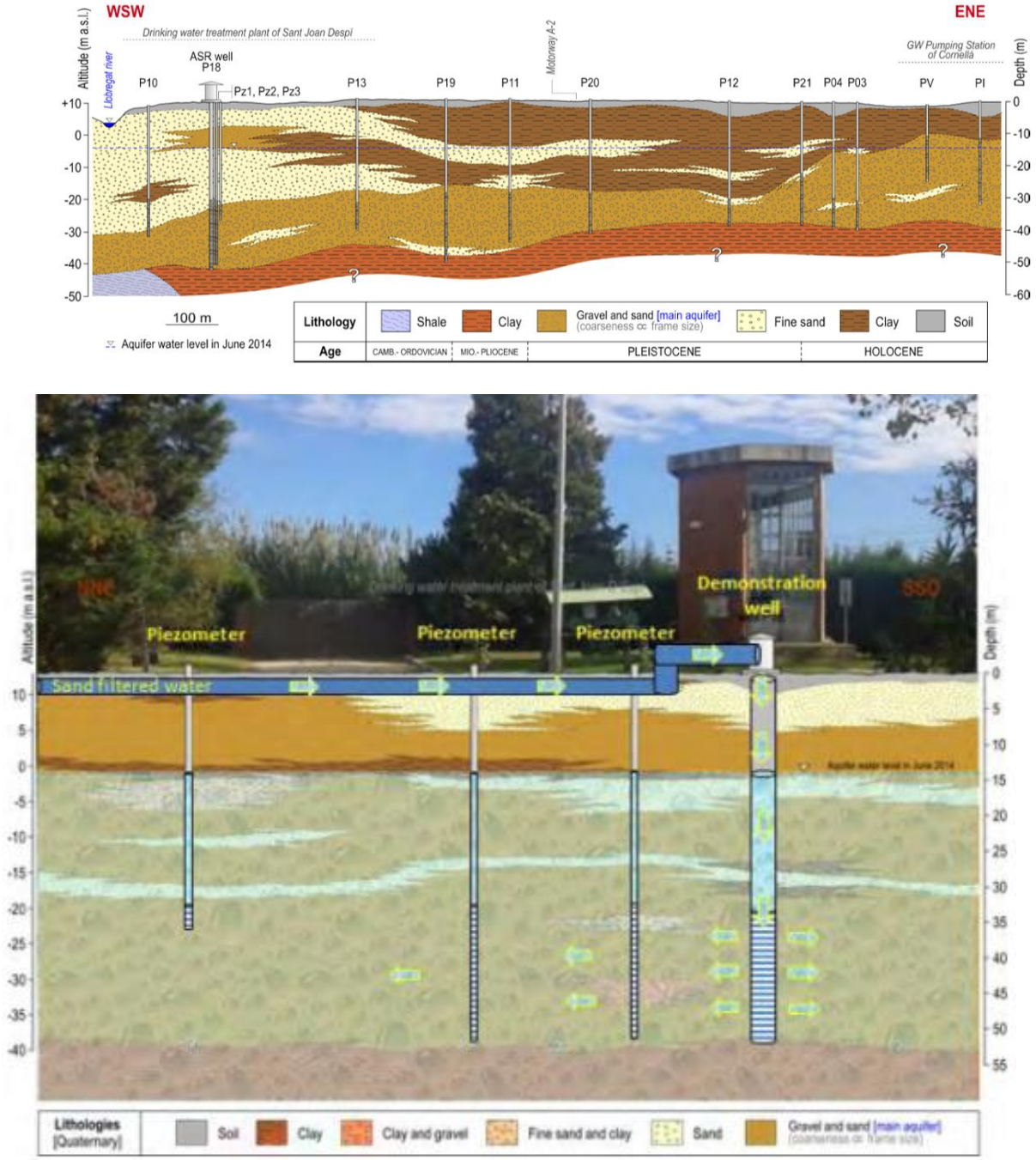


Figure 1.11 Geological cross-section of the Llobregat river, in the area of Sant Joan Despí - Cornellà, as well as the battery of wells located in that area (QUEEN final Deliverable, 2023)

In addition, Well 18 is surrounded by other wells: Well 10 (P10) to the west (85 m away), Well 13 (P13) to the east (300 m), and Well 11 (P11), also to the east (571 m). All piezometers and wells have total depths ranging from 30 to 50 m and are situated between 9 and 12 m above sea level.

Regarding monitoring, all wells are equipped with a hydrostatic indicator level from Endres+Hauser (Waterpilot FMX21). Within the MARCLAIMED framework, an OTT sensor is expected to be installed at PZ2 Well 18. In the meantime, level is measured manually daily at this point.

After deep injection at Well 18, groundwater is extracted at the closer wellfield. Both groundwater and river-sourced water are treated to drinking standards and reintegrated into the metropolitan supply network, effectively closing the loop and reinforcing water security across the region.

1.4.3 Challenges faced and new solutions implemented

Several challenges arose during the permit acquisition process for the MAR activities at the Sant Vicenç dels Horts infiltration basins. Regarding P18, the permit was issued back in 2021. At that period, reclaimed water was not playing a key role. Results obtained in DESSIN Project helped to have a quite smooth path to get the permit, which remains valid despite changes in the matrix of the water used for the recharge. Nevertheless, substantial progress was achieved through coordinated efforts among the involved institutions:

- In January 2024, CUADLL submitted a formal request to the Catalan Water Agency (ACA) for a temporary permit to divert reclaimed water from the El Prat water reclamation facility.
- In May 2024, ACA issued a favourable resolution authorising MAR operations, following:
    - A comprehensive technical evaluation by ACA's concession services.
    - A positive report from ASPCAT, which imposed strict operational and monitoring conditions to safeguard public health and water quality.

The authorisation:

- Permits the use of reclaimed water for aquifer recharge over a two-year period, renewable for an additional two years subject to adequate justification.
- Establishes a maximum flow rate and annual volume: 6,000 m^3/day and 1.0 hm^3/year.
- Defines specific operational requirements, including monitoring protocols, threshold values (e.g., for chlorides), and contingency procedures in case of non-compliance or quality deviations.

To strengthen institutional coordination, a four-year cooperation agreement was signed in May 2024 between ACA and CUADLL. The agreement supports the operation and

maintenance of the recharge infrastructure and includes budgetary commitments from both parties.

Two main challenges were identified during the implementation phase: **clogging** and **elevated nitrate concentrations**. The following mitigation measures were adopted:

Clogging mitigation:

- A trial strategy based on alternating recharge and drying cycles was implemented to reduce surface clogging.
- Surface scarification was carried out to enhance infiltration capacity (most recently in January 2025); however, its effectiveness was limited, and the process proved to be labour-intensive.
- Investigations conducted by the University of Barcelona (2024–2025) revealed a uniform granulometry down to 1.5 m and the presence of a compacted, low-permeability layer at approximately 0.5 m depth, rendering shallow scarification (5–10 cm) largely ineffective.
- The evolution of the infiltration surface is being monitored, considering the effects of repeated wetting–drying cycles, variations in infiltration rates, and the accumulation of organic matter.
- A dedicated infiltration rate assessment is currently ongoing to quantify changes in infiltration performance over time.

Nitrate reduction:

- The biological treatment process at the wastewater treatment plant (WWTP) was upgraded to improve nitrate removal efficiency.
- Preliminary results indicate a significant reduction in nitrate concentrations, which will be further elaborated in the results section.

Sensor deployment:

- The installation of monitoring devices encountered some delays. Specifically, the deployment of the OTT ecoLog 1000 was postponed due to the late delivery of the SIM card and initial difficulties establishing a stable connection with the remote server. The device was ultimately installed at the BSV-3 piezometer on 12 March 2025, and data transmission to the DriveHQ server commenced successfully on April 8, 2025.
- The CTD sensors have generally performed well. Minor issues were reported, including occasional battery depletion and, in the case of the CTD2x model, sporadic difficulties in data retrieval due to connection errors.

1.5 Data collection progress and results

The **Sant Vicenç dels Horts infiltration ponds system** was commissioned on May 16, 2024. Initially, it operated five days a week with a rest over the weekend, but this was adjusted in October 2024 to a ten-day recharge cycle followed by a ten-day rest period, allowing the basin to dry and promote soil cracking, which enhances infiltration through preferential flow paths. Moreover, the enlargement of the wetting and recharge period was aimed at maximizing anoxic conditions for a greater nitrate reduction during recharge.

As of May–June 2025, the system is infiltrating very efficiently, and recharge periods are occasionally extended to approximately 15 days to maximize performance. Additionally, instead of a continuous flow, the system now operates with punctual daily flow volumes delivered upon request.

The **Deep Recharge at Well 18 system** was commissioned on October 22, 2021, and it began operating at a ratio of 30 L/s. In March 2024, improvements in the infrastructure were performed and recharging ratio scaled up to 50 L/s, which is the maximum allowed by the permit. The water used for the recharge was formerly surface water from Llobregat River after undergoing a pre-treatment step at Sant Joan Despí DWTP. Nonetheless, since the end of 2022 up to the end of 2024, reclaimed water has been sent to the river upstream for blending with Llobregat River Water (Indirect Potable Reuse, IPR scheme). That has meant a change in the water matrix reaching the DWTP and, therefore, also a change regarding the water injected into Well 18 during the MARCLAIMED Project.

Total volumes recharged since the beginning of the project have reached **1.5 hm^3** at Well 18 and **0.61 hm^3** at Sant Vicenç dels Horts infiltration ponds (Figure 1.12).

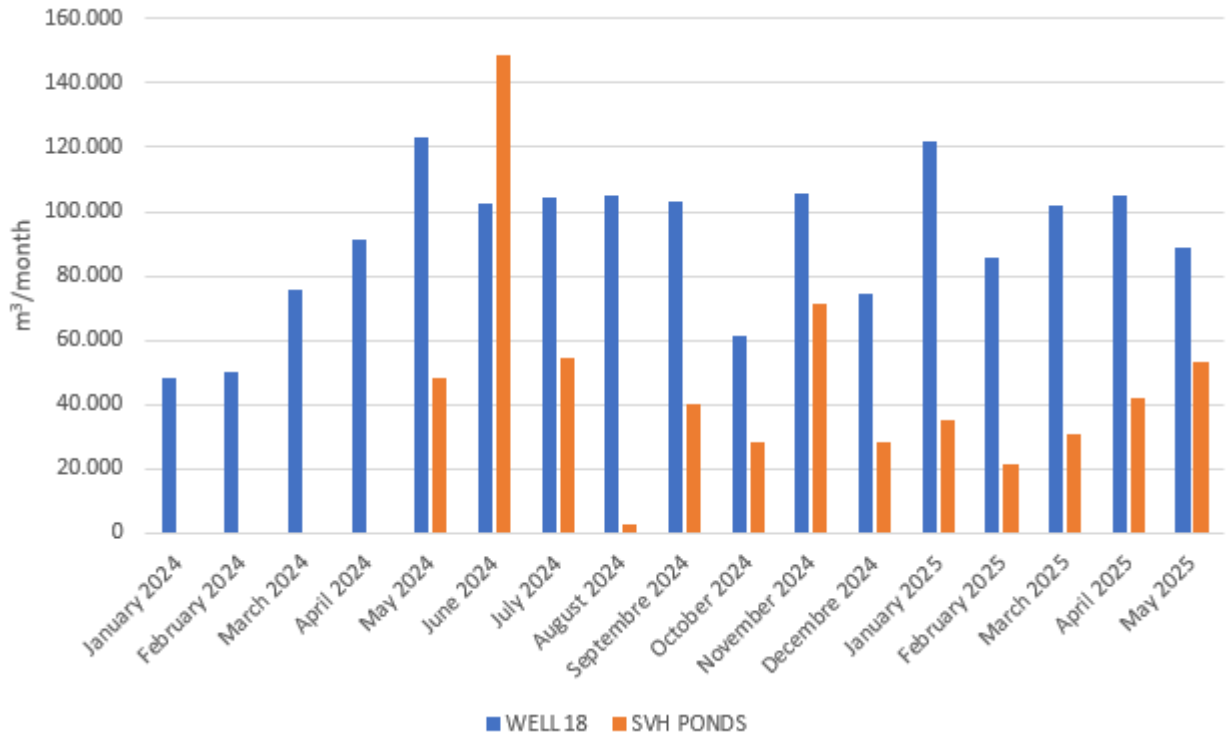


Figure 1.12 Total volumes recharged at Well 18 and Sant Vicenç dels Horts Infiltration Pond

Comprehensive monitoring of both volumetric recharge and recharged water quality is being conducted within DS1 of El Baix Llobregat. This monitoring is imperative to ascertain the aquifer's progression following the implementation of the MAR system with AWR, and to identify and manage any modifications occurring within the area or downstream.

Regarding quality data, a thorough set of parameters (Figure 1.13) are analysed at each point (both at the infiltration ponds and at the deep injection well), in each sampling campaign, in order to be able to perform a thorough analysis as well as risk assessment exercise. The results will be further reported and discussed.

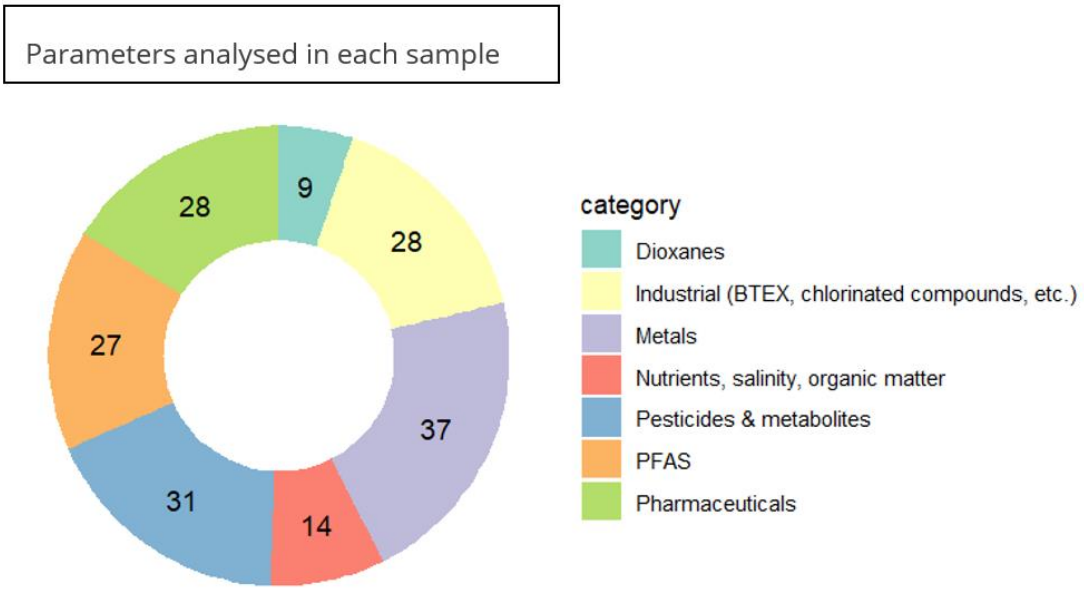


Figure 1.13 Analysed parameters at the infiltration pond and at the deep injection well

1.5.1 Sant Vicenç dels Horts infiltrations ponds

Water table evolution and field operations

The evolution of the infiltration rate as well as the water level at the infiltration pond are shown in Figure 1.14.

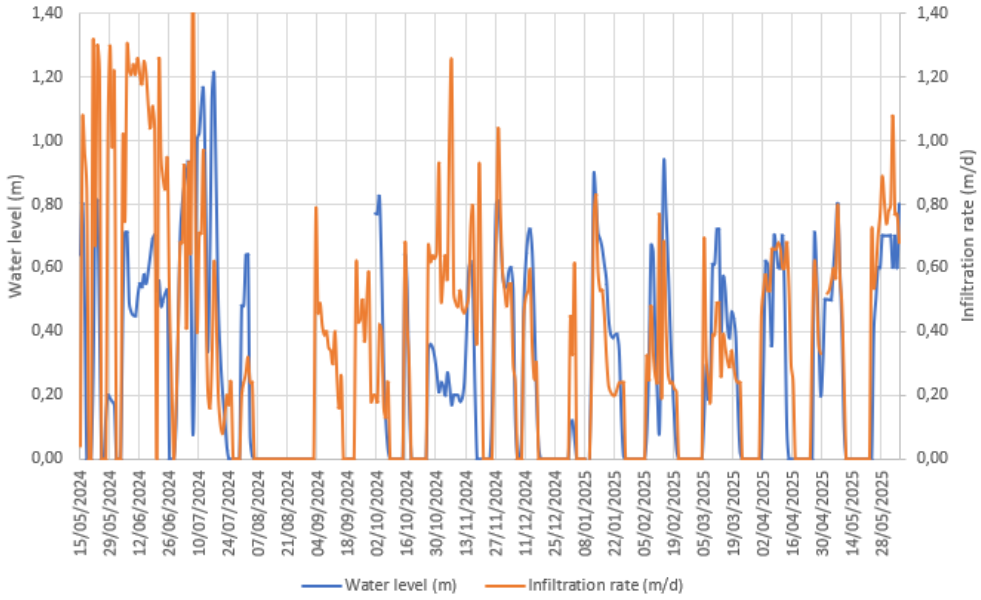


Figure 1.14 Infiltration rate water level at Sant Vicenç dels Horts infiltration ponds

After the first months of operation, a limit was established by ACA in order not to surpass 1 m of water level at the infiltration pond avoiding deep clogging. In fact, when values exceed 0,8 m, ponds management personnel automatically receive an SMS notification on their cell phones.

Results gathered from CTD installed at the different observation points are shown in Figure 1.15.

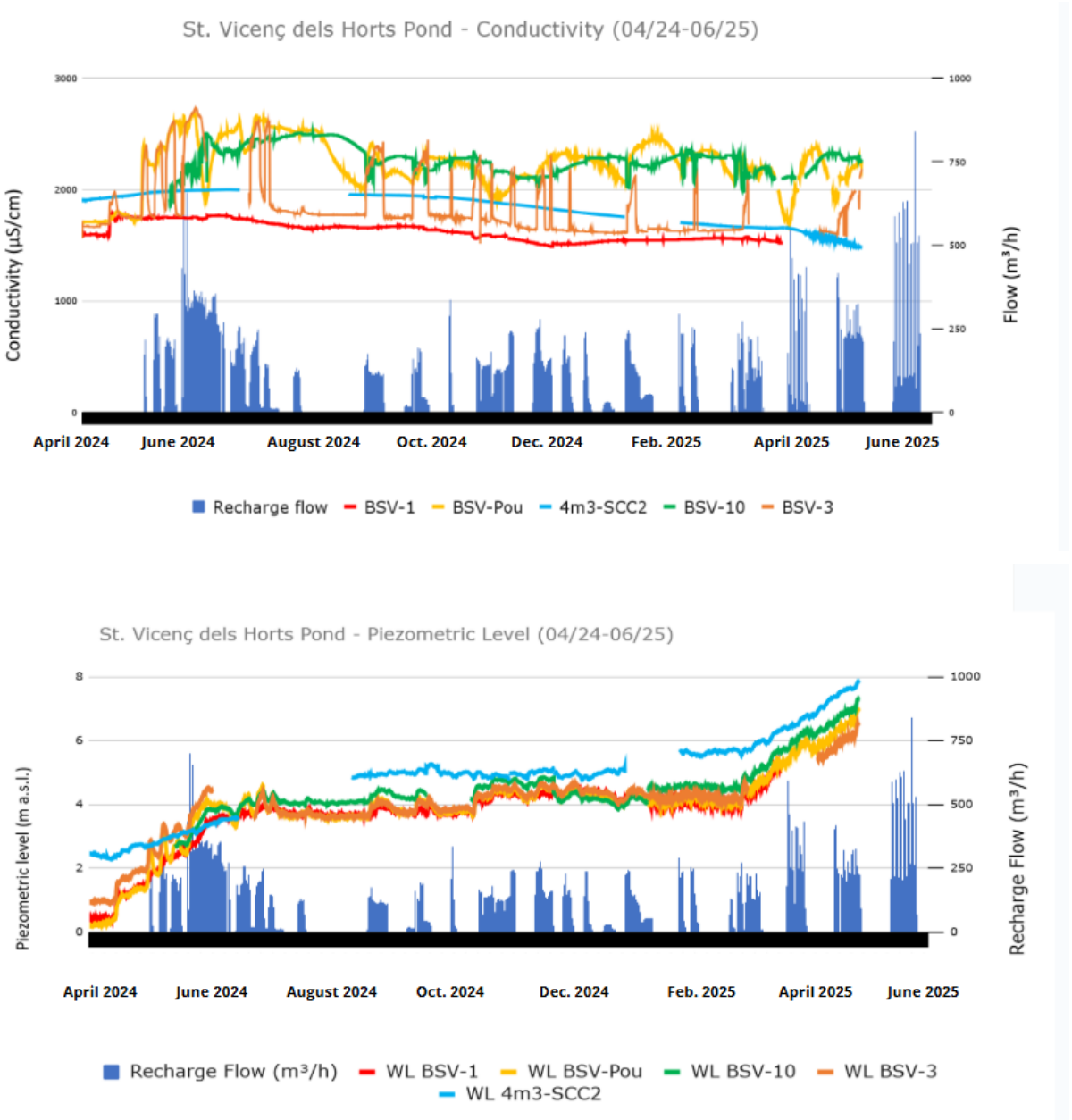


Figure 1.15 Conductivity and piezometric level evolution at monitored piezometers, compared with the recharge flow

During the operation period, the following field operations have been performed (Figure 1.16):

- Two scarification procedures, being the last one in January 2025. Nonetheless, they have had very little effect on improving the infiltration rate.
- Several ground geophysical surveys as well as grain size analysis have also been performed and lead to the conclusion that no important changes have been seen at a depth of 1.5 m (same grain size characteristics as at the beginning of the recharge). Indeed, the most impermeable part is in an intermediate layer at approximately 0,5 m depth, which means that scarification of the first 5-10 cm is not helpful.



Figure 1.16 Field works: scarified area, scarifying machine and geophysical surveys

Water quality campaigns

A total of six sampling campaigns have been conducted since the recharge began, scheduled every 6 to 8 weeks depending on the recharging periods and the volumes of reclaimed water recharged (Figure 1.17).



Figure 1.17 Sampling operations at the infiltration pond

Physicochemical characterization

According to the permit issued for this specific recharge, the main constraints for the water quality to be recharged at SVH infiltration ponds are summarized in Table 1.3, where it is also included the corresponding average values for reclaimed water sent to SVH infiltration ponds.

Table 1.3 Limits for reclaimed water to be recharged through infiltration ponds, according to RD 1620/2007

Parameter	E. Coli (UFC/100 mL)	Total suspended solids (mg/L)	Total Nitrogen (mg N/L)	Nitrates (mg NO_3^-/L)
Limit according to permit	1.000	35	10	25
Average values during recharge period (May 2024 to May 2025)	16% values exceeding the limit	4.6 ±3.4	11.1 ±3.1	26.2 ±14,8

According to the results:

- Values have been kept within limits for Total suspended solids (TSS).
- Values have slightly exceeded Total Nitrogen as well as Nitrates (Figure 1.18). Regarding this, there are two things to be considered: as has previously been explained, this same RW has been widely used during 2024 for IPR, therefore sending it to the river upstream of the main DWTP catchment. For this purpose (drinking water production) ammonium was a stronger constraint, whilst nitrates were not (the parametric value for drinking water according to RD3/2023 is 50 mg NO_3^-/L). That is why, for most of the recharging period, ammonium was preferred rather than nitrates. Moreover, big improvements have been made at the biological treatment in the WWTP (aeration process improvement), so now both nitrates and total nitrogen have significantly decreased since beginning 2025 (Figure 1.19).

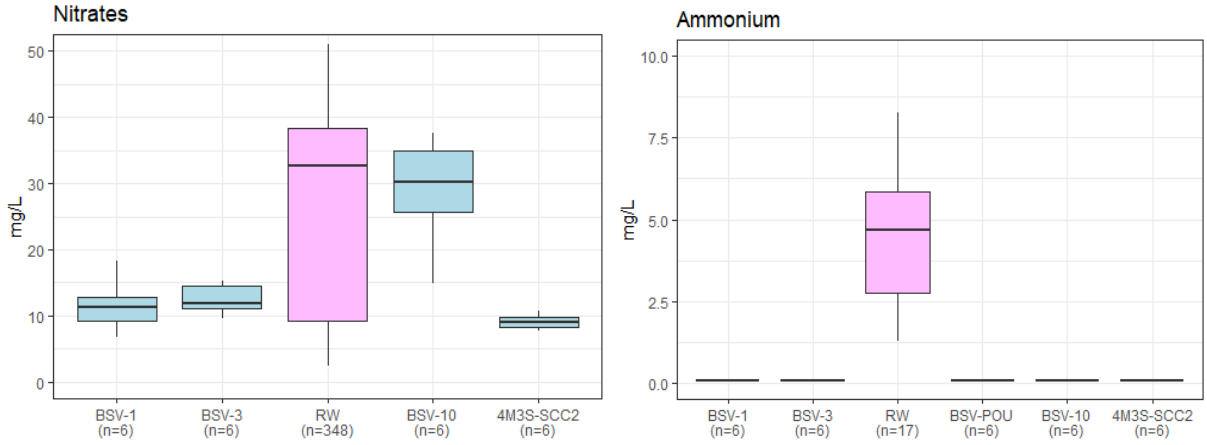


Figure 1.18 Nitrates and ammonium at SVH infiltration ponds

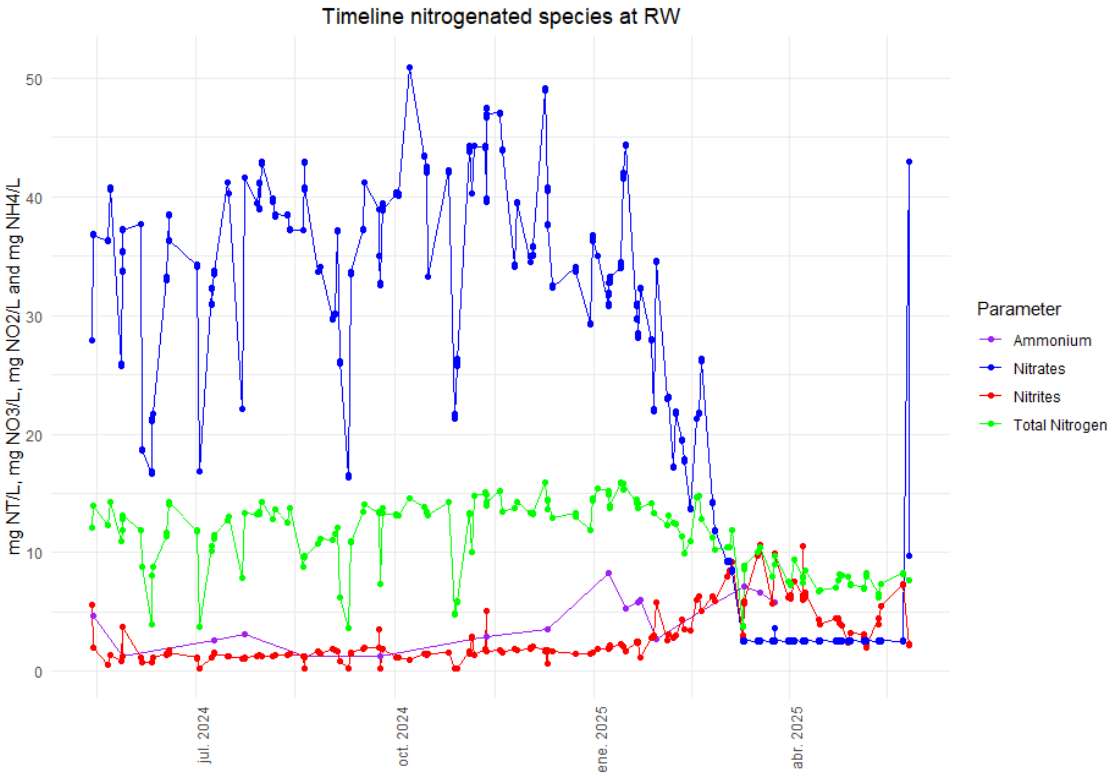


Figure 1.19 Nitrogenated species evolution over time

When an E.Coli value is detected above 1.000 UFC/100 ml, instructions are sent so as to increase Sodium Hypochlorite dose at the tertiary treatment and rapidly decrease these logarithms. Nonetheless, during the sampling campaigns, E.Coli and Total Coliforms have not only been analysed for RW but also at both decantation pond and infiltration pond. Results are summarized on Table 1.4, and they show that, since this is an open air site, therefore exposed to animals being in the wild, there is a natural and unavoidable increase of E. Coli during the recharge process.

Table 1.4 Total Coliforms and E.Coli at SVH ponds (average from five sampling campaigns)

	Total Coliforms (NMP/100 ml)		**E. Coli (NMP/100 ml)**	
	Average log	SD	Average log	SD
Decantation pond	6,41	1,24	5,49	1,88
Infiltration pond	6,78	0,59	5,45	1,05

Regarding water quality, and despite no strict constraint being established on that, RW has currently another weak point which is salinity. In fact, these infiltration ponds are located in a saline river basin, so there are salt mines upstream (which means that, in a normal

situation, salinity values are already high) and the sea downstream (with the corresponding sea water intrusion problems).

The industries located at the delta region take groundwater for their production processes, and the rejection from the reverse osmosis processes goes to the WWTP, therefore increasing RW conductivity (Figure 1.20). Besides this, big efforts are being made to divert these brackish waters before getting into the WWTP. Once this goal is achieved, conductivity values at the RW are expected to have a decrease of about 400-500 µS/cm.

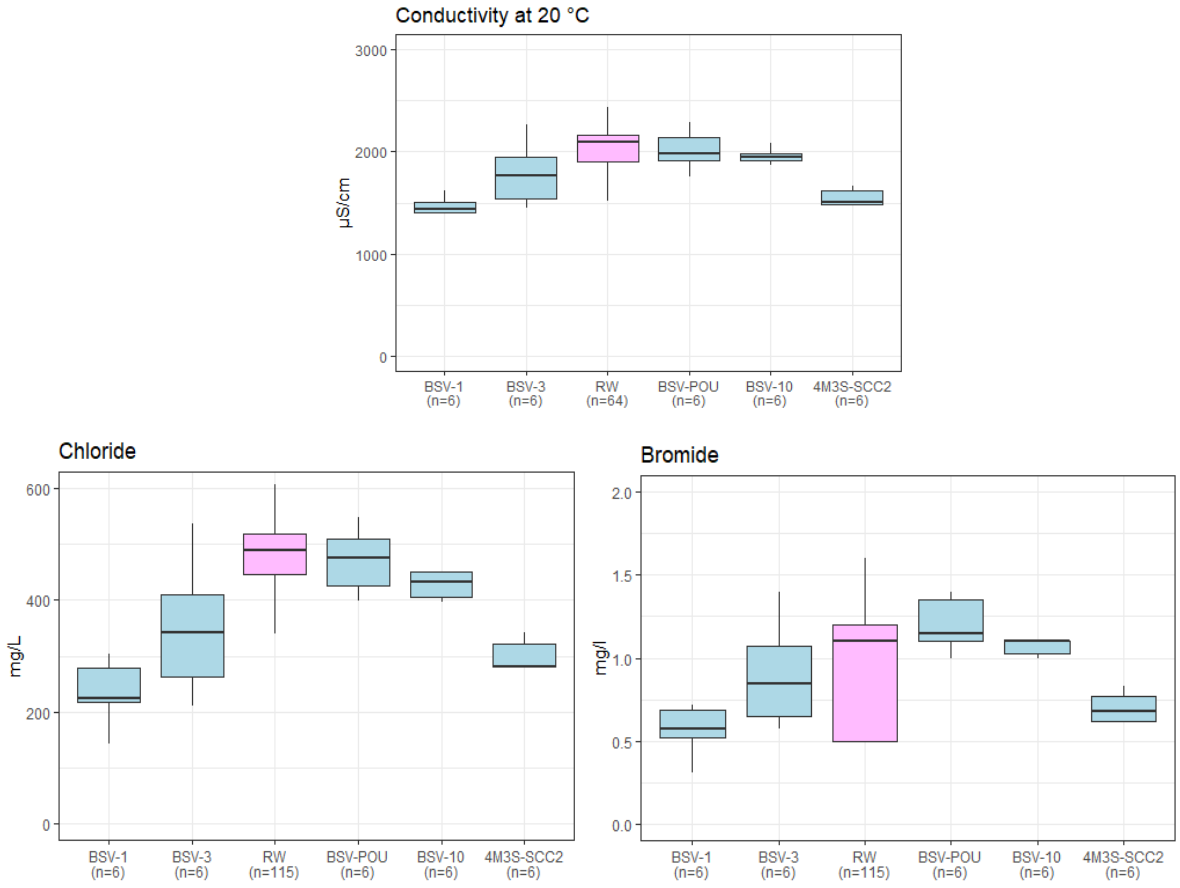


Figure 1.20 Salinity evolution during the recharge process

The relative proportion of major cations and anions, for the different observation points, before and after the recharge is shown on a Piper diagram (Figure 1.21). As it can be seen, there is a difference between the blank samples and the latest sampling campaign towards more chlorides and more sodium/potassium, especially at BSV-Pou and BSV-10 and, to a lesser extent, at BSV-3. On the contrary, BSV-1 is barely altered.

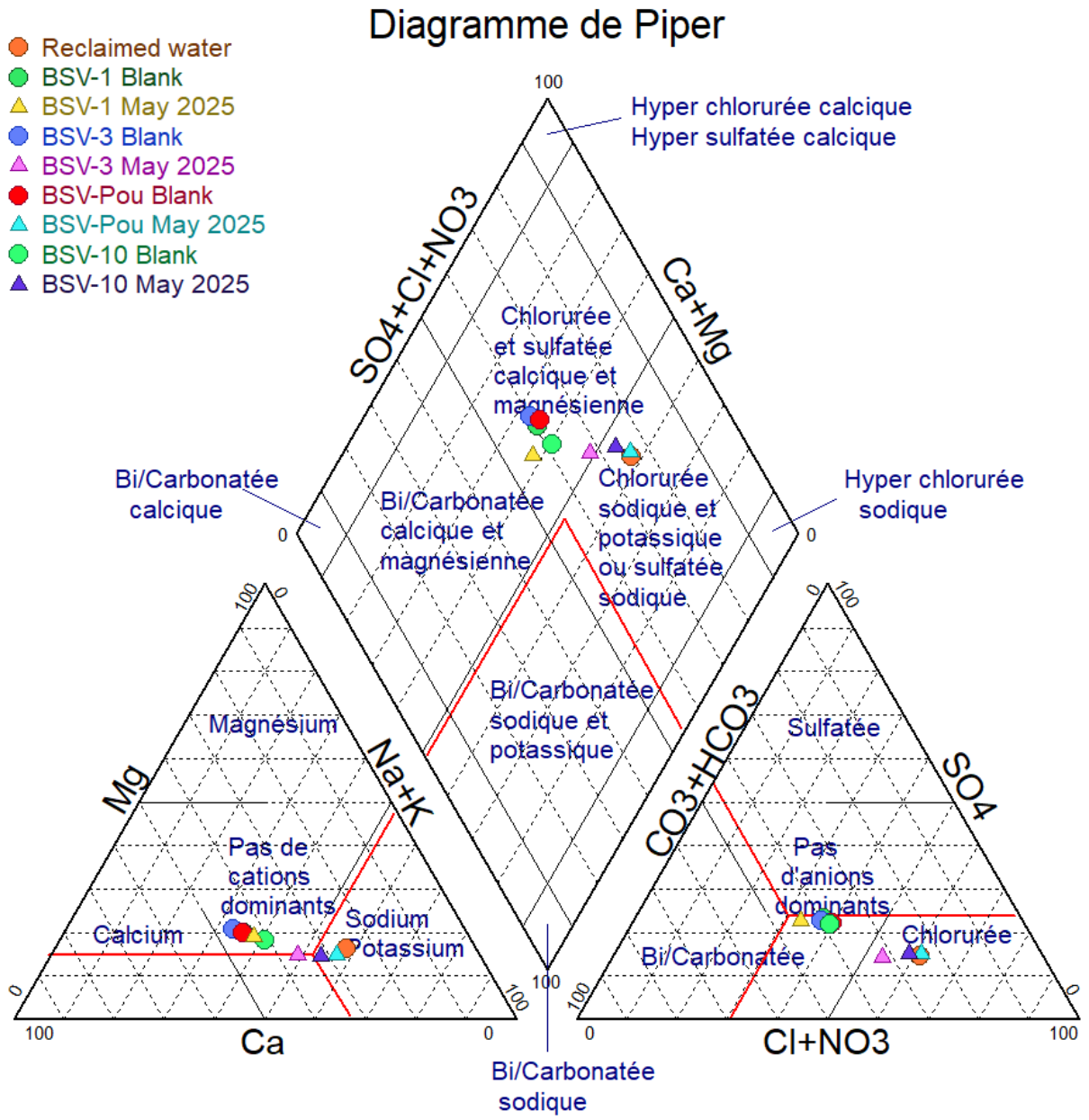
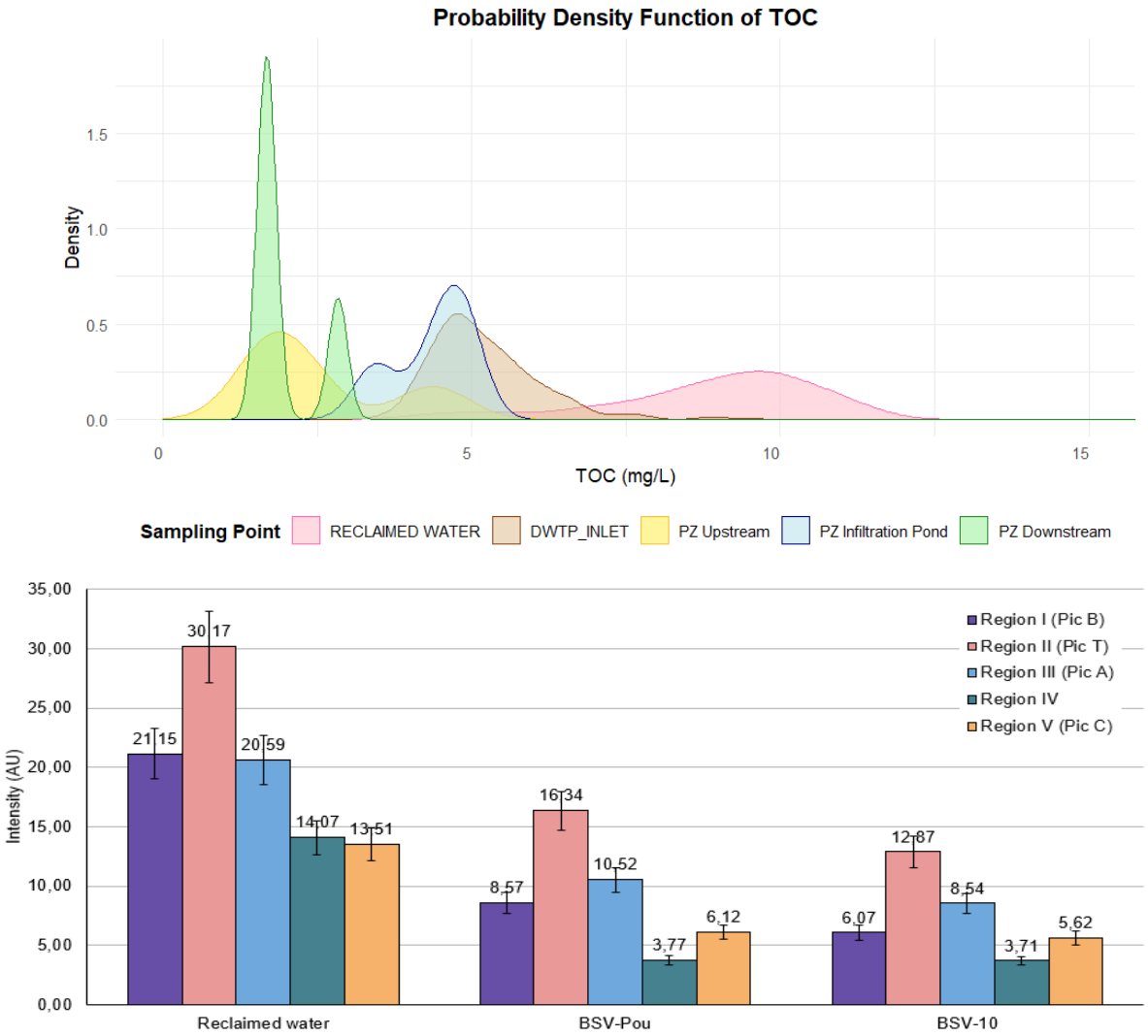


Figure 1.21 Piper diagram representing reclaimed water and main groundwater observation points both before and after recharge

On the contrary, a key-point related to the recharge of reclaimed water is its organic matter (Figure 1.22). Indeed, organic matter poses a challenge at the DWTP because it is the main precursor, from surface water, for certain disinfection by-products formation (mainly trihalomethanes). If this reclaimed water with high organic matter content is recharged at the infiltration ponds, TOC values are reduced already by half at the first observation point downstream (BSV-POU). In one of the campaigns, also a fluorimetry analysis was performed

in order to see the main regions of the organic matter. Indeed, the intensity of all regions suffers a decrease around half of the former value when water is recharged (Figure 1.22).



Region I: Simple aromatic compounds such as benzene and phenols

Region II: Aromatic proteins such as tyrosine and tryptophan

Region III: Fulvic acids

Region IV: Microbial by-products

Region V: Humic acids

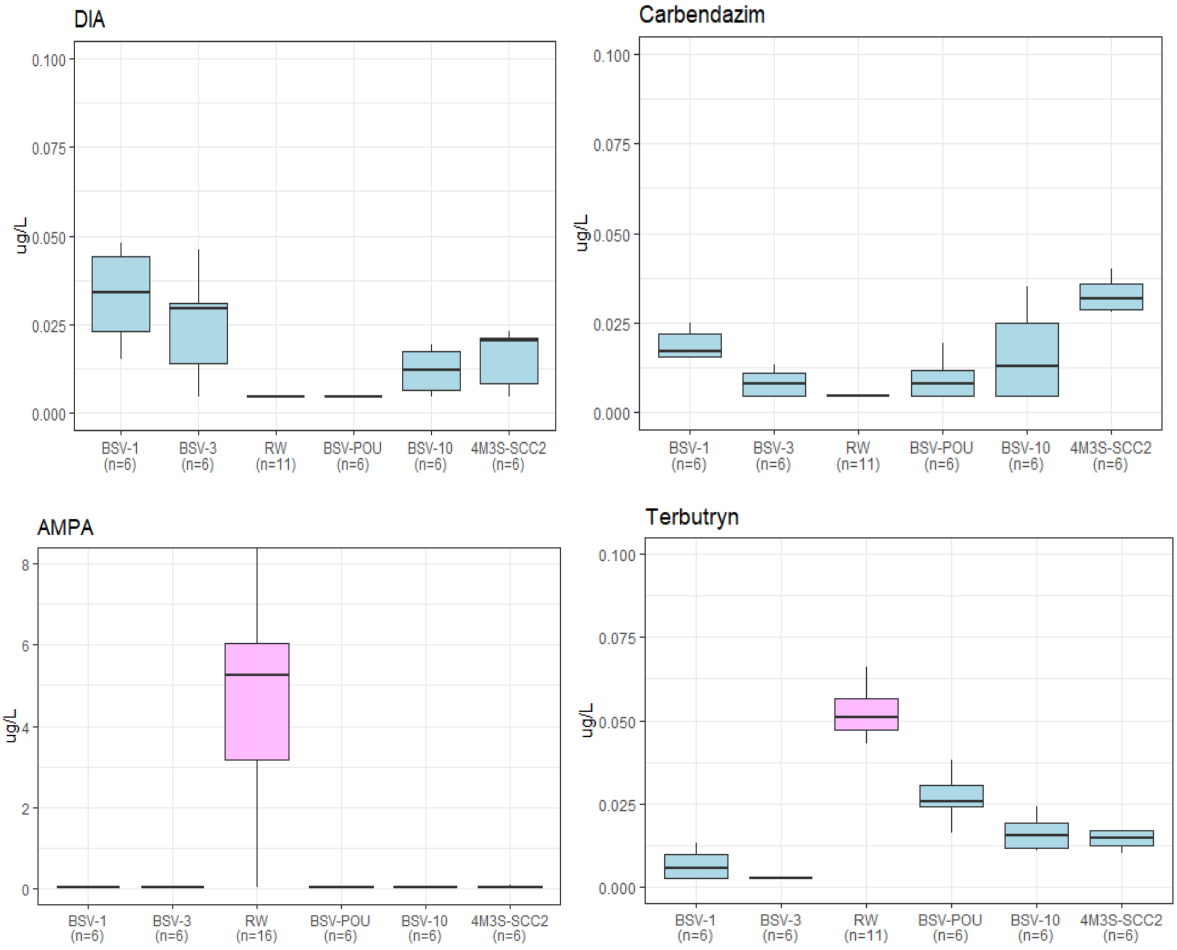
Figure 1.22 Organic matter evolution during recharge

Pesticides

Regarding pesticides, three different behaviours are observed:

- Some pesticides are not detected in RW whilst they are known to be detected in groundwater at Vall Baixa aquifer. This means that a dilution is observed in the area of recharge or that there are contributions from other sources. This is the case for Carbendazim and Desisopropylatrazine (DIA).
- Some other pesticides are completely removed during the recharge process. This is the case for AMPA, which is detected at very high concentrations in RW (normally between 3 and 6 µg/L), and it has never been detected in groundwater samples, not even at BSV-POU.
- Some other pesticides present in RW are much more persistent. That is the case for diuron, imidacloprid, and terbutryn.

Plots for the different behaviours of pesticides are summarized in Figure 1.23.



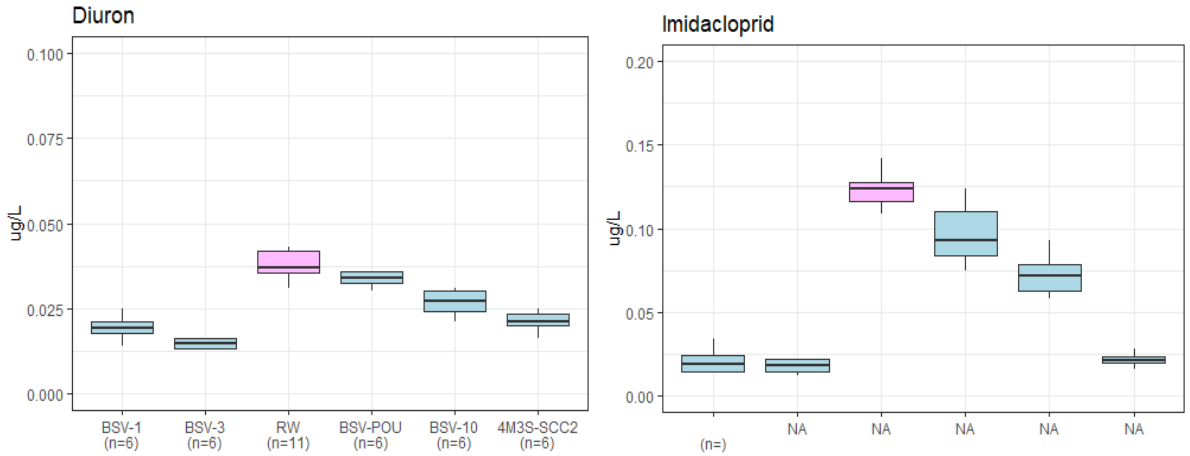


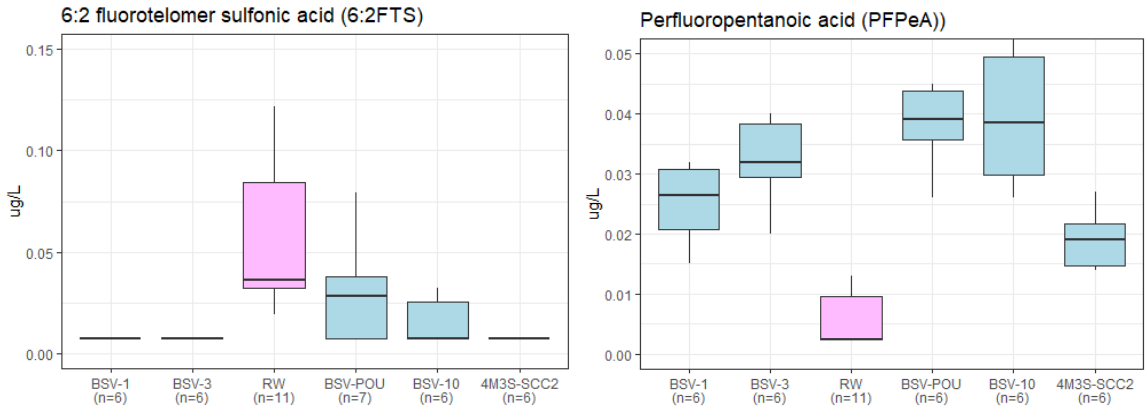
Figure 1.23 Behaviour of pesticides during recharge process

Per- and Polyfluoroalkyl substances (PFAS)

Degradation paths for PFAS need to be carefully tackled.

In some cases, degradation products lead to short chain PFAS, which, depending on the facility technology to treat the water of the wells located downstream, could pose problems.

What has been seen so far is that 6:2 FTS, which is among the ones at highest concentration in RW, decreases while crossing the non-saturated zone, whilst short chain PFAS (PFBA, PFHxA, PFPeA, etc.) increase (Figure 1.24). With all, the sum of PFAS gets not altered with water recharged at the infiltration ponds, with values around 0,1 µg/l, so just at the limit of the parametric value for drinking water according to RD 3/2023.



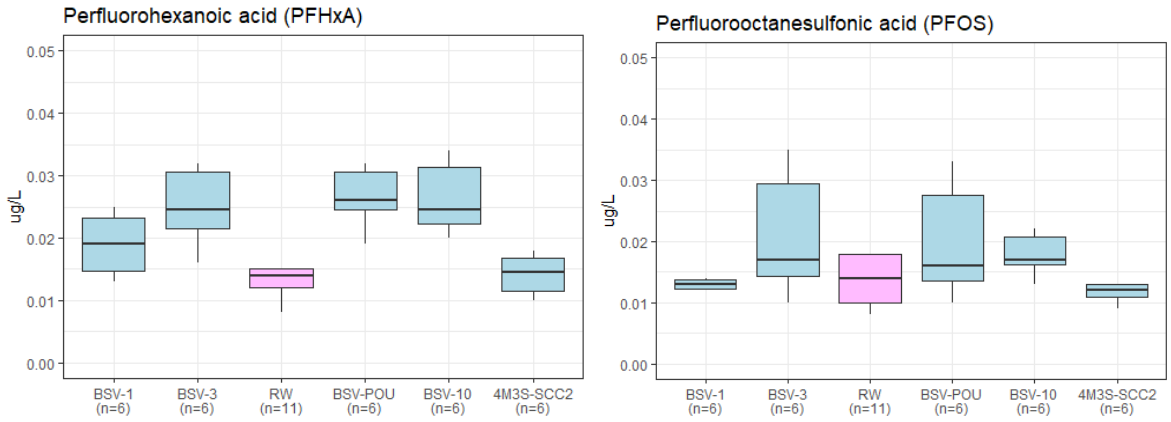


Figure 1.24 PFAS evolution during the recharge process

Pharmaceutical compounds

The decision on the selection of target pharmaceutical compounds (PhCs) for their analysis is based on their toxicity or persistence. Some PhCs are completely removed from RW while they cross the vadose zone. Once recharged, all values are below PNEC (predicted non-effect concentration).

Figure 1.25 shows, some PhCs that are completely removed while they cross the vadose zone. That is the case for Diclofenac, Losartan, O-Desmethylvenlafaxine, and Valsartan. In fact, they are usually found in RW at concentrations that exceed 1.000 ng/L, but they are not detected neither at BSV-POU (located right at the end of the infiltration pond) nor in the piezometers downstream.

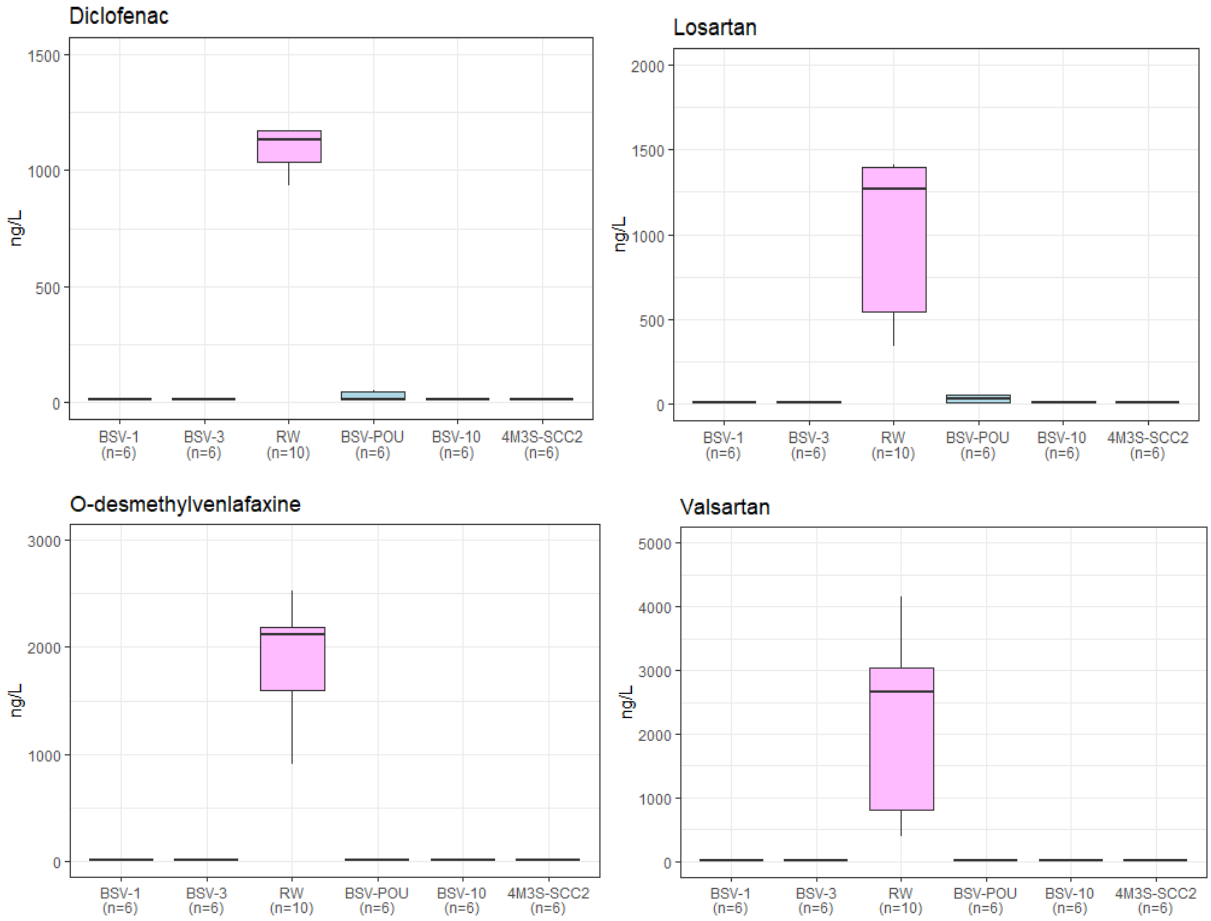
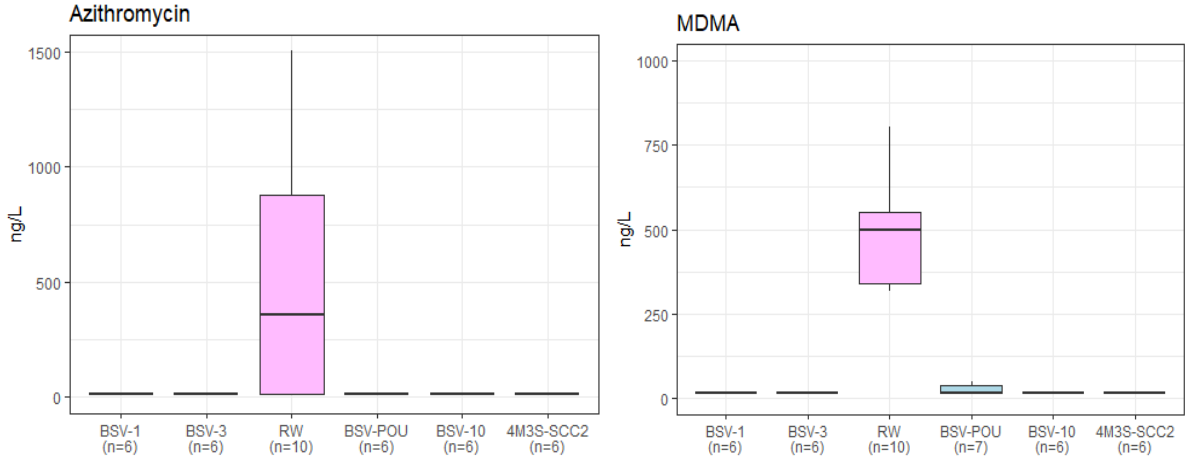


Figure 1.25 Pharmaceutical compounds completely removed at the non-saturated zone (I)

With the same behaviour, but slightly lower concentrations at RW, many other pharmaceuticals could be mentioned (e.g., Azythromicin, MDMA, Ciprofloxacin, Doxycycline, Methamphetamine, Ofloxacin, Vanlafaxine). Some of them are summarized in Figure 1.26.



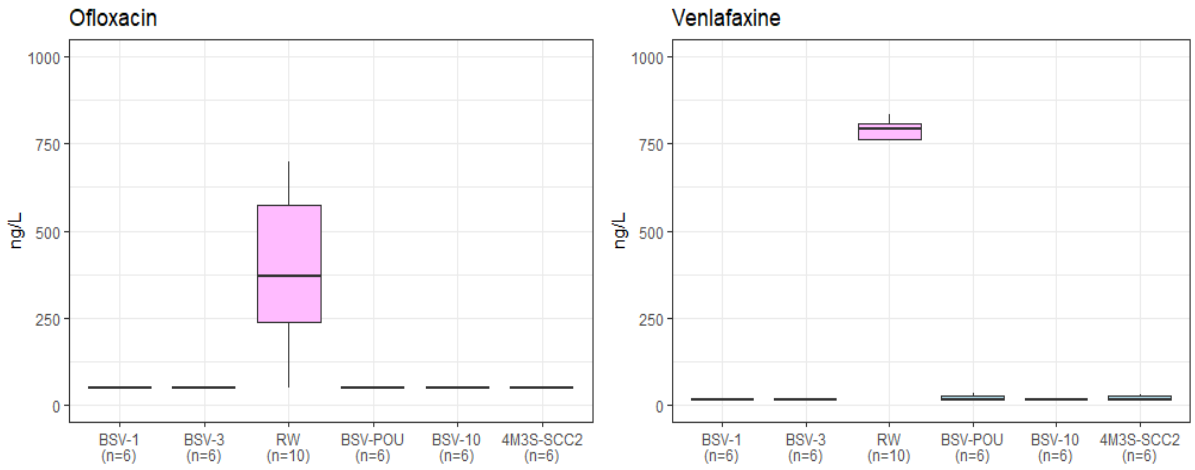
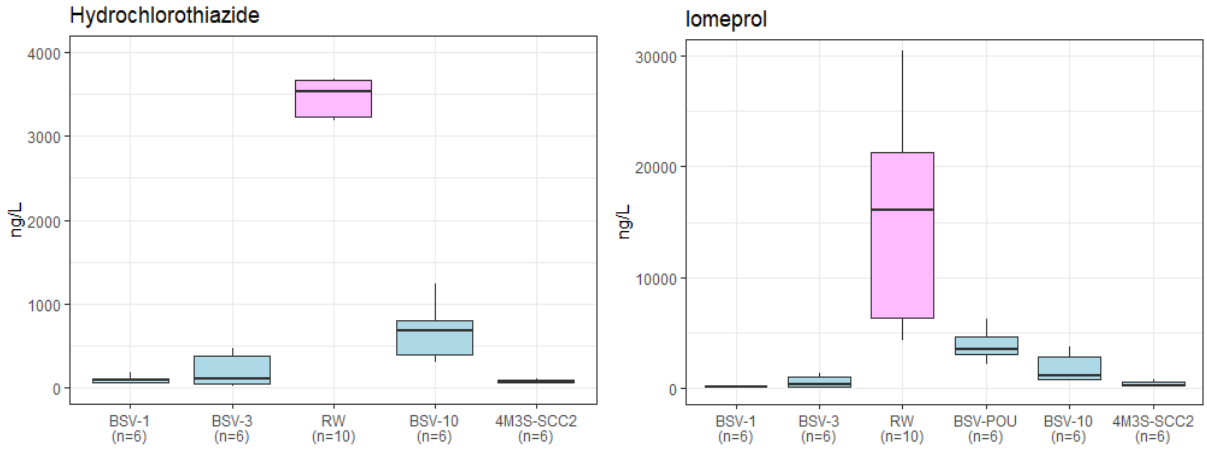


Figure 1.26 Pharmaceutical compounds completely removed at the non-saturated zone (II)

On the contrary, in some others, the concentrations decrease despite they are not completely removed at BSV-POU (e.g., Hydrochlorothiazide, Iomeprol, Sulfamethoxazole, Lorazepam, Bisoprolol, Amantadine). Nonetheless, once this water travels further away, the correspondent concentrations go back to expected native groundwater values (either dilution or degradation) (Figure 1.27).



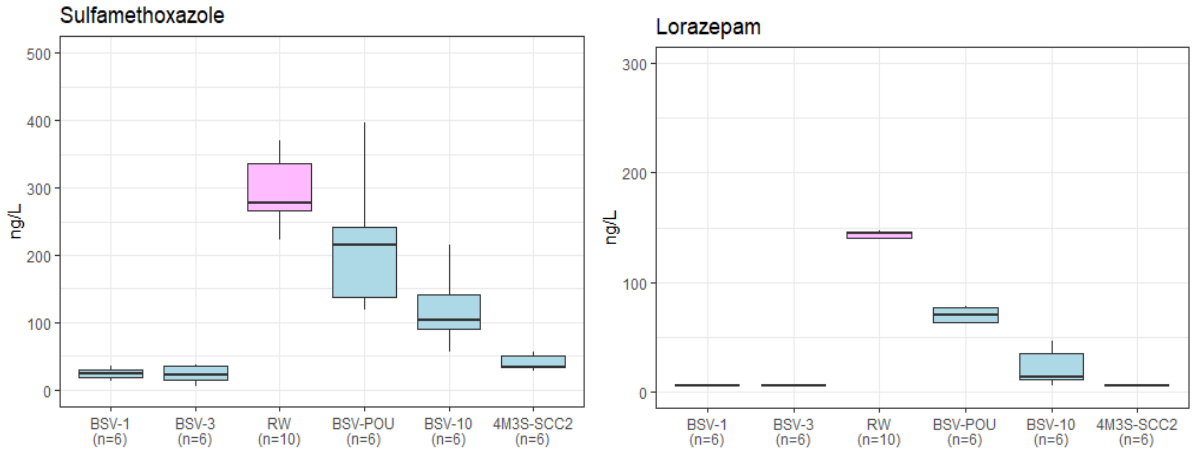
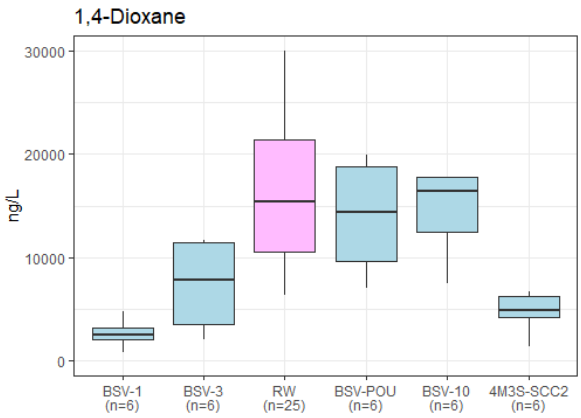


Figure 1.27 Pharmaceutical compounds partially removed at the non-saturated zone (III)

Despite a decrease in many parameters is seen, all those compounds get transformed and the key point is what is obtained instead. To tackle this, a non-target analysis is being performed to assess degradation pathways. Results are being analysed and conclusions from them will be ready soon.

Other industrial compounds

From the very first moment that reclaimed water from El Prat de Llobregat reclamation facility was intended for indirect potable reuse, a clear issue arose with 1,4-dioxane, which was reaching values far above the guidance limit established by the World Health Organization (50.000 ng/L).



Big efforts were made at that point to detect its origin and force industries towards a decrease in the released concentrations.

Thanks to that, since recharge at the infiltration ponds began in May 2024, 1,4-dioxane concentrations in RW have been kept below the recommended value by the WHO (Figure 1.28).

Figure 1.28 1,4-dioxane levels

Another already known contamination in the Lower Llobregat River Valley aquifer is that of organochlorinated compounds (1,1,2-trichloroethane, trichloroethylene and tetrachloroethylene). This contamination comes from ancient industries in the area, which carried out extraction of aggregates and filled them up with contaminated deposits. As in can be seen in Figure 1.29, concentration of 1,1,2-trichloroethane and trichloroethylene + tetrachloroethylene are sensitively higher at BSV-1 and BSV-3 (before infiltration pond) than in BSV-POU, BSV-10 and 4m3SCC2 (after reclaimed water is infiltrated, without this compounds).

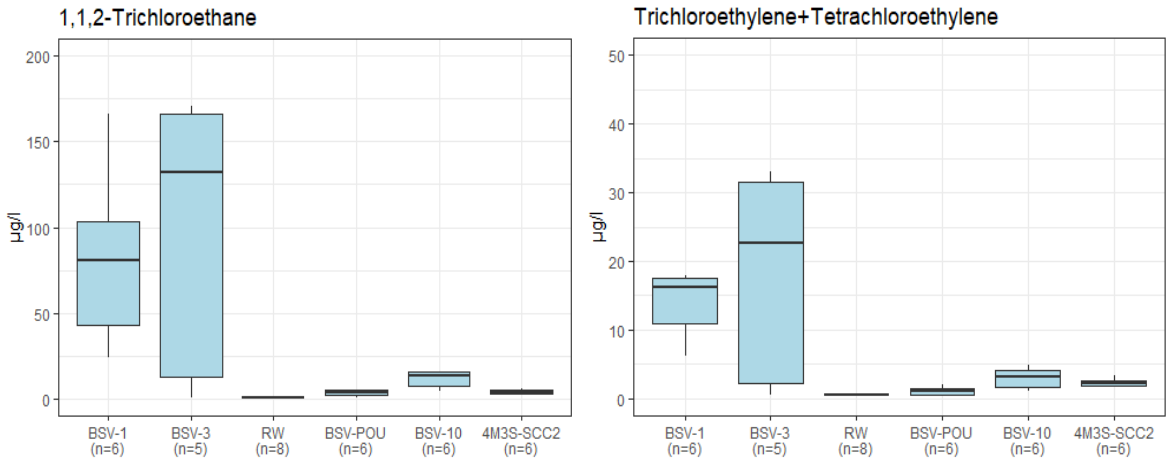


Figure 1.29 Organochlorinated compounds in the recharge observation points

Microbiological parameters

A summary of main microbiological parameters followed during the recharge is shown on Table 1.5. As it can be seen, Clostridium, E. Coli and Somatic coliphages suffer an important reduction while crossing the non-saturated zone, whilst Total Coliforms, which is an indicator of the water quality (but not a pathogen by itself), suffers only a slight decrease. To be noticed that the conditions in which sampling campaigns are performed (field works with sometimes not easily disinfection of sampling hose) can also have an effect on these results.

Table 1.5 Logarithms of microorganisms found at each sampling point

	Clostridium perfringens (UFC/100ml)			E. Coli (NMP/100ml)			Somatic coliphages (Ufp/100ml)			Total Coliforms (NMP/100ml)		
Sampling point	N	Average log	SD	N	Average log	SD	N	Average log	SD	N	Average log	SD
BSV-1	6	0	0	6	0	0	6	0	0	6	2,06	0,79
BSV-3	6	0	0	6	0	0	6	0	0	6	0,26	0,22
RW	6	**2,74**	**0,47**	68	**0,83**	**1,19**	11	**3,15**	**0,78**	68	**1,31**	**1,45**
BSV-POU	6	0,42	0,65	6	0	0	6	0	0	6	1,56	0,58
BSV-10	6	0,31	0,35	6	0,05	0,12	6	0	0	6	0,60	0,54
4M3S-SCC2	6	0,53	0,36	6	0	0	6	0	0	6	1,65	0,94

1.5.2. Deep recharge at Well 18

Water table evolution

Since the recharge at Well 18, as stated before, began in October 2021, water table evolution is shown since then. Levels at Well 18 and PZ2 WELL 18 showed a very close evolution while a recharge of 30 L/s was performed. Nonetheless, since recharge was increased up to 50 L/s in spring 2024, levels at WELL 18 have become slightly higher (Figure 1.30).

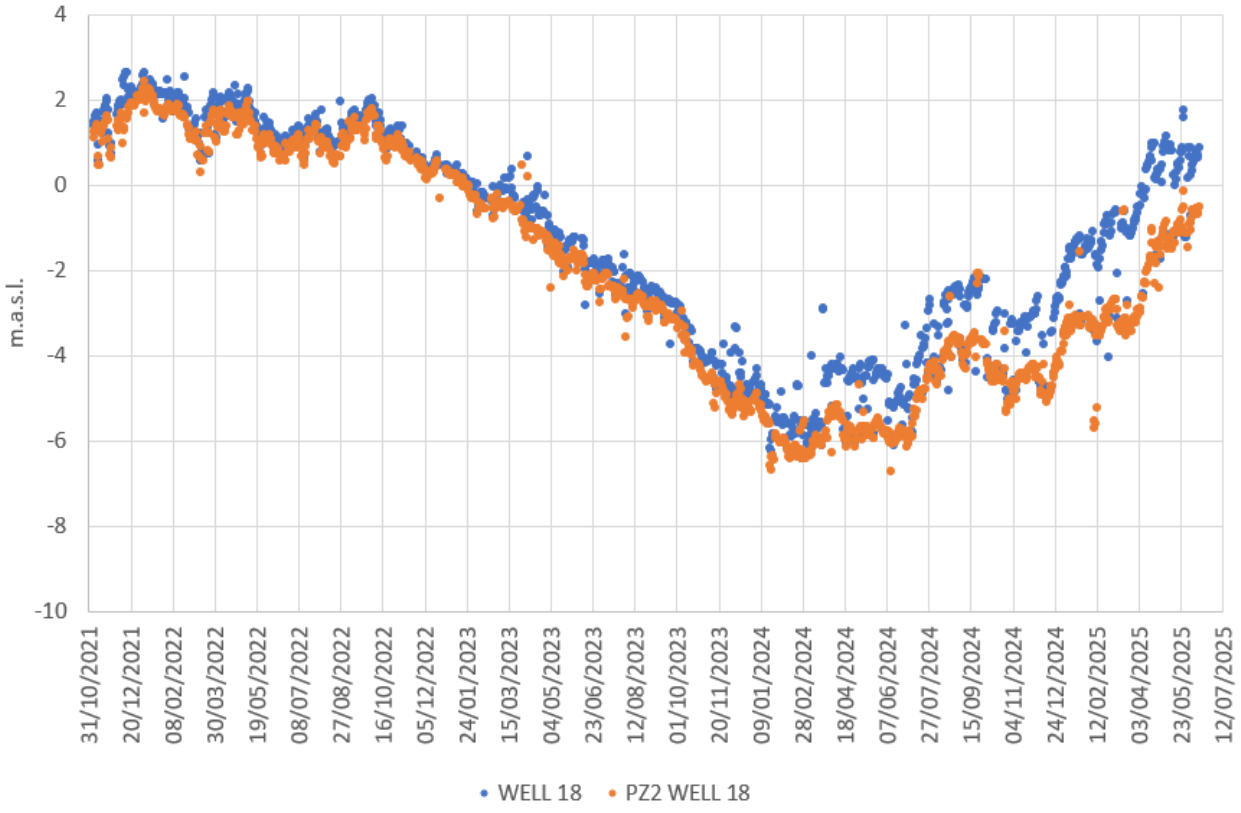


Figure 1.30 Water table evolution at Well 18 and PZ2 WELL 18

Although recharge at Well 18 is performed continuously (unless issues on surface water which stop water catchment at the DWTP), several cleaning processes are performed along the year to maintain recharge efficiency and avoid clogging.

Thus, cleanings are performed every 50.000 m^3 of water injected. The cleaning consists of a backwash during 20 min at a water flow of 120 L/s. With this recharging flow of 50 L/s, cleanings are performed, approximately, every 15 days of recharge and evolution of turbidity and metals is conducted to make sure that restored values are achieved after the backwash process.

Another thing to be noticed is the impact of hydrodynamics in the area. In fact, there are three well fields nearby Well 18, which are called after: Finques, Riuet and Interiors Cornellà (Figure 1.32).

In the area where Well 18 is located, the extension and hydrodynamics of recharged water needs to be understood in the context of a simultaneous exploitation in close wells.

Despite the continuous recharge done at Well 18, the withdrawals in the area (Figure 1.31) create an important cone of depression, which means that the natural water flow (blue arrow in Figure 1.32) is significantly modified towards Interiors Cornellà (red arrow). The resultant vector of main water flux is depicted (green arrow). Therefore, despite the natural regional flow towards the sea discharge, during the analysed period groundwater flow dynamics were mainly characterized by groundwater flux from Well 18 to Well 13.

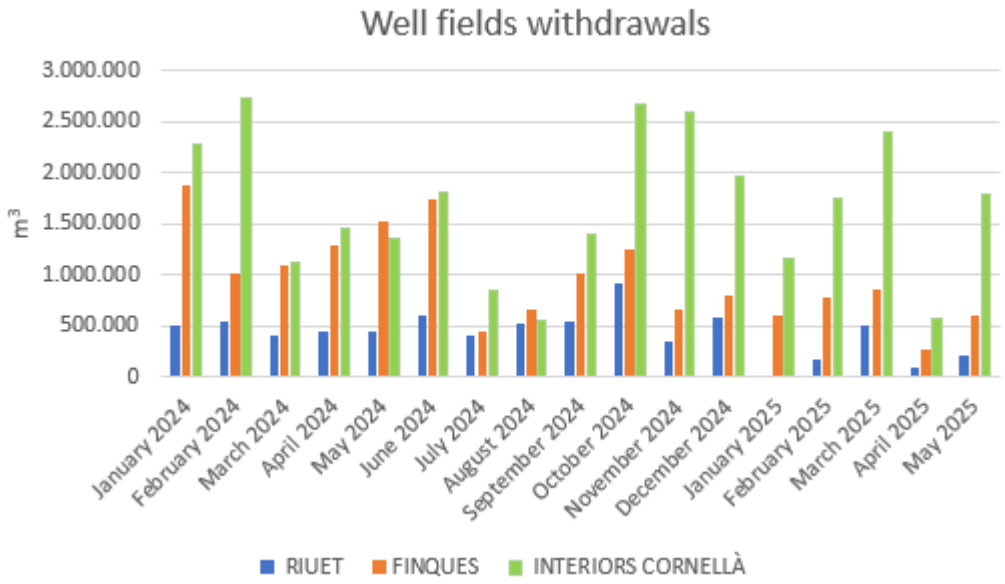


Figure 1.31 Well fields withdrawals

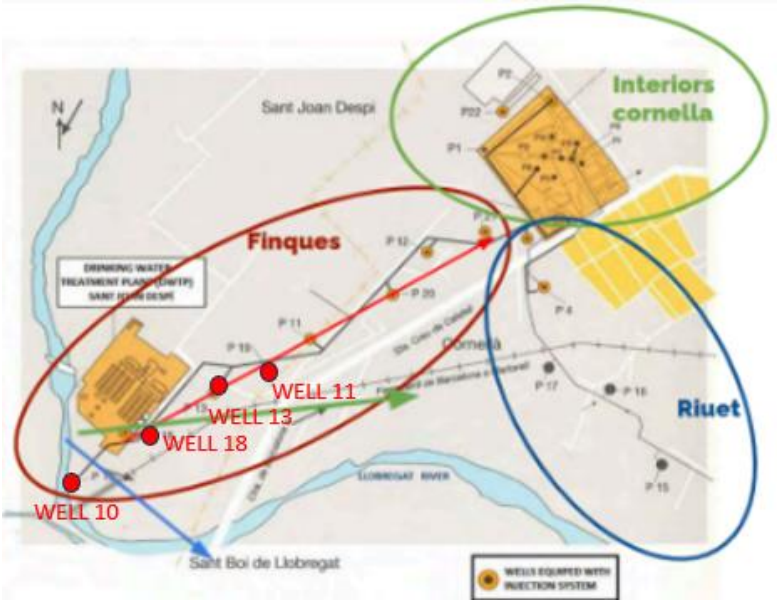


Figure 1.32 Natural water flow

Water quality campaigns

Sampling campaigns (Figure 1.33) have been conducted every three months since the recharge began. Despite the MARCLAIMED Project officially started in 2024, results presented here date back to January 2023, when, due to IPR implementation, reclaimed water mixed with surface Llobregat River water became the source for recharge.



Figure 1.33 Sampling campaigns at Well 18 and nearby piezometers

Physicochemical characterization

With the IPR scheme, there was a change in the Llobregat river water and, therefore, a change in the water used for MAR. The main concern, as previously stated, is the salinity of reclaimed water. Despite this, salinity values come down to normal groundwater levels, even in the area not that far away from the recharge well (Figure 1.34).

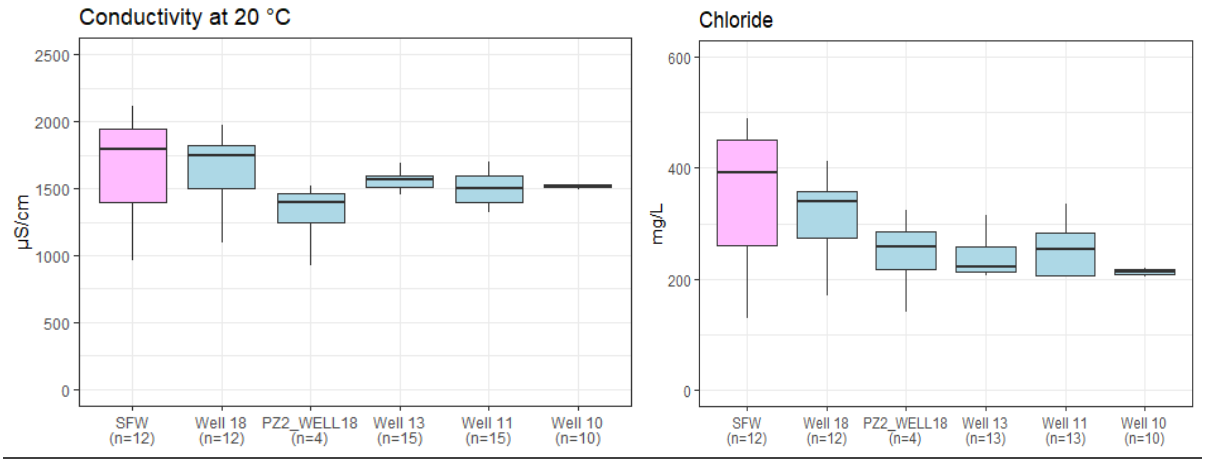


Figure 1.34 Salinity in the recharge Well 18 and observation wells

Main tracers of the extension of water recharged

As shown in the previous section, the first observation well which should be expected to receive recharged water is Well 13. In fact, there are three clear organic compounds which could be used as tracers (Figure 1.35):

- **1,4-dioxane** an industrial compound highly soluble in water, mobile, persistent and hardly removed by natural degradation processes. As explained before, it is present in reclaimed water (and thus in sand filtered water) at higher concentrations than those of groundwater. Values depicted for Well 13, Well 11 and Well 10 are at the average range they were before recharging partially reclaimed water at Well 18.
- **1,1,2-Trichloroethane** a contamination in groundwater in this aquifer, whilst it is never detected either in reclaimed water nor in sand filtered water. Indeed, Well 18 and Well 13 have historically been the most contaminated ones in the area by this organic compound, which concentrations used to raise up to 60-80 µg/L. On the contrary, at Well 10 concentrations have historically remained below 5 µg/L.
- **Chlorates** are occasionally detected in surface water from Llobregat River (either coming from reclaimed water disinfection process or from some other industries in the river upstream) whilst they are not detected in groundwater (some exceptions like Well 10, which suffers from some other recharge sources, should be separately considered). Nonetheless, the main contribution to chlorates concentrations in sand filtered water is the dioxichlorination performed at the pretreatment process in Sant Joan Despí DWTP.

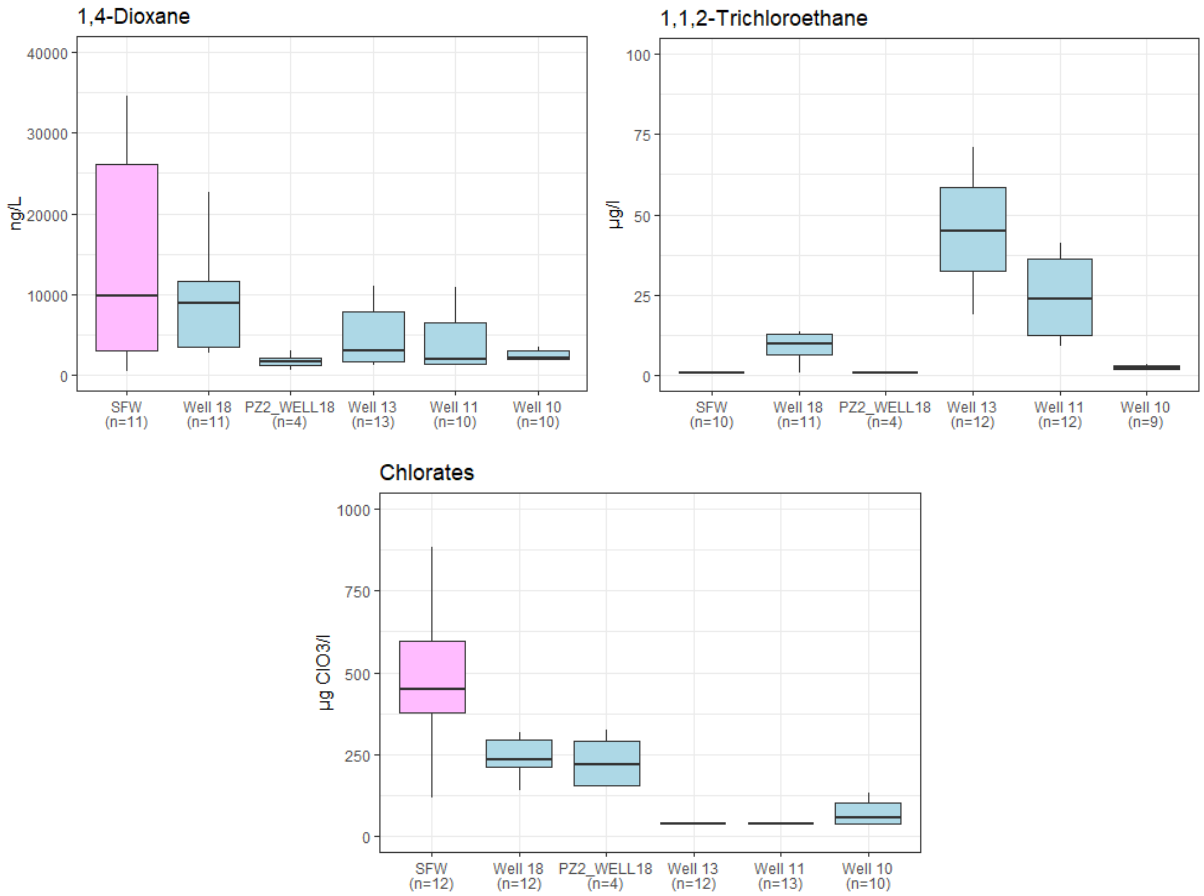


Figure 1.35 Concentration of tracer compounds in SFW, Well 18 and observation wells

Based on the previously shown results, it could be stated that, with the volumes recharged, in the analysis of extractions and the evolution of persistent contaminants, only a slight portion or water recharged at Well 18 would reach Well 13. Thus, PZ2 WELL 18 would be the only observation point that would receive recharged water from Well 18 at a significant rate.

Pesticides

Among all pesticides analysed, some of them are known to be moderately persistent (Diuron, Terbutryn and Isoproturon) or even highly persistent (Imidacloprid). All these pesticides (Figure 1.36) are found at slightly higher concentrations in reclaimed water than in groundwater, around Well 18 and nearby wellfield. Nonetheless, once again, dilution plays a key role and thus concentrations, already in Well 13, go down to normal values for groundwater in Vall Baixa aquifer.

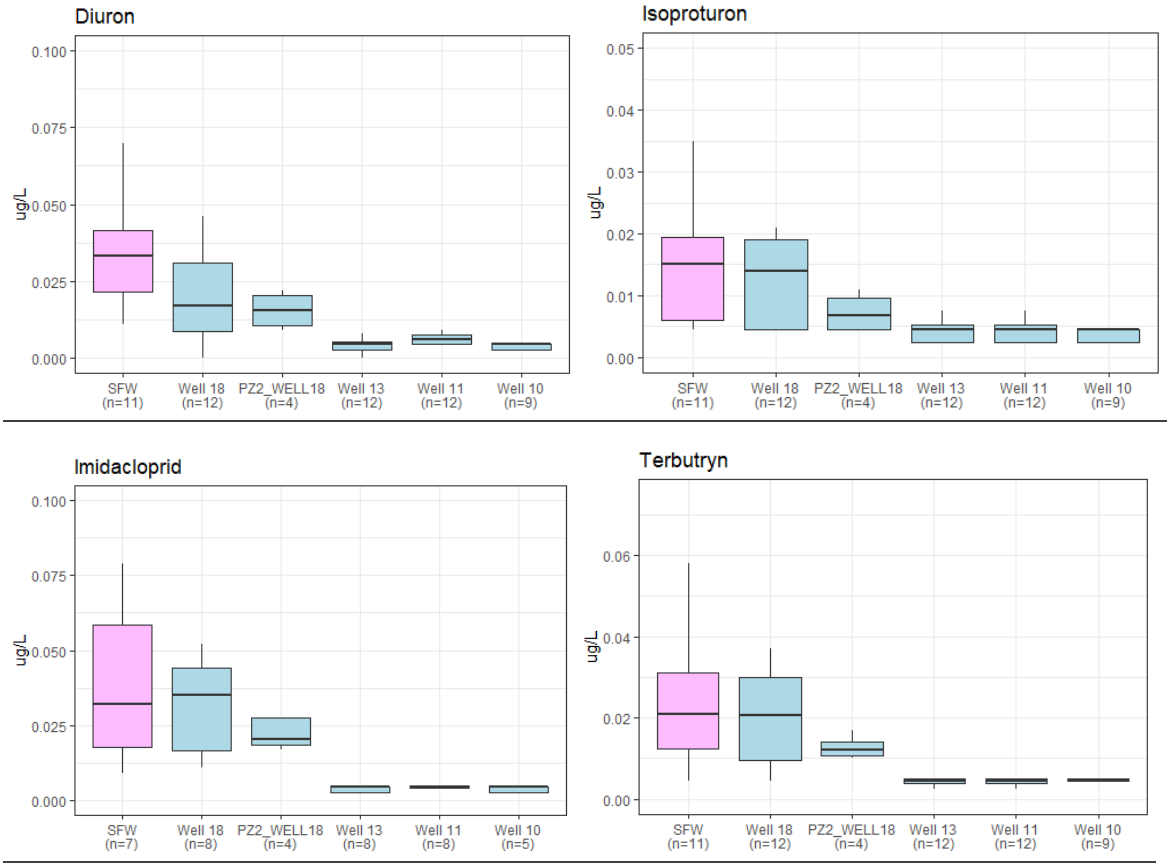


Figure 1.36 Concentration of pesticides in SFW, Well 18 and observation wells

PFAS

The sum of PFAS as well as the individual PFAS do not show significant differences between recharged water and groundwater (Figure 1.37), meaning that recharge with AWR at this point has no negative effect on groundwater regarding PFAS.

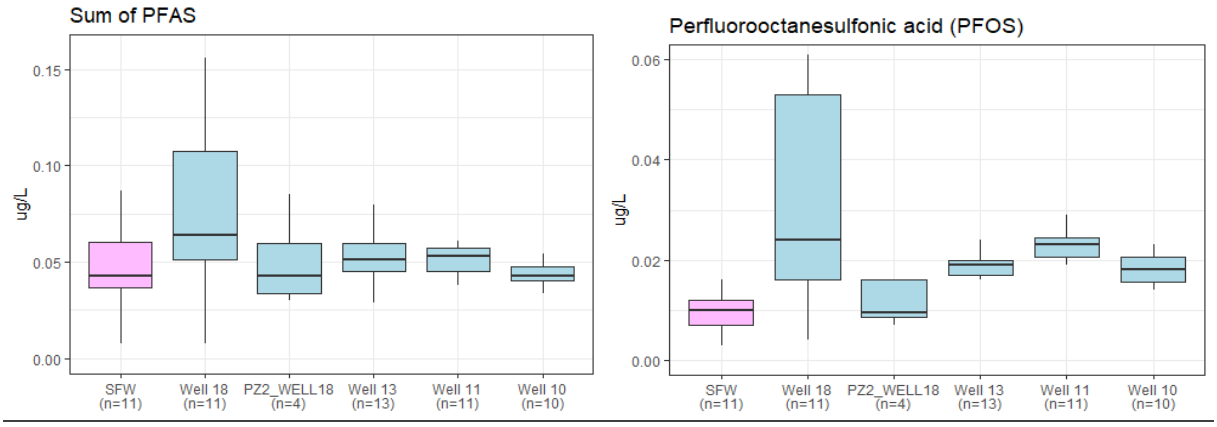


Figure 1.37 Concentration of Sum of PFAS and PFOS in SFW, Well 18 and observation wells

Pharmaceutical compounds

Another thing to highlight is the important effect of the pretreatment process at Sant Joan Despí DWTP, during which the pre-oxidation plays a key role in degrading many PhCs as well as reducing organic matter before injection. This treatment process definitively enhances water quality before injection as it can be seen in table below (Table 1.6).

Table 1.6 Variations of concentration of pharmaceutical pollutants due to pretreatment process. Mean values per point

Parameter	Units	Reclaimed water (n=28)	Surface water (n=25)	Sand filtered water (N=8)	Well 18 (N=8)	Well 13 (N=8)
Amantadine	ng/l	306,9	173,9	143,5	200,6	66,0
Amoxicilin		399,6	<500	<500	<500	<500
Azithromycin		927,8	52,8	40,1	36,6	<25
Bisoprolol		237,9	125,5	51,4	51,4	<10
Carbamazepine		132,1	67,9	47,4	42,5	<25
Cephalexine		198,1	66,2	<125	<125	<125
Ciprofloxacin		1312,0	504,9	267,0	199,8	<125
Diclofenac		1419,0	460,1	<25	<25	<25
Doxycycline		725,4	<500	<500	<500	<500
EDDP		42,8	17,7	13,8	13,7	<10
Hydrochlorothiazide		2106,2	637,5	538,0	486,5	10,9
Iomeprol		14127,7	4263,1	4319,0	2055,4	134,5
Iopromide		273,9	161,1	152,7	<50	<50
Lorazepam		156,5	72,8	52,4	39,0	<10
Lormetazepam		72,5	36,2	28,8	21,5	<10
Losartan		1192,5	424,4	217,3	18,5	<10
MDMA		557,3	208,7	74,8	30,3	<25
Methamphetamine		208,8	71,5	46,8	35,0	<50
O-desmethylvenlafaxine		1851,3	772,7	<25	<25	<25
Ofloxacin		742,5	169,6	<100	<100	<100
Salbutamol		363,0	73,7	<25	<25	<25
Sulfamethoxazole		331,7	175,1	17,6	28,1	22,5
Valsartan		1913,8	490,6	308,4	12,6	<10
Venlafaxine		718,6	310,1	100,3	141,3	<25

Microbiological parameters

Regarding microbiological parameters in this deep recharge, a slight increase is detected in Well 18 when compared to SFW regarding Clostridium perfringens and total Coliforms. This could be explained because samples of Well 18 are taken after backwashing processes, so any microbiological clogging could be dragged to the sample. Nonetheless, values come down to normal groundwater logarithms at Well 13 (Table 1.7).

Table 1.7 Logarithms of microorganisms found at each sampling point

	Clostridium perfringens (UFC/100 ml)			E. Coli (NMP/100 ml)			Somatic coliphages (Ufp/100 ml)			Total Coliforms (NMP/100 ml)		
Sampling Point	N	Average log	SD	N	Average log	SD	N	Average log	SD	N	Average log	SD
SFW	12	0,69	0,68	12	0,14	0,22	12	0,13	0,38	12	1,64	0,76
Well 18	12	1,70	0,78	12	0,00	0,00	12	0,00	0,00	12	2,83	0,69
Well 13	12	0,00	0,00	12	0,00	0,00	12	0,03	0,09	12	0,19	0,38

1.6 MARCLAIMED IDST implementation (MARCLAIMED tools, input data gathering, connection, and first results)

1.6.1 MARCLAIMED tools implementation

Extensive details on the application of each of the MARCLAIMED tools in DS1 and associated first results are provided in the WP1 deliverables:

- D1.1 – Predictive Models for MARVIS, PREDMAR and MARAISER
- D1.2 – MAR with AWR impact at municipal scales for OASIS FLOW
- D1.3 – Economic and financial aspects for MARINSURE and RECOVER

At this stage of the project, the integration of the tools within the IDST is still in progress. Therefore, no other details regarding the site-specific implementation of each tool in DS1 can be provided at this time.

1.6.2 Input data gathering

All data collected in DS1 are transferred to an FTP server in the project's infrastructure. The data collection module of the Integrated Decision Support Tool (IDST) regularly monitors the FTP server for new files. Upon detecting new files, it fetches them, converts the data into the relevant format specified by the NGSI-LD model used in the project, and then sends the converted data to the IDST database for storage and further processing.

Due to enhanced security measures from the DS1 side, the data transfer to the FTP server is not trivial and is still ongoing. Hence, no data from DS1 is available on the IDST at this stage.

1.7 Conclusions

The DS1 includes two complementary MAR systems: (i) the Sant Vicenç dels Horts infiltration pond and ii) the deep injection well (Well 18). These systems have been deployed to increase groundwater availability and quality, while mitigating aquifer stress and pollution risks.

As of May 2025, a total of 1.5 hm³ of water has been successfully recharged at Well 18, and 0.61 hm³ at the Sant Vicenç dels Horts infiltration pond. These volumes contribute to the KPI_6.2 (volume recharge increase) and have already supported a reduction of the local Water Exploitation Index (KPI_6.3).

Water quality has been extensively monitored at both systems, covering microbiological, physicochemical, and emerging contaminants. The Sant Vicenç dels Horts infiltration pond demonstrated high effectiveness in natural attenuation processes. The vadose zone promotes the degradation or removal of multiple contaminants:

- Microbiological degradation: significant reductions (up to 4-log) were observed for Clostridium perfringens, E. coli, and somatic coliphages between the reclaimed water and observation wells.
- PFAS: although total concentrations remained stable (~0.1 µg/L), transformation processes were detected (e.g., 6:2 FTS decreased while short-chain PFAS increased), suggesting sorption and precursor degradation mechanisms.
- CEC removal: PhCs such as Diclofenac, Losartan, and Valsartan, and pesticides like AMPA were completely removed, despite relatively high initial concentrations.
- 1,4-dioxane: concentrations remained below WHO guideline value throughout recharge operations, attributed to early mitigation protocols.

These results support KPI_6.1 by demonstrating early detection and attenuation of multiple contaminants.

The infiltration pond was also used to test operational optimization. Extended recharge cycles (up to 15 days) under optimized WWTP conditions (since early 2025) led to enhanced anoxic conditions and improved nitrate removal efficiency, tending to reach the 5 % improvement in MAR system performance.

At Well 18, recharge has stabilized at 50 L/s since spring 2024. Frequent backwashing (every 50,000 m³) and continuous monitoring have maintained injection capacity and prevented clogging. The change in recharge water matrix - due to upstream IPR contributions - has introduced reclaimed water constituents into the injection zone. Their distribution is being monitored to study transport under current hydraulic conditions, including interactions with nearby wellfields.

A MAR resilience indicator (KPI_6.5) has been defined and will be evaluated considering the sustained performance of both systems under varying water qualities and demand scenarios.

1.8 References

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Gámez Torrent, D. (2007). Sequence Stratigraphy as a tool for water resources management in alluvial coastal aquifers: application to the Llobregat delta (Barcelona, Spain). PhD Thesis, UPC, Departament d'Enginyeria del Terreny, Cartogràfica i Geofísica. DOI: 10.5821/dissertation-2117-93567

Queralt (2025). La recàrrega d'aqüífers al Llobregat amb aigua regenerada, una manera de tancar el cicle de l'aigua. VI Congrés de l'aigua a Catalunya. Aigua convivencia i supervivencia. Barcelona 18-19 March 2025.

Queralt *et al*. (2020). Improving Water Quantity and Quality Supply Security by Managed Artificial Recharge Technologies in the Lower Llobregat Aquifers Integrated into a Conjunctive Surface and Groundwater Management Scheme for Barcelona, Spain. Journal of Environmental Science and Engineering A9 (2020) 119-139. DOI: 10.17265/2162-5298/2020.04.001

2 DS2: Comporta (PT)

2.1 Introduction and objectives

The second MARCLAIMED Demo Site (DS2) is located at Comporta, in the Alentejo region, Portugal (Figure 2.1). It is the 1st example of a Wastewater Treatment Plant (WWTP) with a Soil-Aquifer Treatment MAR (SAT-MAR) system in Portugal, being fully functional and operating since October 1st, 2021. The WWTP is equipped with a technologically advanced treatment system, including primary, biological treatment and additional disinfection to produce water for reuse, and treatment of sludge by dehydration. The SAT-MAR system is composed of four infiltration basins that receive the treated effluent of 589 to 2500 p.e., having a maximum discharge of 582 m^3/day and an average value of 137 m^3/day.

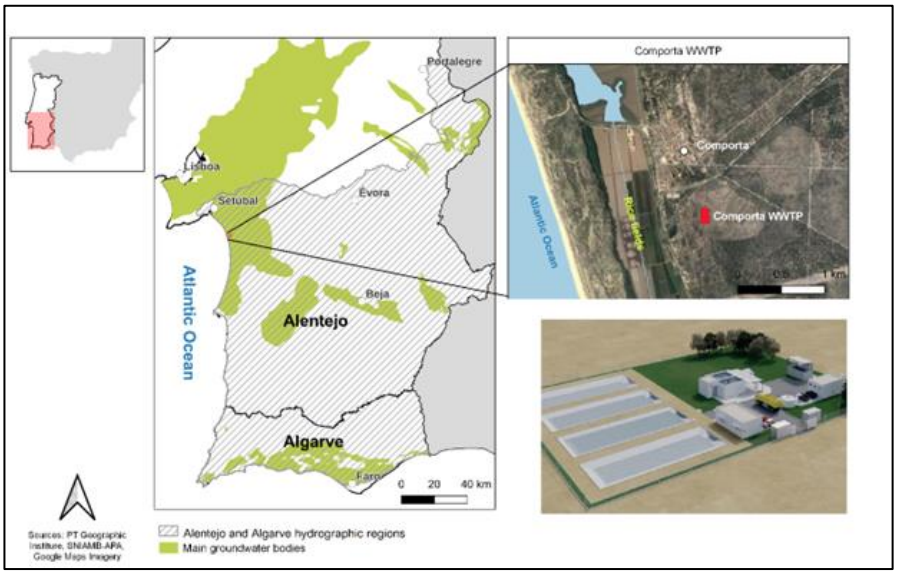

Figure 2.1 Location and general layout of Comporta WWTP_SAT-MAR system

Comporta WWTP_SAT-MAR was licenced after a cost-benefit and hydrogeological study, which determined that this solution was the most favourable alternative compared to the conventional practice of directly discharging treated effluents into surface water bodies, in order to protect Sado estuarine ecosystem, a sensitive area classified as a Nature Reserve located over the Margem Esquerda Tejo-Sado aquifer system - the largest aquifer system of the Iberian Peninsula. Besides the benefits gained from the water quality improvement during infiltration, it was considered a way of using alternative water resources to mitigating water scarcity in the area.

2.2 Motivation for the site selection and expected outcomes

The motivation of choosing Comporta as a DS for MARCLAIMED project derived from previous interactions with local and regional stakeholders (Ghannem *et al*., 2024), which acknowledge the relevance of Comporta, but also raised their concerns in upscaling its SAT-MAR concept to similar WWTP without deeper knowledge about the groundwater quality preservation. Therefore, the **goal of DS2** is to increase the understanding and gaining trust in WWTP_SAT-MAR systems for further improving the Treated Wastewater (TWW), in such way that it "does not compromise the achievement of the environmental objectives for groundwater" (cf. Article 11(3)(f) of the Water Framework Directive).

So, Comporta was chosen to be an example of SAT-MAR, to be replicated in other parts of the Alentejo region to alleviate water stress in this water-scarce region, provided it proves to be a good example. DS2 **key-objectives** are to obtain detailed information on ongoing treatment processes in the WWTP_SAT-MAR system, including new solutions, in the effective improvement of infiltrated water quality, and to improve public/social acceptance of MAR systems, while helping to protect sensitive natural areas providing benefits for local economic activities.

So, the **expected outcomes** of the MARCLAIMED project for DS2 are to: 1) improve water quality during infiltration (also with new experimental solutions) and optimizing infiltration rates; 2) improve understanding of the risk of groundwater contamination resulting from SAT-MAR; 3) improve awareness and practices of public water services; and 4) improve social and political acceptance, reliability and trust in SAT-MAR systems as a structural solution for small WWTPs in viable regions and in the context of water scarcity.

2.3 Geological/hydrogeological setting

As mentioned in section 2.1, Comporta area is located over the *Margem Esquerda Tejo-Sado* aquifer system, which, considering only its subarea south of the Sado River, is geologically composed of (top to bottom): (1) Quaternary rocks, mostly identified as sand dunes, dunes, and some sands and gravels outcrops; (2) Pliocene rocks, made of sands, sandstones, clayey sandstones and clays; (3) undifferentiated Miocene and Pliocene formations, consisting of alternating sands, sandstones and clays; (4) Miocene formations, composed of conglomerates, sandstones, biocalcarenites, clays and detrital-carbonate layers (cf. Geological Maps of Portugal at scale 1:50 000, from National Laboratory for Energy and Geology, sheets 39-A *Águas de Moura* and 39-C *Alcácer do Sal*).

Although surface outcrops are limited, the Miocene formations play a significant role at depth, forming the main body of the aquifer system, which extends beyond 250 meters. The aquifer system lies over metamorphic low permeability rocks of Carbonic age.

This aquifer system is made up of a succession of detrital units, with frequent lateral and vertical facies variations, which originate a porous, multilayered, complex aquifer system,

made up of an alternation of aquifer units (sands, sandstones, calcarenites, limestones) separated from each other by units with aquitard to aquiclude behaviour (clays, marls), thus defining a succession of confined to semi-confined aquifers, underlying free aquifer layers in the area closest to the surface. In some cases, it is expected that these less pervious layers occur in the form of lenses, allowing some connection between the different aquifer units.

The aquifer system is fed by direct recharge from rainwater. Recharge is distributed, occurring throughout the area where the aquifer system occurs. Semi-confined and confined aquifer units are recharged by drainage from the most superficial units, when the hydraulic potentials of these formations are greater, or from the infiltration of rainwater in areas where these formations outcrop.

Three types of flow systems can be defined, depending on the distance between the recharge and discharge sites: (1) local system – short-distance flows, whose discharge areas are the watercourses adjacent to the recharge zones (the one being analysed in MARCLAIMED); (2) intermediate system – longer-distance flows where discharge does not occur in the watercourse closest to the recharge zone but in another more distant one, for example to the Sado river or the Sado estuary; and (3) regional system – extensive and deep flows, with circulation on a basin scale.

In addition to recharge by infiltration of rainwater, there are also two possible sources of flow external to the aquifer system: on the ocean side there may be flow from the sea into the aquifer, and on the southern and eastern borders there may be inflow from adjacent geological formations; It is considered that, on the northern border, the inflow or outflow is negligible. In areas where unconfined aquifers occur, if extractions from catchments are intense, there may also be induced infiltration from watercourses, particularly in periods of low annual recharge.

In the framework of a previous project (AGREEMAR – https://www.agreemar.inowas.com/), considering these geological and flow conceptual models, a regional finite-difference numerical flow model has been developed in the area, using a refined grid in the location of the infiltration basins to allow determining the effect of infiltration water in the groundwater flow system. Details of the model can be found at Glass *et al*. (2024) and a concise summary of the results can also be found at Leitão *et al*. (2024).

Model results were considered as estimates due to incomplete knowledge of the parameters that represent the groundwater system. They indicate that the hydrogeological conditions in Comporta would allow infiltration rates 16x higher (2188 m^3/day) than the current average infiltration rate (137 m^3/day). The water infiltrated at Comporta could increase the groundwater level locally by 6.5 m for the maximum infiltration rate compared to the current average infiltration rate, therefore contributing locally to alleviating water stress. Concerning the area of influence, the water level rise would be approx. 1 m at about 500 m from the infiltration basins. Particle tracking modelling was also used showing a

minimum travel time of 10 years to reach the Vala Real stream, set at the rice fields West of Comporta MAR site, considering the current average infiltration rate (Figure 2.2).

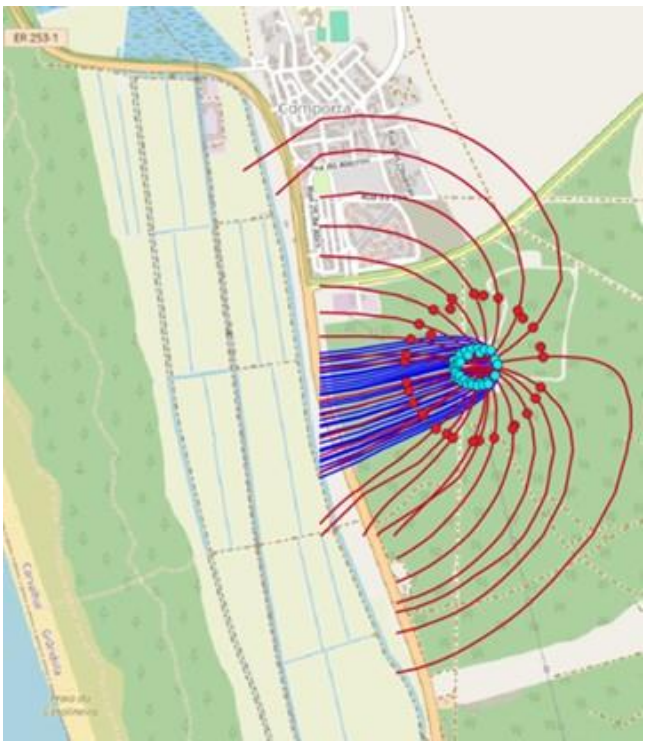

Figure 2.2 Pathlines originating in the infiltration basins towards Vala Real and particles for 1 year travel time (blues = current average infiltration rate, reds = maximum infiltration rate) (Leitão et al., 2024)

Concerning the **groundwater quality**, Comporta's area has good background values, with low electrical conductivity values ranging from 66 to 135 µS/cm. The existing hydrogeochemical facies is sodium-chloride (Figure 2.3). It is possible to observe a shift in the groundwater facies from the first two months of operation of the WWTP (since October 2021, red triangles) to the following four-month period (light blue triangles), mainly due to the increase in chloride, sodium and bicarbonate. At the current situation (black triangles), both chloride and bicarbonate have stabilized in higher concentrations than initial values. In section 2.5 below more information will be given about groundwater quality.

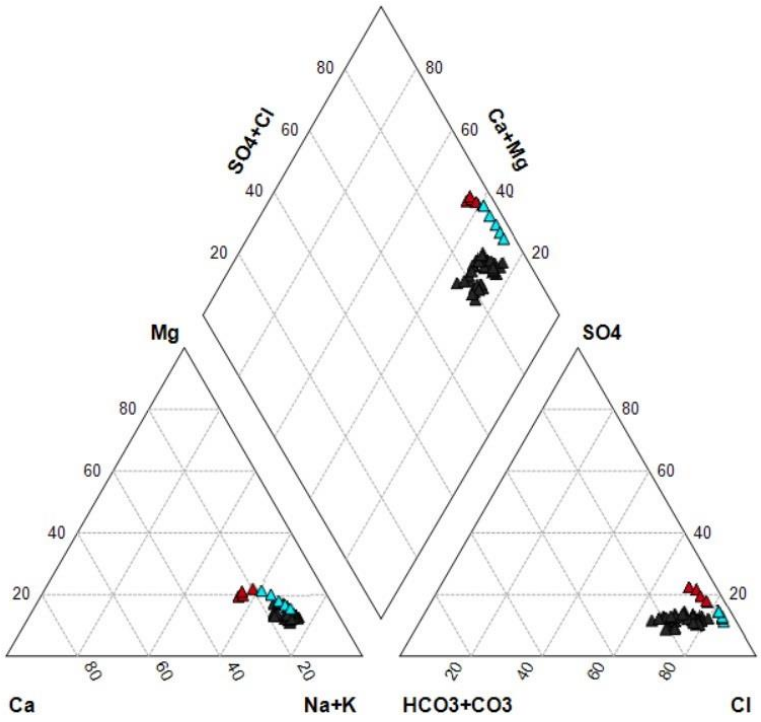

Figure 2.3 Piper diagram showing in red the projected values until December 2021, in blue the transition period, and in black the more recent values

Any such activity is likely to contribute to a change the groundwater quality, the important being to guarantee that MAR "does not compromise the achievement of the environmental objectives established for the groundwater", since WFD does not define quality limits for the recharged water, rather it specifies that the activity cannot compromise the achievement of the environmental objectives for water bodies.

2.4 Existing infrastructures and MARCLAIMED contributions

The initial infrastructures of Comporta, which exist since October 2021, are represented in Figure 2.4. The monitoring schema derived from the Permit includes monthly analysis of TWW inflow, prior to the discharge at the basins, for pH, TSS, BOD_5, COD, N, P, oil and grease, together with monthly analysis in piezometer 1 (PZ1) of pH, T, EC, HCO_3^-, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+}, K^+, Br, Si, and the piezometric level. This schema is running up to now.

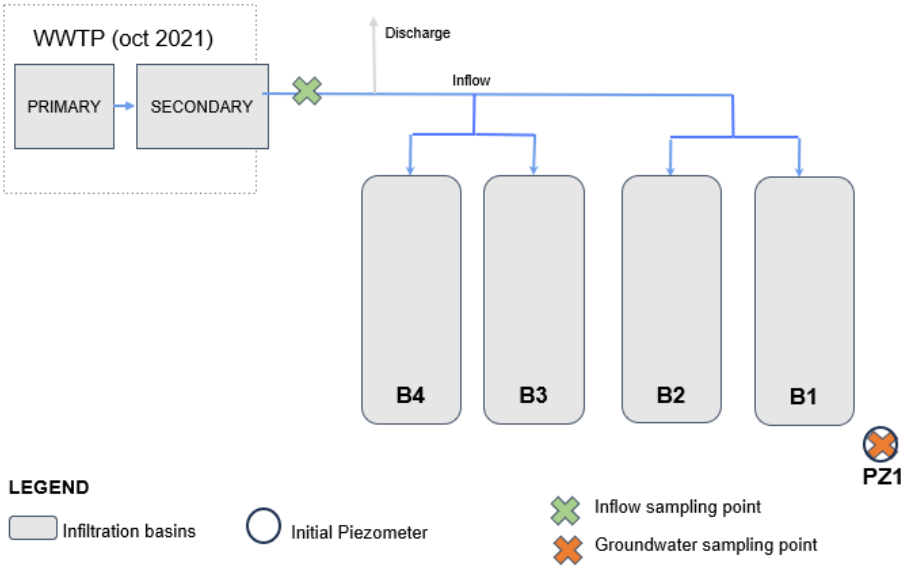

Figure 2.4 Comporta WWTP_SAT-MAR system initial schema and sampling points

To achieve MARCLAIMED expected technical outcomes (cf. section 2.2), a set of actions has been put in place to complement the existing monitoring and sampling schema. Besides a **new complementary monitoring and sampling infrastructure** and the respective planning schema, **two new reactive organic layers** (ROL) were placed at the bottom of two of the four existing infiltration basins, replacing the existing 20 cm gravel, as shown in Figure 2.5.



Figure 2.5 Aspects of the placement of the two reactive organic layers in Basins 1 and 2, at Comporta WWTP_SAT-MAR

In Basin 1 (Figure 2.4), the ROL contains biological charcoal (biochar, 30%) and sand (70%), and in Basin 2, the ROL is composed of Granular Activated Carbon (GAC) (15%) and sand (85%). ROLs are designed to release organic carbon into the infiltration water, which promotes the growth of soil biomass. This process is essential for the biodegradation of pharmaceutical compounds, the precipitation of iron and manganese, possibly promoting denitrification, as well as the removal of pathogens.

It was expected that these SAT-MAR installations provide a significant step towards improving the water quality of the system, as it allows for increased biodegradation and adsorption processes, thus improving the quality of treated wastewater as it infiltrates through the soil.

To evaluate the system's performance, and to understand the risk of groundwater contamination resulting from SAT-MAR, the following set of infrastructures were installed (Figure 2.6 and Figure 2.7):

- Vadose zone: in April 2024, two Teflon cups were installed at depths of -25 cm and -50 cm in each of the B1, B2, and B4 basins, totalling six cups overall.
- Groundwater: in June 2024, AgdA has provided budget for the installation of three new piezometers (PZ2, PZ3 & PZ4, the latter being the reference situation), drilling up to 12 m depth, with PVC casing until 10 m. The piezometers have been isolated from the surface until about 4 m depth.



Figure 2.6 Monitoring and sampling equipment installed under MARCLAIMED at Comporta WWTP_SAT-MAR

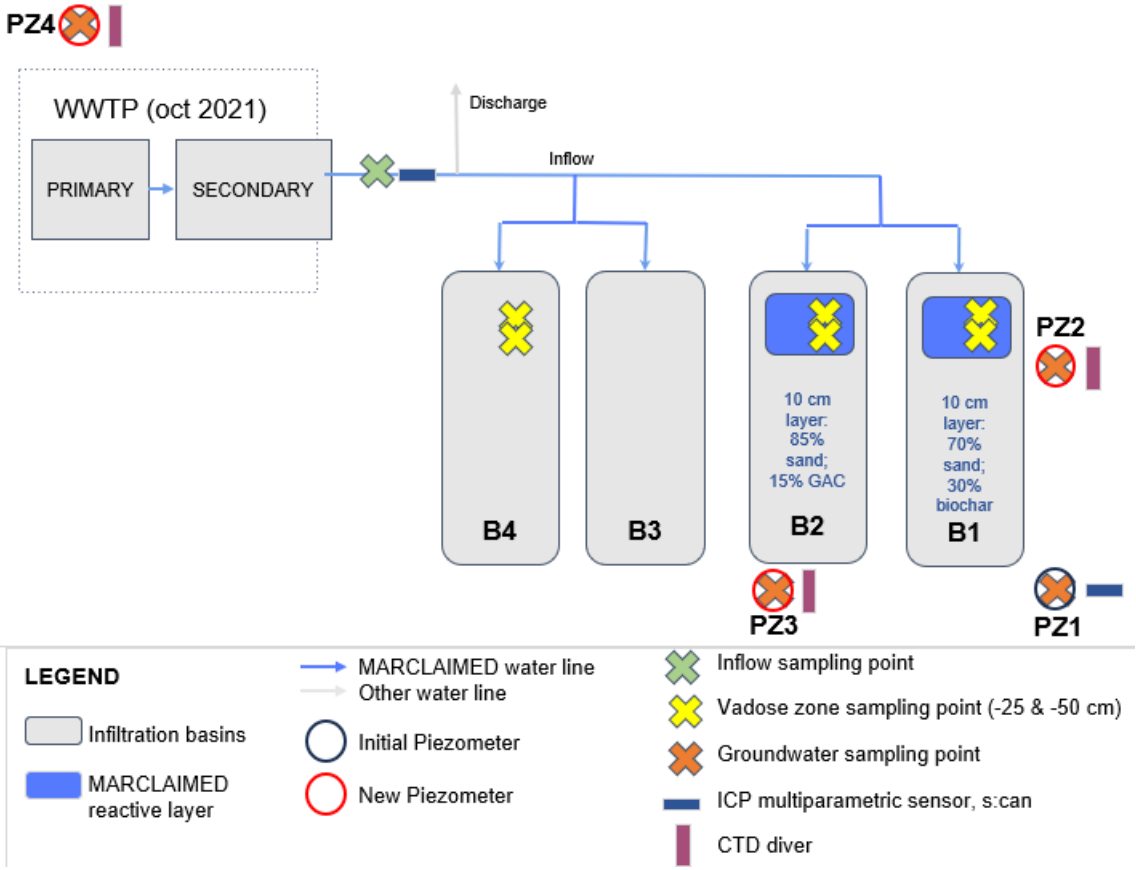

Figure 2.7 Comporta WWTP_SAT-MAR schema and current infrastructures installed under MARCLAIMED

To access the **water quality online**, the following monitoring programme was settled:

- TWW and PZ1: in July 2024, two multiparametric probes (**ICP, S::can**) were installed: one at the TWW discharge point (inflow for the basins, readings each 5 minutes) and the other in PZ1 (readings each 30 minutes). The parameters being measured are: TSS, BOD_5, COD, NO_3^-N, TOC, DOC, UV254, temperature, color, chloramine, Chl-a, turbidity, EC, ORP, pH, BTX.
- PZ1 (in December 2024) and PZ2, PZ3 & PZ4 (in July 2024): four **CTD divers** were installed for continuous monitoring of the EC, temperature, and water level depth (readings each 30 minutes), besides a temperature and depth (pressure) sensor installed at surface for atmospheric data collection.

A MARCLAIMED **water quality sampling programme** was set, consisting of the following (Table 2.1):

- TWW, B1, B2, B4 (all at 25 cm and 50 cm depth), PZ1, PZ2, PZ3 & PZ4: manual samples each three month, for two years, for the following analysis – temperature, pH, redox, DO, TOC, NO_3^-, NO_2^-, NH_4^+, N_{total}, PO_4^{3+}, P_{total}, Cl^-, Na, Ca, K, Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Li, Mg, Mo, Ni, Sb, Se, V, Zn, and a list of approx. 50 pharmaceutical compounds (PhCs) (cf. section 0).

Table 2.1 MARCLAIMED water quality sampling programme at Comporta WWTP_SAT-MAR

Sampling plan	#	Infrastructure's designation	2024		2025				2026	
			Jul	Out	Jan	Apr	Jul	Out	Jan	Apr
TWW (basin inflow)	1	TWW	x	x	x	x	x	x	x	x
Vadose zone (suction cups)	6	B1_25; B1_50; B2_25; B2_50; B4_25; B4_50	x	x	x	x	x	x	x	x
Groundwater (piezometers)	4	PZ1; PZ2; PZ3; PZ4	x	x	x	x	x	x	x	x

2.5 Data collection progress and results

2.5.1 CTD sensors and manual piezometric level analysis

The **piezometric levels** have been analysed mainly using the CTD sensors. At each visit for CTD data collection, also manual GW measurements were conducted – Table 2.2 – for which the summary statistics is presented in Table 2.3 and mapped in Figure 2.8.

Table 2.2 Manual measurements of GW depth (sorted by sampling point, date) conducted in Comporta's piezometers

Sampling point	Date, time	GW depth (m)		Sampling point	Date, time	GW depth (m)
PZ1	2024/07/04 11:08:00	6.36		PZ3	2024/07/04 11:13:00	5.91
PZ1	2024/07/17 11:08:00	6.35		PZ3	2024/07/11 10:43:00	5.88
PZ1	2024/08/20 10:15:00	6.20		PZ3	2024/07/17 11:13:00	5.87
PZ1	2024/10/03 11:25:00	6.25		PZ3	2024/08/20 12:03:00	5.73
PZ1	2024/12/21 15:26:00	6.24		PZ3	2024/10/03 11:10:00	6.08
PZ1	2025/01/09 10:10:00	6.28		PZ3	2024/10/10 10:56:00	6.03
PZ1	2025/01/16 14:10:00	6.26		PZ3	2024/12/21 15:00:00	6.14
PZ1	2025/01/23 10:40:00	6.11		PZ3	2025/01/09 10:30:00	6.11
PZ1	2025/04/16 11:48:00	5.69		PZ3	2025/01/16 10:50:00	6.20
PZ2	2024/07/04 11:09:00	6.04		PZ3	2025/01/23 11:00:00	6.09
PZ2	2024/07/11 10:23:00	5.81		PZ3	2025/04/16 10:48:00	5.34
PZ2	2024/07/17 11:09:00	5.92		PZ3	2025/04/16 12:00:00	5.40
PZ2	2024/08/20 11:51:00	5.88		PZ4	2024/07/04 11:16:00	6.00
PZ2	2024/10/03 10:50:00	6.18		PZ4	2024/07/11 10:56:00	6.00
PZ2	2024/10/10 10:50:00	5.95		PZ4	2024/07/17 11:16:00	6.00
PZ2	2025/01/09 10:30:00	6.30		PZ4	2024/08/20 12:11:00	6.03
PZ2	2025/01/16 14:08:00	6.31		PZ4	2024/10/03 10:20:00	6.13
PZ2	2025/01/23 10:44:00	6.10		PZ4	2024/10/10 11:02:00	6.15
PZ2	2025/04/16 10:07:00	5.45		PZ4	2025/01/09 10:50:00	6.25
PZ2	2025/04/16 10:41:00	5.46		PZ4	2025/01/16 14:14:00	6.22
				PZ4	2025/01/23 11:09:00	6.23

Table 2.3 Statistical summary of the manual measurements conducted in Comporta's piezometers

Sampling point	Terrain Level (m a.s.l.)	Piezom. head height	GW depth (m)			GW level (m a.s.l.)		
			Min.	Avg.	Max.	Min.	Avg.	Max.
PZ1	10.60	0.58	5.69	6.19	6.36	4.35	3.83	3.67
PZ2	10.97	0.95	5.45	5.95	6.31	4.57	4.07	3.71
PZ3	10.99	0.97	5.34	5.90	6.20	4.68	4.12	3.82
PZ4	11.00	0.99	5.50	6.00	6.25	4.51	4.01	3.76

The local groundwater flow is conducted from ESE to WNW towards the "Vala Real" irrigation channel and the sea, with higher groundwater levels recorded in PZ4 (reference piezometer) and lower levels observed in PZ2. These observations are based in ground surface levels measurements with centimetric to millimetric resolution.

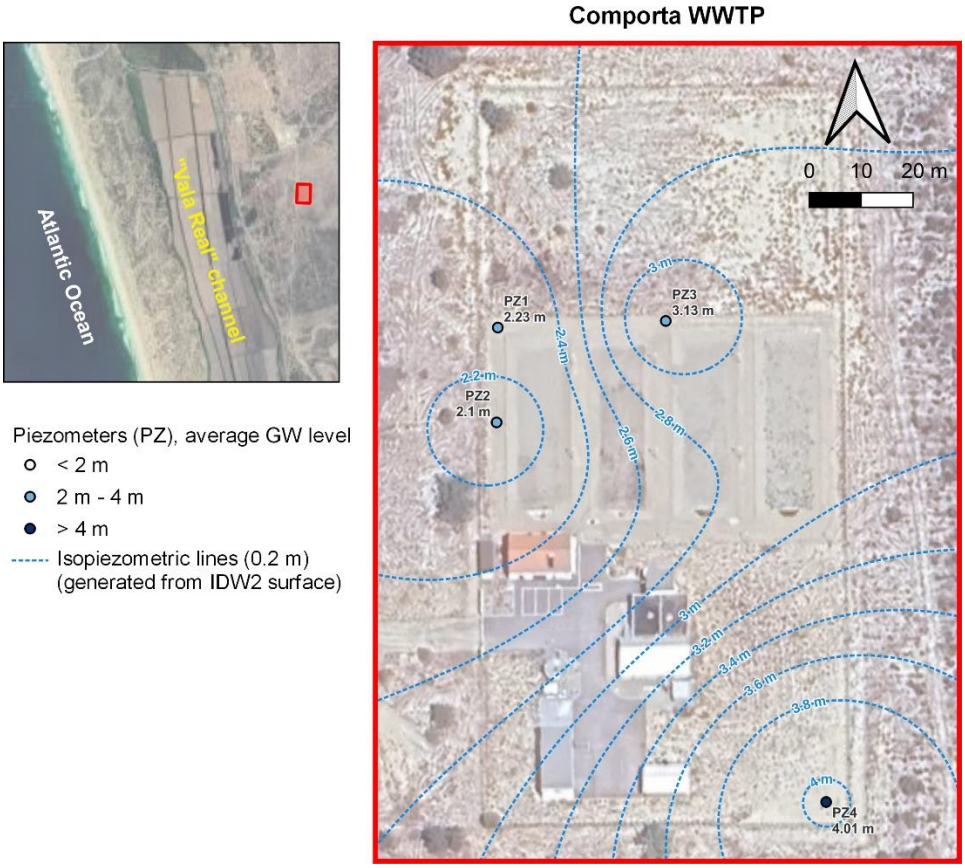

Figure 2.8 Average groundwater level distribution at the Comporta WWTP site, interpolated with IDW2

Concerning the **piezometric level variations**, a direct comparison was conducted with the (1) discharged volumes in the basins, reported by the WWTP SCADA sensors, and (2) daily rainfall records in the nearest meteorological stations (Comporta – 23E/01C and Montevil 23F/01UG from SNIRH, 2025) – presented in Figure 2.8 for PZ2, PZ3 and PZ4,. It is possible to observe the following, for the period between June 11th 2024 and April 24th 2025:

- No clear GW level response after small rainfall episodes, particularly in PZ4, but general GW level increase after major rainfall episodes (October 2024, January 2025, and altogether rainier February and March 2025).
- Clear effect of the infiltrated water in the closest piezometers' GW level (PZ2 and more noteworthy at PZ3), with decreasing GW levels after decreasing discharged volumes.
- Connection of TWW system with the pluvial water system (confirmed by AgdA) results in increased discharged volumes to the basins after rainfall episodes, which in place create localized mounding in the closest piezometers.
- PZ4 (reference piezometer) shows no response to the discharged volumes.

The slightly noticeable change of the basin discharges (retrieved from the WWTP SCADA sensors) to an increasing trend from mid-January onward pattern does not explain by itself the increase in the groundwater levels in all piezometers, strongly suggesting that natural recharge induced by the important rainfall events can be responsible for the replenishment of the aquifer.

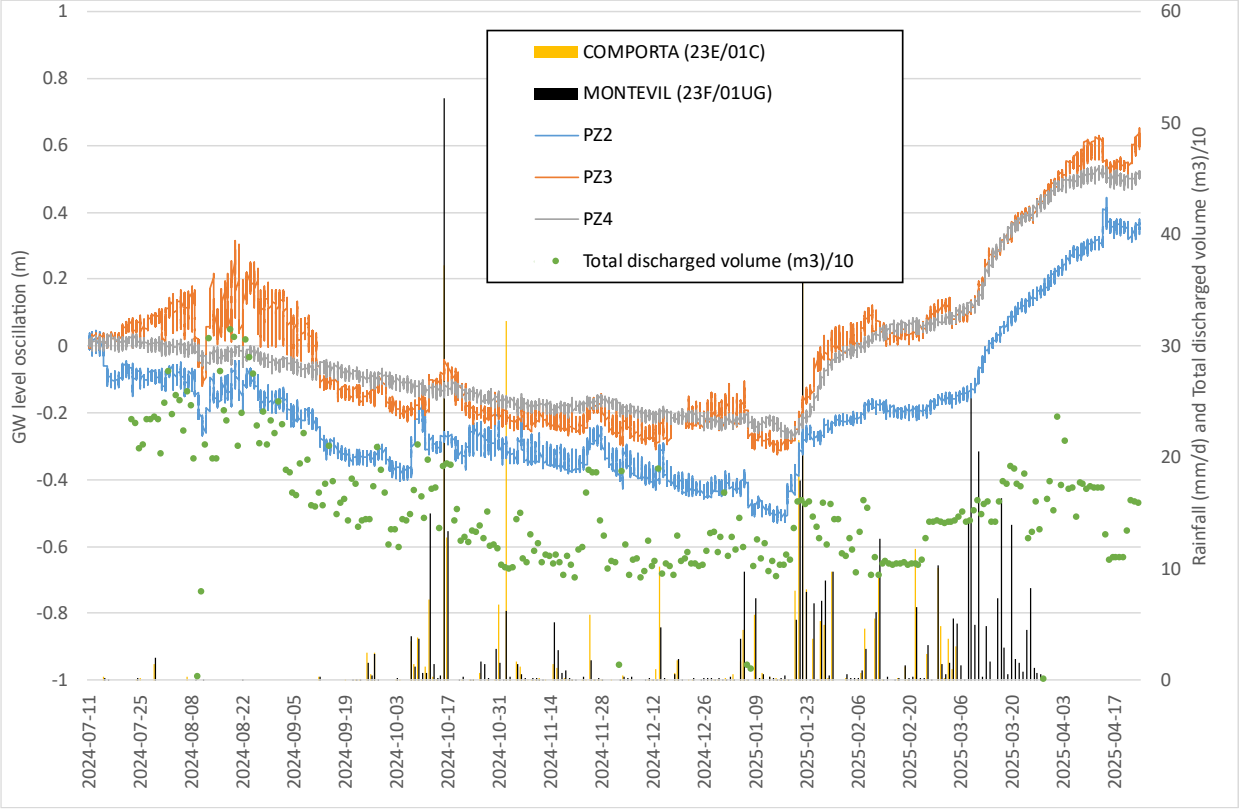

Figure 2.9 GW level oscillation (CDT divers), Rainfall (SNIRH, 2025) & TWW discharges (SCADA sensors)

Distinct thermal behaviours among the piezometers have been observed through variations in temperature alongside rainfall and discharge volume patterns, providing some key insights on the aquifer response (Figure 2.10):

- PZ3 shows high temperature variability, followed by PZ2, suggesting the influence of surface conditions, namely the infiltration from the basins.
- PZ4 follows the typical seasonal temperature variation with lower temperatures in the winter and higher temperatures in the summer. Thermal inertia is observed when comparing PZ4 temperature decrease delay in comparison with expected atmospheric temperature variations in winter.

- There is a brief response to the rainfall events in PZ3 and PZ4 with lowering of the GW temperatures after those events in the summer and the reversed effect (decrease of temperature) in the winter. This response to the rainfall events can be related also with the already referred connection of TWW system with the pluvial water system.

In summary, PZ3 is highly responsive to the temperature and prone to infiltration effects, PZ2 is moderately responsive, and PZ4 is almost non-responsive to temperature variations, showing a thermal buffer, as expected in natural conditions, with no visible effects from the infiltration basins.

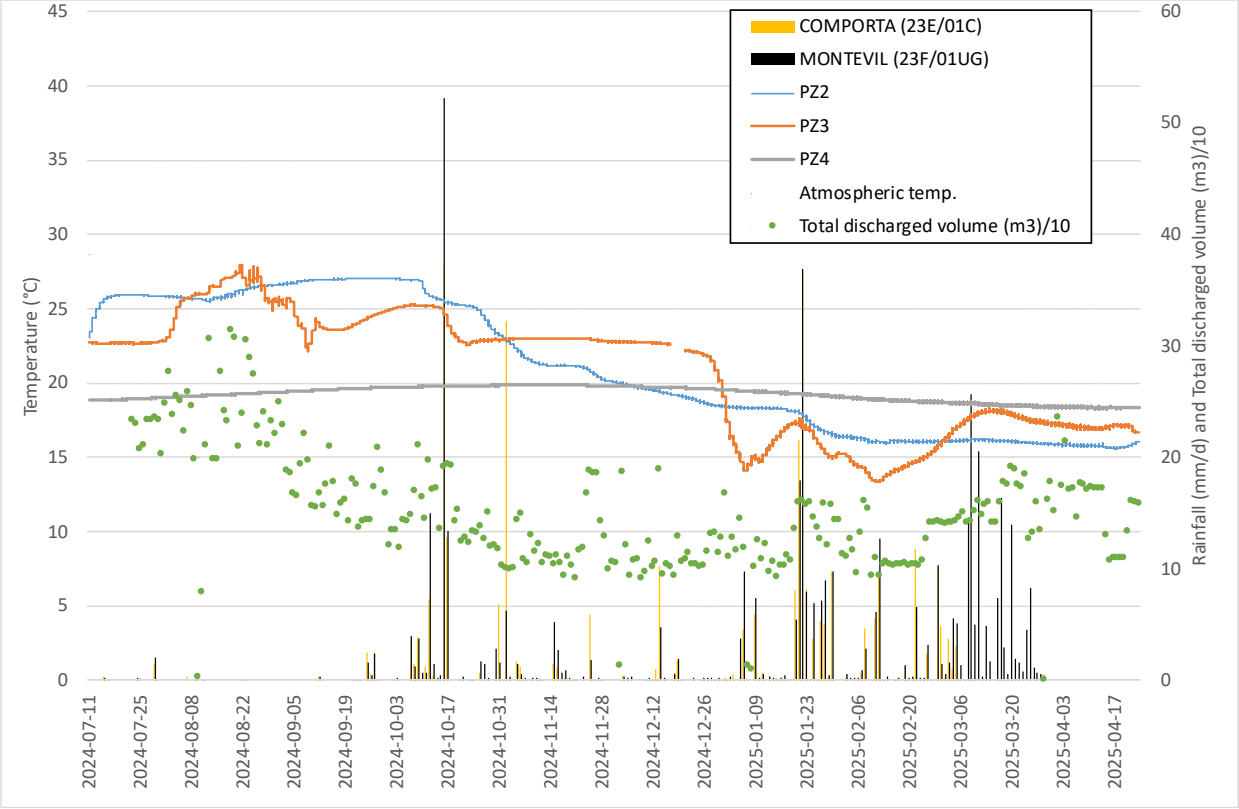

Figure 2.10 Temporal variation of groundwater temperature (CDT divers), rainfall (SNIRH, 2025), and TWW discharge (SCADA sensors)

Some of the previous observations are confirmed when analysing the EC parameter (Figure 2.11):

- PZ4 records very low (often lower 100 µS/cm) and stable EC, showing the expected infiltration basins upgradient behaviour with fresh, pristine, water.

- EC varies after intense rainfall periods, highlighting potential dilution resulting from both natural and induced recharge.
- PZ3's CTD diver showed unresponsive behaviour for this parameter between June and December 2024, resulting in replacing the sensor. For that purpose, the CE data recorded prior to December 21st 2024 is not presented.
- PZ2 shows an overall declining trend in EC values with some oscillation, particularly after November 2024.
- Although the months of February and April 2025 have several rainfall events, the potential dilution effect stopped in PZ3, showing an EC increase particularly noted in April.

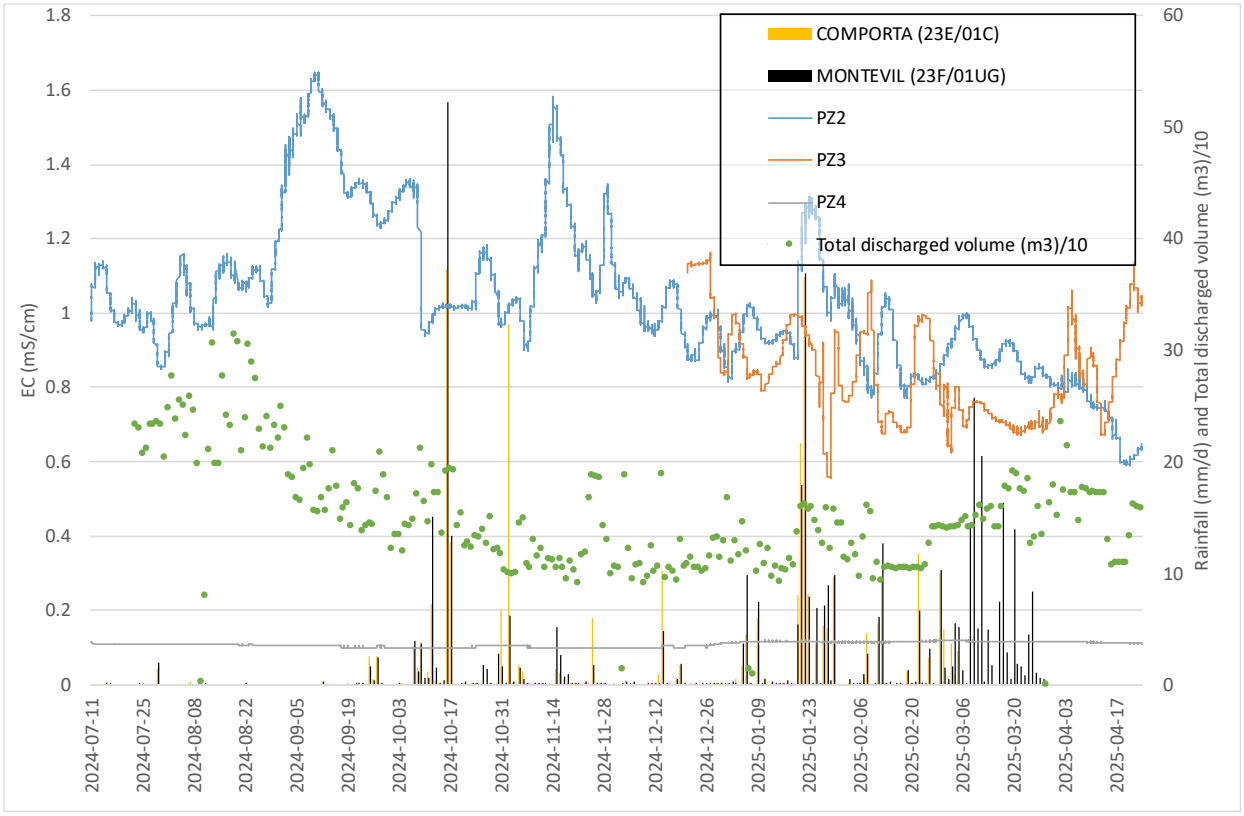

Figure 2.11 Temporal variation of groundwater electrical conductivity (EC) (CDT divers), rainfall (SNIRH, 2025), and TWW discharge (SCADA sensors) highlighting recharge-related dilution events

This information is expected to be expanded soon, as the CTD divers are still collecting data in the sites' piezometers, along with providing more insights regarding the PZ1 behaviour.

2.5.2 S::can sensors online analysis

The results presented below refer to the 10-month-long continuous monitoring of TWW (inflow) and groundwater (PZ1) using the S::can multiparametric probe parameter's results. Rainfall data from the Comporta and Montevil stations are also included (SNIRH, 2025).

As shown in Figure 2.12, the fluctuation of EC values in TWW was higher than in PZ1. Although both TWW and PZ1 exhibited similar median values (981 and 985 µS/cm, respectively), EC concentrations in PZ1 remained comparatively more stable, therefore with much lower variance over the monitoring period. A slight downward EC trend was observed for PZ1. EC values at PZ1 seem to respond to the TWW discharges into the basins, but with several days delay. EC measurements from PZ1 in past campaigns aligned with values from continuous monitoring. On the other hand, PZ1 does not show many noticeable responses to rainfall events; however, the connection of the pluvial system to the Comporta WWTP may have contributed to occasional natural dilution of the aquifer following heavy rainfall episodes.

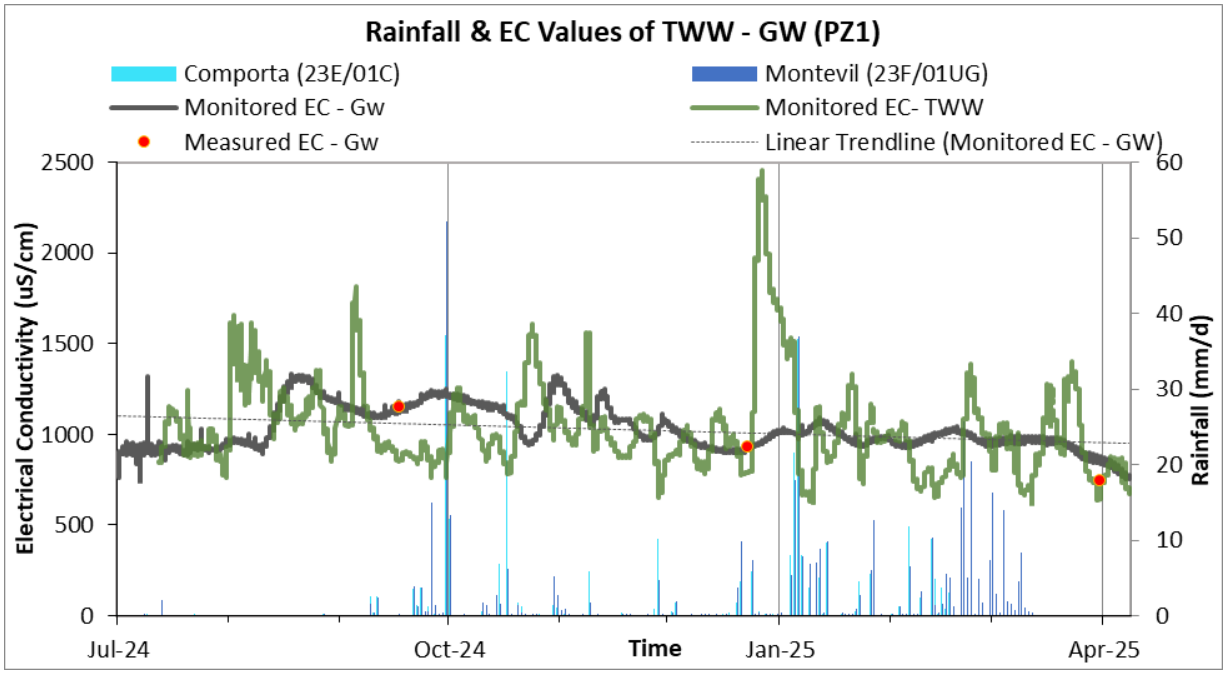

Figure 2.12 Rainfall & EC in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP. Manually measured values from previous sampling campaigns included

The median pH values for both PZ1 and TWW waters were found very similar, with 6.2 and 6.1 respectively (Figure 2.13). Compared to the relatively stable values observed in PZ1, the pH values in TWW showed higher variability and more acidic values. The stable pH in PZ1, despite high variability in TWW, suggests natural buffering by the aquifer or vadose zone soil, possibly enhanced by installed ROLs and the gravel in the infiltration basins. This slight increase in pH provided by the basins favours metals adsorption, as is further discussed in section 0. Rainfall events exhibited no observable impact on pH levels at PZ1.

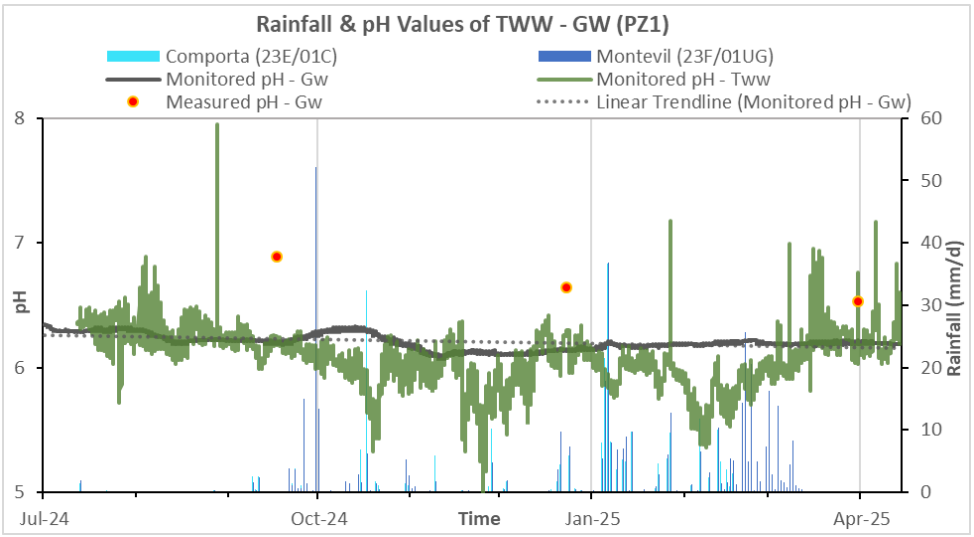

Figure 2.13 Rainfall & pH in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP. Manually measured values from previous sampling campaigns included

Figure 2.14 presents two instant decreases in ORP values (redox) of TWW that occurred in August 2024 and February 2025. A corresponding reduction in ORP values in PZ1 following the August decrease in TWW was observed. However, the second decrease in TWW ORP in February did not result in a similar reduction in PZ1 and might be due to a malfunction. The first discrepancy may reflect the oxidizing conditions of the aquifer and the vadose zone, particularly after the installation of ROLs in basins 1 and 2 in mid-September. Consequently, an increasing trend in ORP values was observed at PZ1, suggesting elevated dissolved oxygen levels and a potential reduced biological activity within the water body. The monitored ORP values showed no response to rainfall events. A significant gap was observed between the monitored and measured ORP values at PZ1. This difference may be attributed to the ORP sensor of the S::can probe, for which maintenance is planned soon.

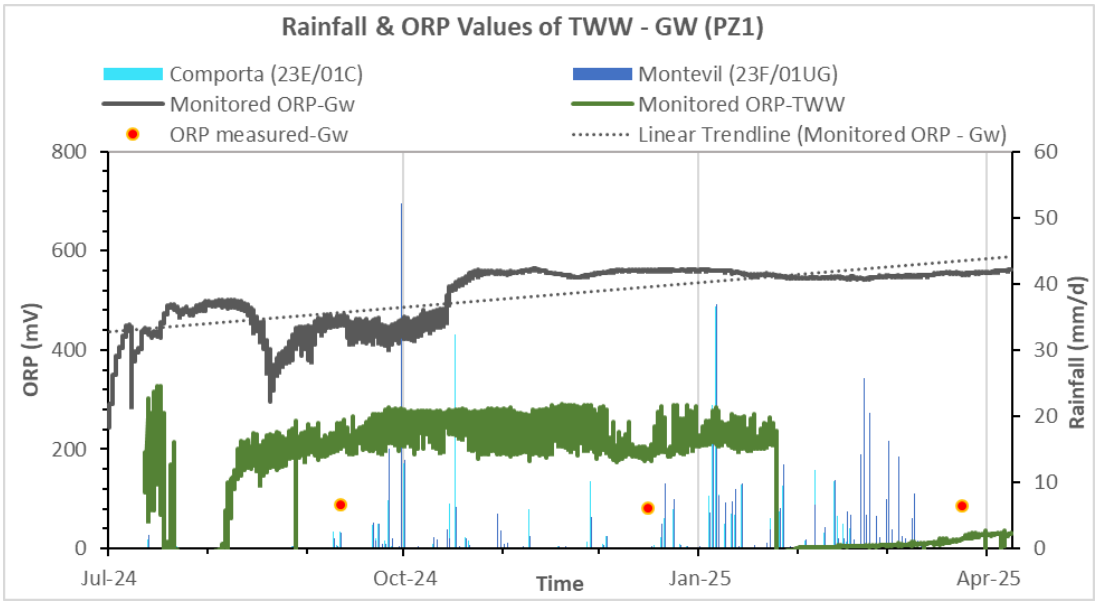

Figure 2.14 Rainfall & ORP in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP. Manually measured values from previous sampling campaigns included

TWW and GW exhibited similar DOC (Dissolved Organic Carbon) concentrations at the beginning of the monitoring period. Both datasets have very similar median values (7 and 6 mg/L), respectively. However, as indicated by the trendline in Figure 2.15, a clear decline in DOC values in PZ1 became evident starting in December 2024. The observed decline following the installation of ROLs in basin 1 and 2 suggests most of the organic carbon compounds from the TWW is being broken down and consumed by microorganisms in the vadose zone, contributing to the PhCs biodegradation (see details in section 0). Rainfall events between January and April may have contributed to TWW (infiltration water) dilution, leading to DOC reduction in GW.

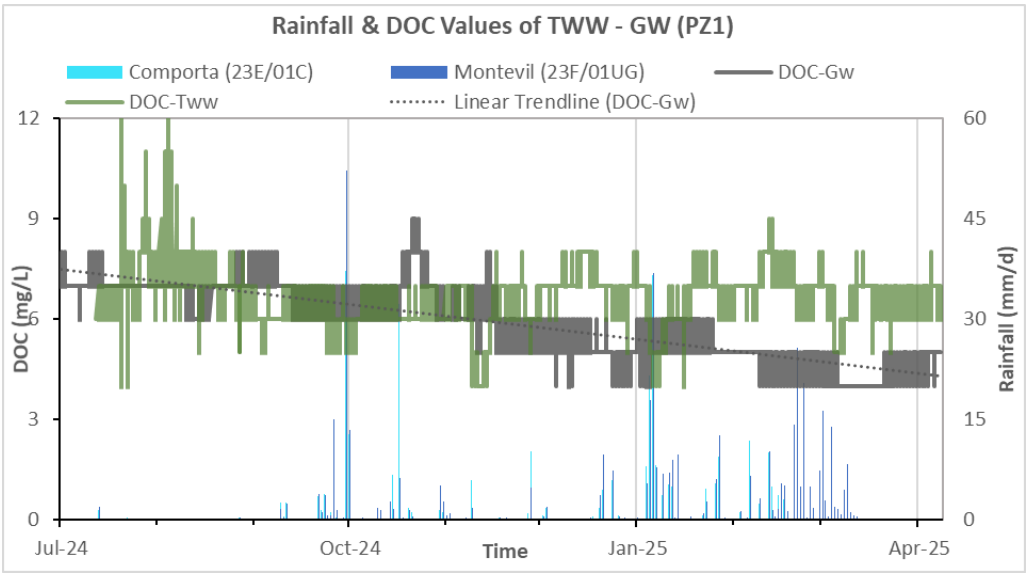

Figure 2.15 Rainfall & DOC in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP

A strong depletion of TOC was observed from TWW to GW (Figure 2.16). Despite the unstable and occasionally elevated concentrations in the TWW, the TOC level in GW remained consistently lower and exhibited a decreasing trend. The findings highlight the consistent reduction of organic carbons over time within the SAT-MAR system. The measured TOC values aligned well with continuous measurement. Only limited dilution of TWW may be expected following heavy rainfall events, such as those in January 2025.

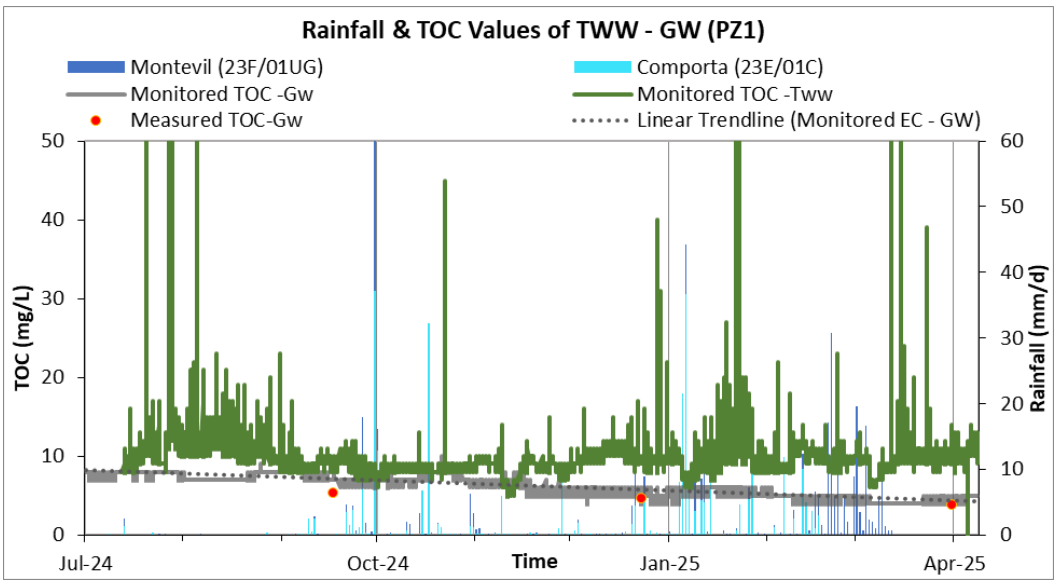

Figure 2.16 Rainfall & TOC in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP. Additionally, manually measured values included for each sampling campaign at Comporta WWTP

BOD_5 estimated values in groundwater exhibited a declining trend, whereas TWW showed greater variability, despite similar median concentrations for TWW and GW (14 mg/L and 12 mg/L, respectively). BOD_5 reduction observed in PZ1 in Figure 2.17 may indicate the removal of biologically degradable compounds (e.g., PhCs) in vadose zone. No clear impact of rainfall events was observed on BOD_5 concentrations.

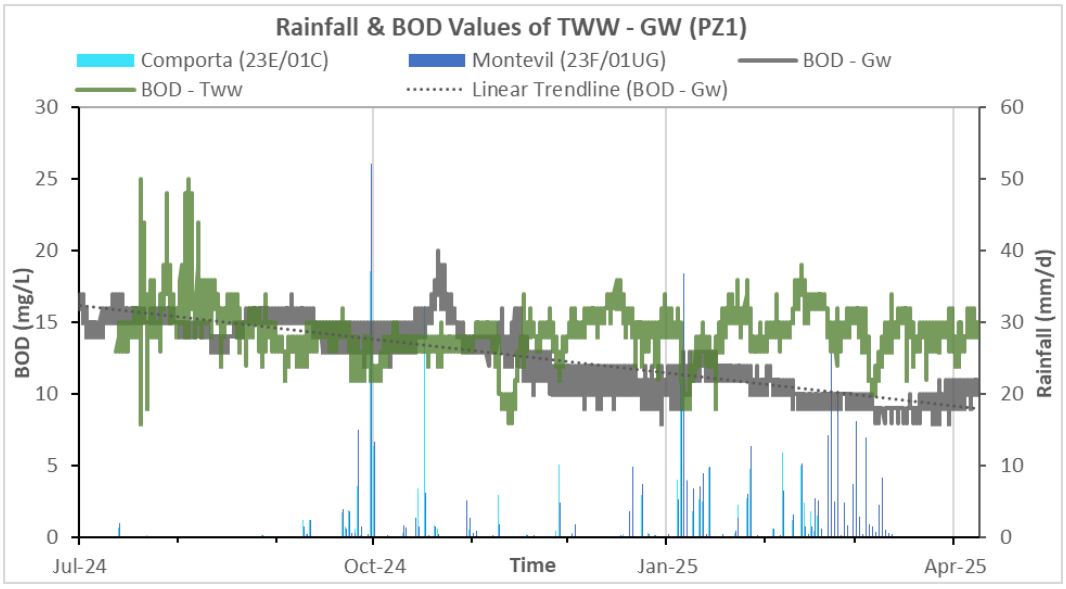

Figure 2.17 Rainfall & BOD_5 in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP

Although TWW carried elevated COD concentrations, groundwater in PZ1 showed a clear decreasing trend, maintaining relatively low and consistent COD estimated values (Figure 2.18). Seasonal changes in microbial community due to temperature may lead to reduced COD and BOD_5 estimated values in GW, when compared to the elevated levels in TWW. The lower COD concentrations observed in groundwater compared to the relatively high levels in TWW likely reflect organic matter and PhCs biodegradation during infiltration.

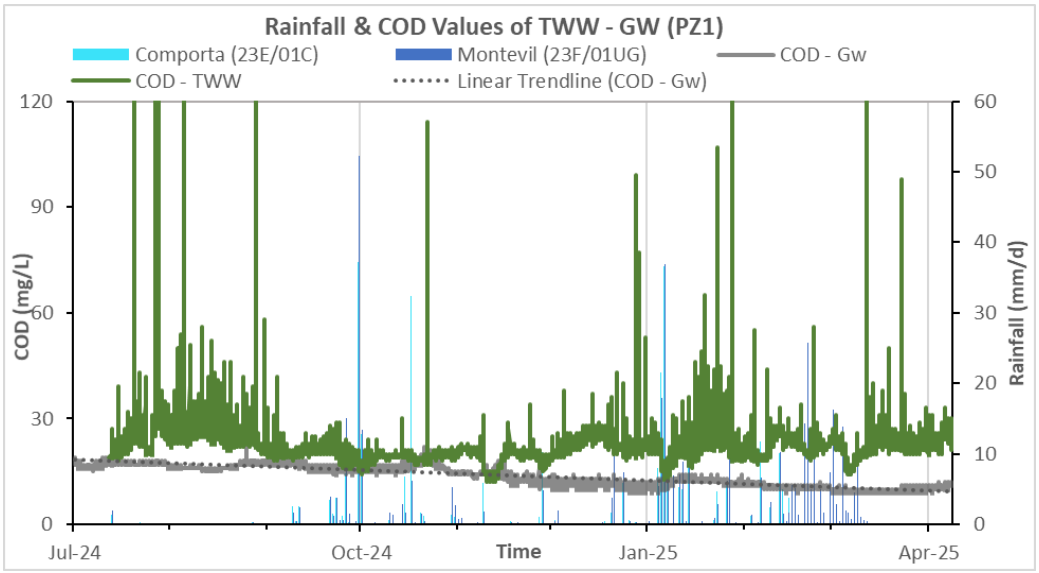

Figure 2.18 Rainfall & COD in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP

Chl-A (Chlorophyll-A) levels in TWW exhibited considerable variability and were higher than those observed in groundwater. Although Chl-A values in PZ1 were generally stable, a slight increasing trend was observed over time (Figure 2.19). The values are considered high, showing that the recharge zone is shallow, and exposed to light and nutrients.

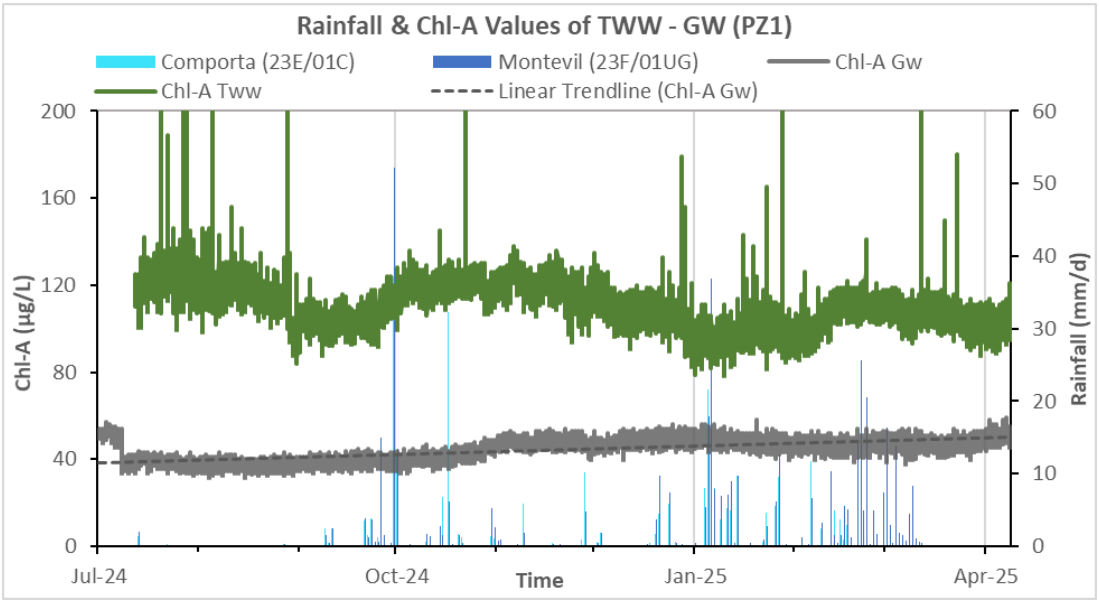

Figure 2.19 Rainfall & Chl-A in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP

TWW showed variations in the concentration of UV254 (absorbance of water at a wavelength of 254 nm, ultraviolet light) with occasional peaks. This wavelength is strongly absorbed by aromatic organic compounds (e.g., PhCs). In PZ1, a slight downward UV254 absorbance trend can be observed, where the values were found lower and consistent (Figure 2.20). A considerable strong reduction of UV254 from TWW to GW suggests effective biodegradation or adsorption of aromatic substances content, commonly associated with PhCs content in Comporta WWTP. This is consistent with the data presented in section 0. An increasing concentration difference in GW relative to TWW was observed since October. This change may indicate a positive effect of the ROLs installed in two of the infiltration basins in mid-September. Heavy rainfall effects may have contributed to a minor reduction in TWW absorbance.

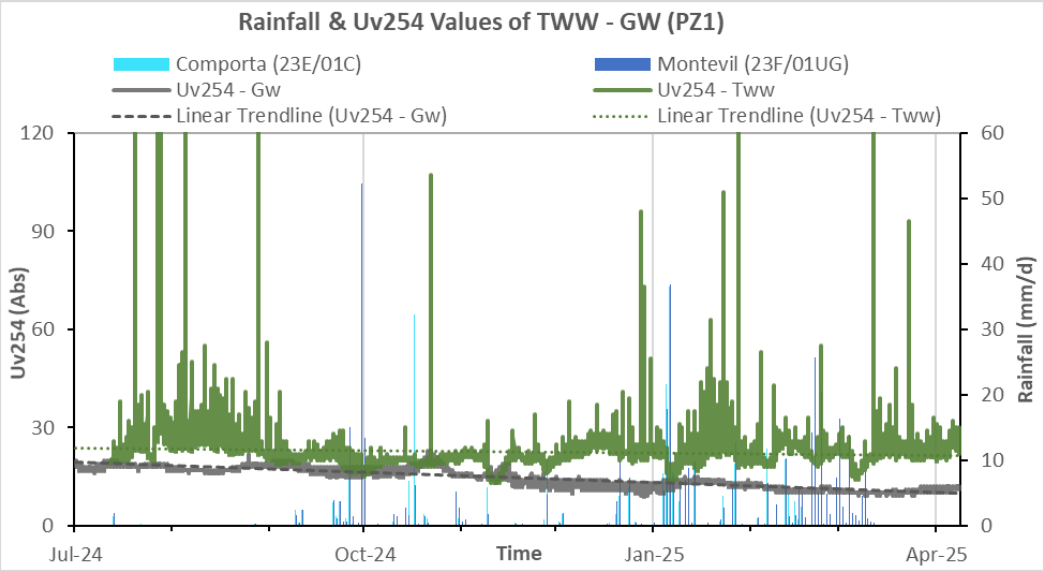

Figure 2.20 Rainfall & Uv254 in TWW and GW (PZ1) continuously monitored using the S::can probe at Comporta WWTP

In brief, a general declining trend was observed for organic matter indicators, BOD_5 and COD, and UV254, all consistent with the biodegradation, adsorption and removal of PhCs compounds. Further monitoring and risk assessment analysis will continue to ensure that environmental objectives are not compromised.

2.5.3 Laboratory analysis results

Major ions and electrical conductivity

Information about the groundwater facies is being taken monthly by AgdA since October 2021, and concerns PZ1.

Consistently with what was referred in section 2.3, a clear shift could be seen in the groundwater facies of PZ1[1] after a couple of months of the WWTP working, mainly as a result of the contribution of Cl^-, Na^+, and HCO_3^- (Figure 2.21). The EC values in the groundwater reflect mainly Cl^- and Na^+ concentrations, having also contributions from all other ion's concentrations.

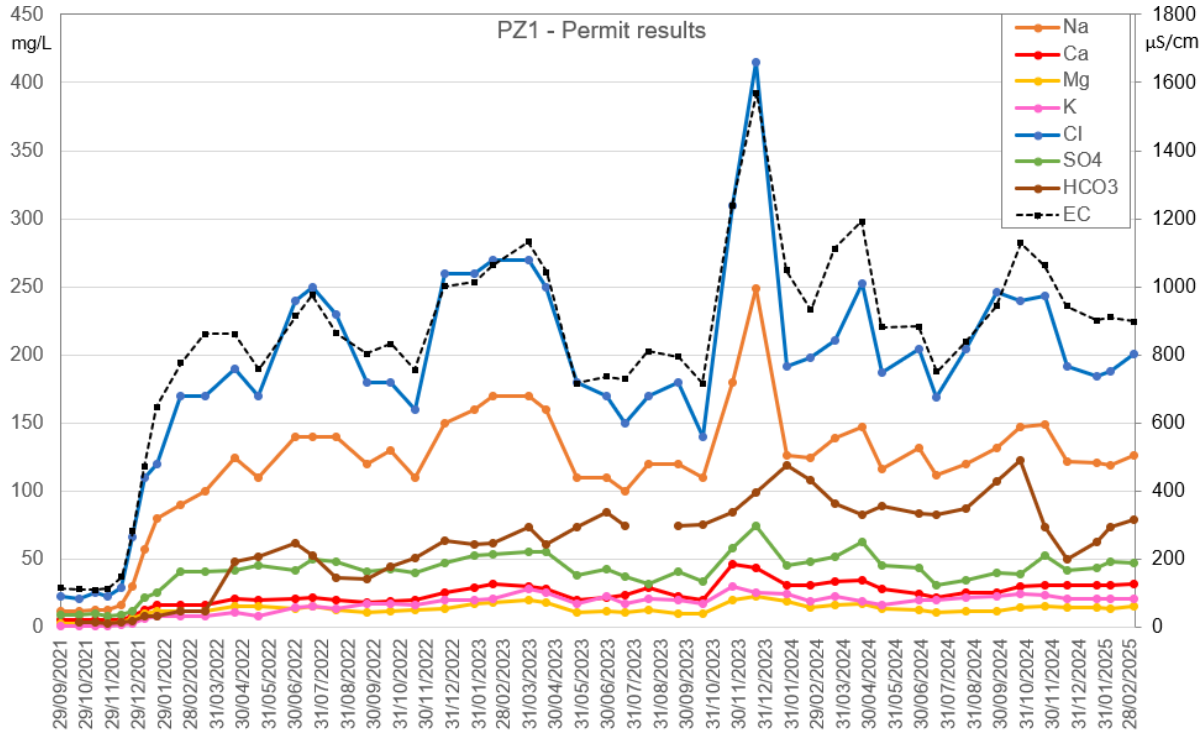

Figure 2.21 Major ions concentrations and EC values in PZ1

A Principal Components Analysis (PCA) was run to help visualizing possible relations (in a monoplot) between variables, reducing the dimensionality of the data. The results are shown in Figure 2.21.

[1] PZ1 is the only piezometer with information since 2021, considering that PZ2, PZ3 and PZ4 were only constructed by AgdA in 2024.

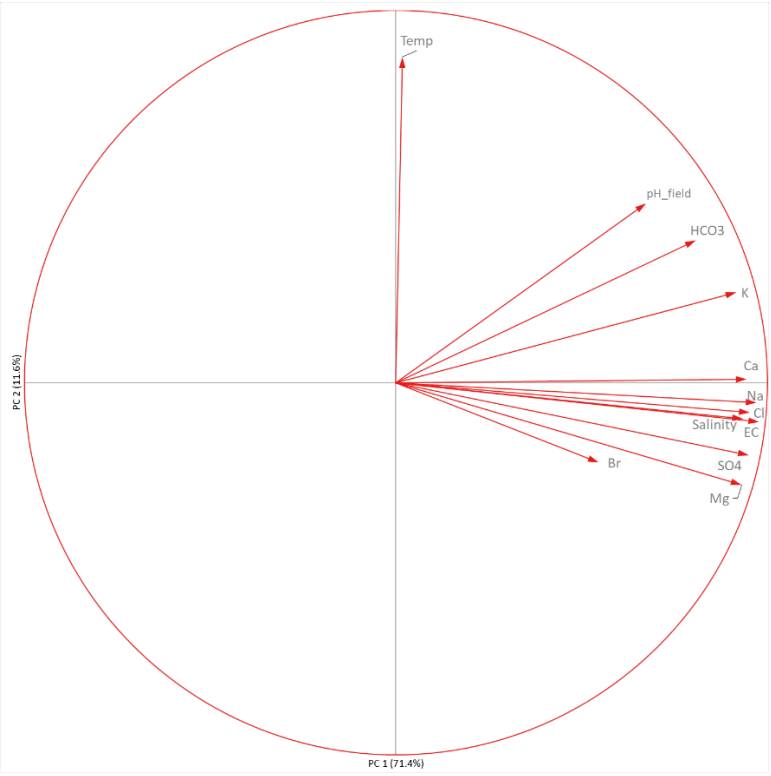

Figure 2.22 PCA analysis with the main groundwater quality characteristics at PZ1

One can see that the 1st PC explains the majority (71.4%) of the total variance of the dataset, and the second category of water samples contributing 85.7% of the variance cumulatively. The elements belonging to the same PC, with close component quadrant vectors, suggest that the variables are correlated and derive from a common origin (TWW). All variables but Br have a good representation (cf. high extension of the arrow).

After some years of operation, the major ions concentration seems stable, with some situations where chloride surpasses the maximum value allowed in groundwater (250 mg/L).

Nutrients

The results presented below refer to the first three sampling campaigns, as well as data from the s::can probes installed in the TWW and PZ1 sampling locations for continuous monitoring.

Nitrogen is released from the TWW primarily in the form of nitrate, but also as ammonia, ammonium ions, and nitrite (Figure 2.23).

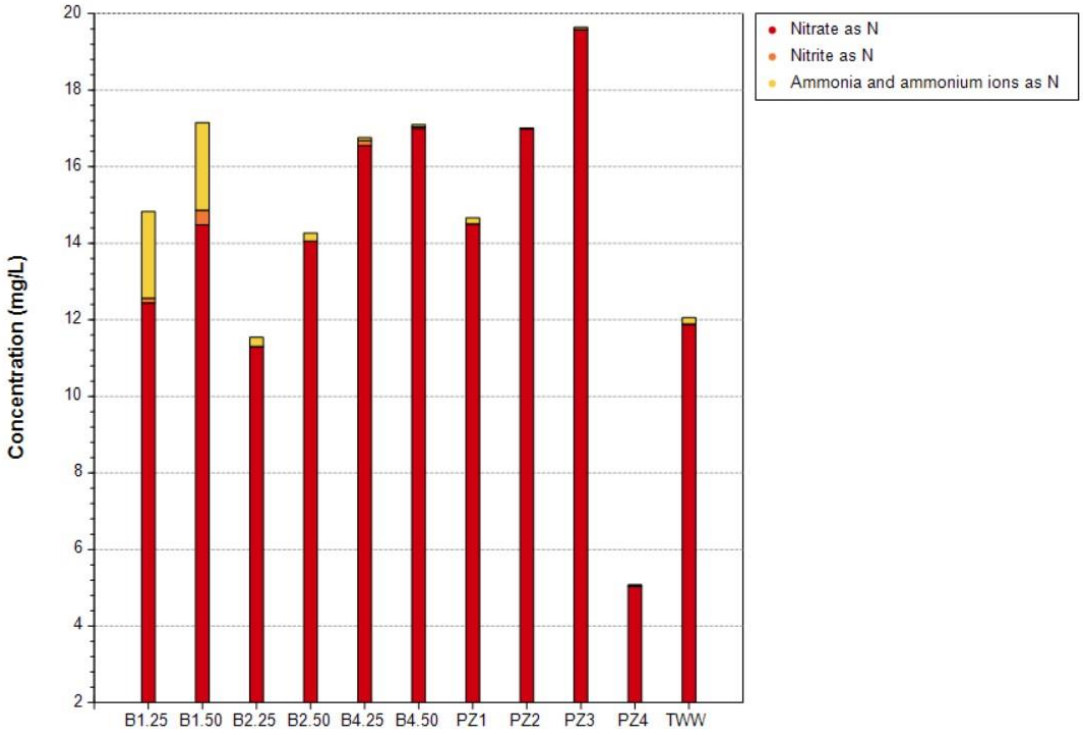

Figure 2.23 Sum of N species in the water samples at Comporta WWTP_SAT-MAR

Due to the existing aerobic conditions at the basins, microbial denitrification [that converts nitrate (NO_3^-) into nitrogen gas (N_2)] is inhibited in most of the vadose and the groundwater samples. Only Basin 1 shows signs of some nitrate reduction to ammonium ($NO_3^-+2CH_2O+2H^+ \rightarrow NH_4^+ + 2CO_2 + H_2O$). This should be possible due to a higher carbon availability provided by the biochar, when compared to the Granular Activated Carbon (GAC) existing in the Reactive Organic Layer (ROL) at Basin 2. However, nitrogen is only retained, not removed.

The concentrations of N are very high in the TWW, with values of NO_3^- surpassing 50 mg/L (threshold values for groundwater) (Figure 2.24 and Figure 2.25). Furthermore, it is likely that the secondary treated wastewater still contains some dissolved and particulate organic nitrogen. These are not measured as nitrate or ammonium initially but, during infiltration, microbes in the unsaturated zone can mineralize these forms to ammonium, which is then rapidly nitrified to nitrate under aerobic conditions. As a result, the infiltrating water can even gain mobile nitrate during passage through the basins.

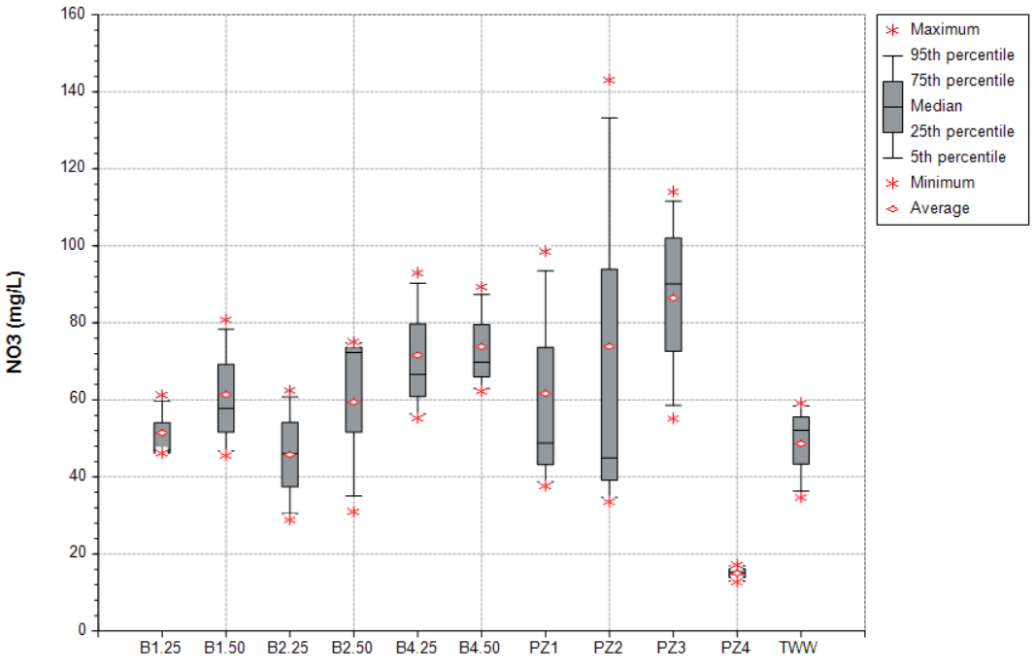

Figure 2.24 Box-plot diagram of the nitrate's concentration in the water samples at Comporta WWTP_SAT-MAR

Even considering that the N maximum content allowed for the TWW outflow is not included in the Permit, to guarantee that MAR "does not compromise the achievement of the environmental objectives established for the groundwater", it is important to consider further TWW treatment for the reduction of N content prior to enter the groundwater.

Figure 2.25 presents the continuous measurement of nitrates (as N) in TWW and PZ1, which shows clear variations through time. This might reflect periods with some problems in the WWTP.

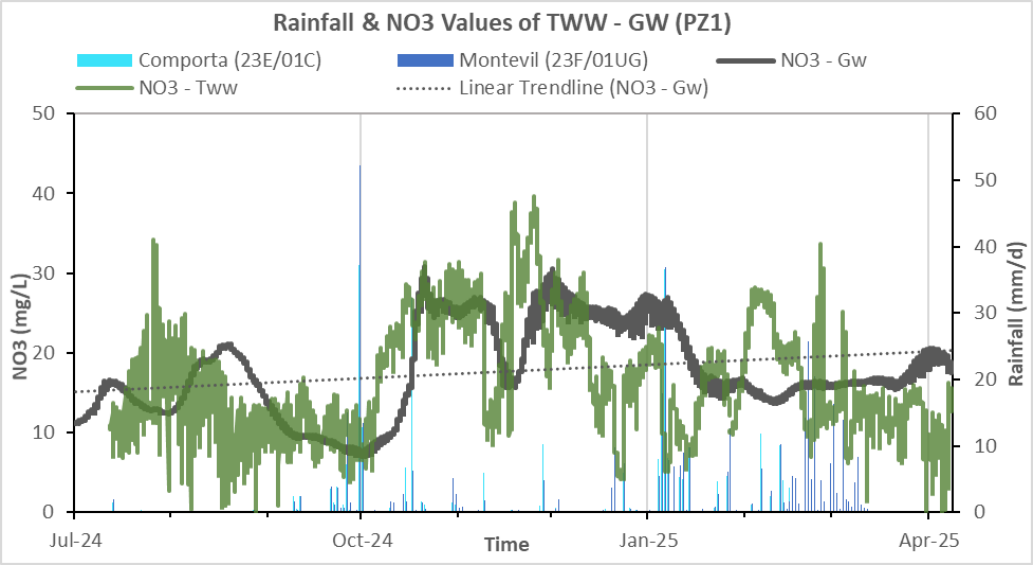

Figure 2.25 Concentration of NO3- (as N) in PZ1 measured in the S::can probe at PZ1

Concerning another major nutrient, phosphates, Figure 2.26 presents the results obtained. Considering that the threshold value in Portugal is 0.4 mg/L, this contamination represents a main concern.

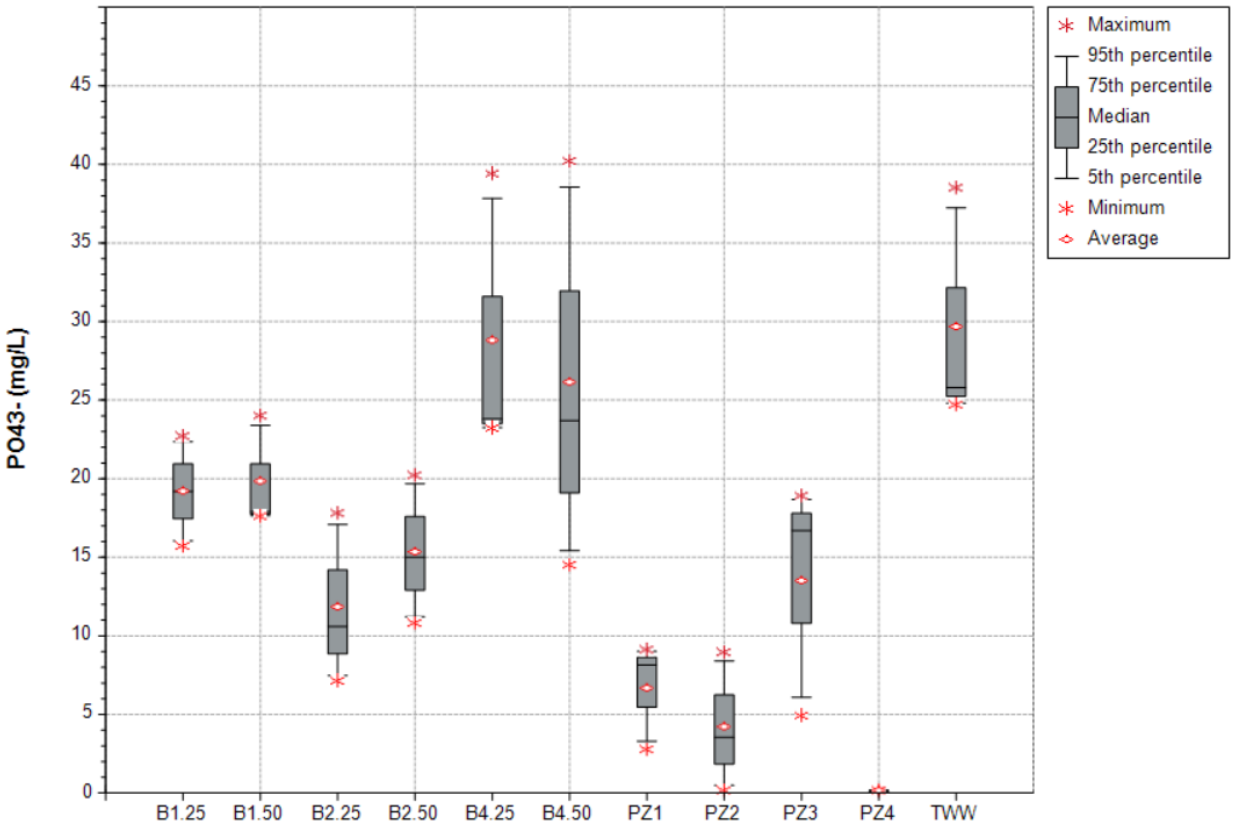

Figure 2.26 Box-plot diagram of the phosphate's concentration in the water samples at Comporta WWTP_SAT-MAR

Figure 2.26 also allows to see that B4 values are very close to the TWW ones, and that B2 presents the best removal ability. Although the groundwater concentrations are lower than those in the vadose zone - primarily due to adsorption processes - the high contaminant TWW source levels prevent effective removal. The concentrations remain well above the threshold value and are significantly higher than those observed at the reference piezometer (PZ4).

As it happens for N, to guarantee that MAR "does not compromise the achievement of the environmental objectives established for the groundwater", it is important to consider further TWW treatment for the reduction of P content prior to enter the groundwater.

Metals and metalloids

The results presented below refer to the first three MARCLAIMED sampling campaigns.

Figure 2.27 presents a first glance of the metals and metalloids water analysis results, by presenting the sum of their average concentrations (of the three campaigns so far) for the TWW, vadose zone (basins, B) and piezometers (PZs).

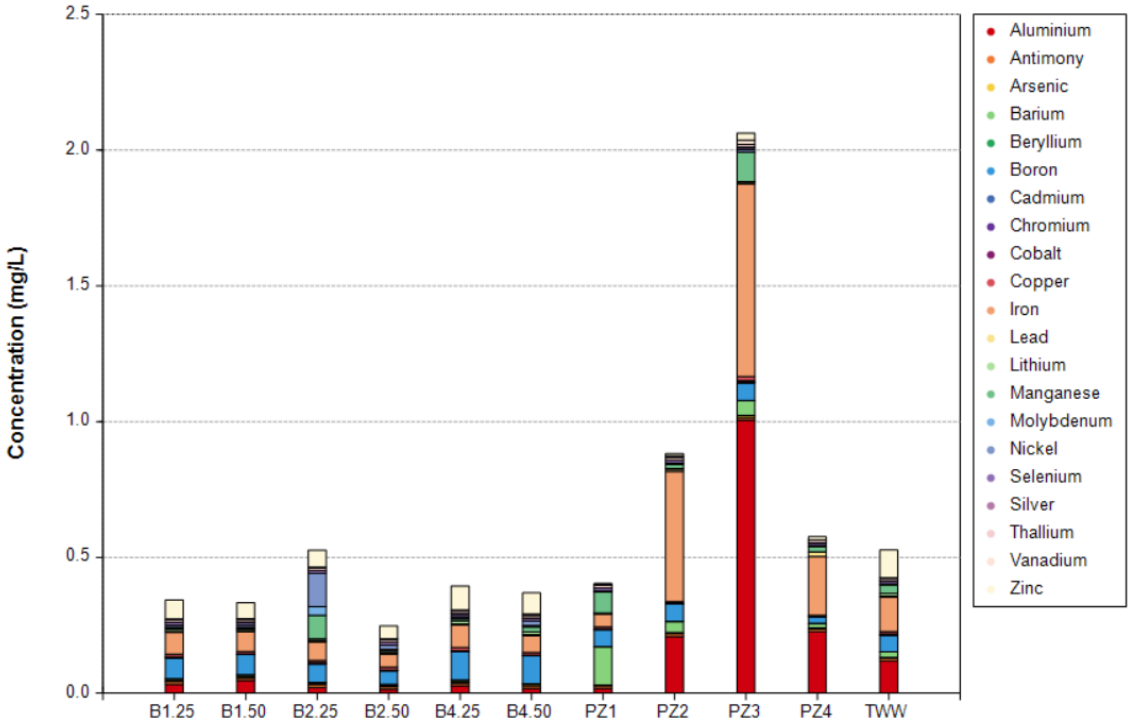

Figure 2.27 Sum of metals and metalloids in the water samples at Comporta WWTP_SAT-MAR

The piezometer's water is richer in dissolved iron and aluminium, with PZ1 showing different concentrations possibly because it is screened at different depths (12.5 – 18.4 m & 24.3 and 36 m, while the other three piezometers are screened from 7 – 10 m). The higher pH conditions in similar redox environment in the vadose zone (Figure 2.28) might also favour some metal's precipitation.

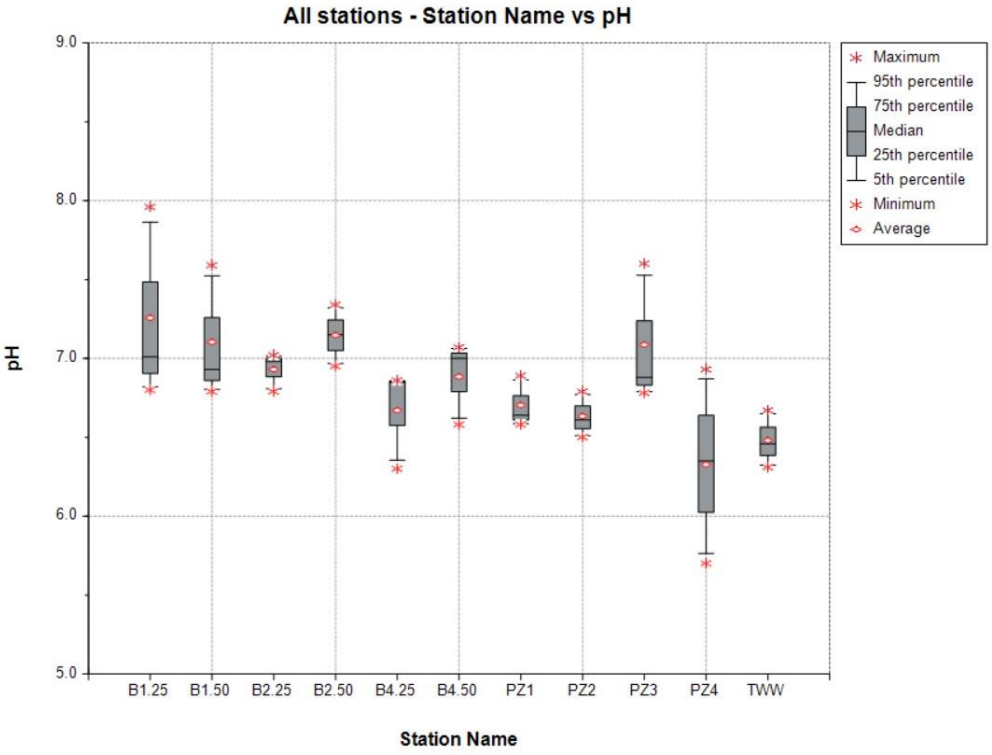

Figure 2.28 Box-plot diagram of the pH values (left) and Redox values (right) in the water samples at Comporta WWTP_SAT-MAR

Figure 2.29 presents a detection summary of the metals and metalloids with concentrations in the TWW. From the 21 parameters analysed, eight had concentrations below the Maximum Detection Limit (MDL, also referred in this report as Limit of Detection, LoD), and two had concentrations above the standard. Of the two, only zinc concentrations exceed the standards in the vadose zone, while in the groundwater, it is aluminium that exceeds the standards (Figure 2.30).

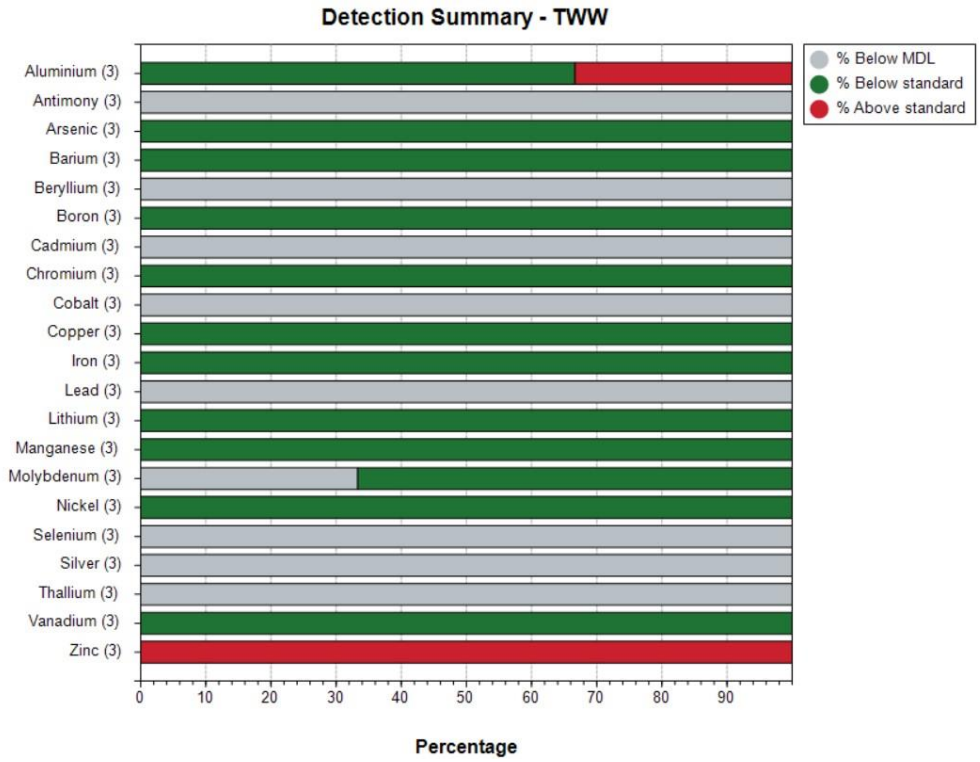

Figure 2.29 Detection summary of the metals and metalloids in the TWW samples analysed at Comporta WWTP_SAT-MAR

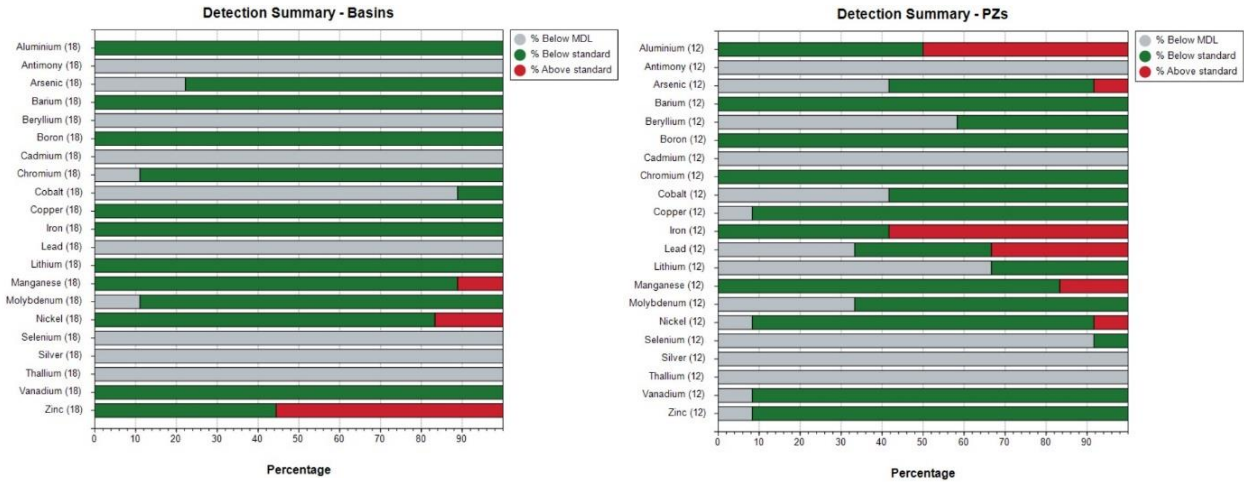

Figure 2.30 Detection summary of the metals and metalloids in the vadose zone (left) and groundwater (right) samples analysed at Comporta WWTP_SAT-MAR

While the presence of zinc in vadose zone water samples appears to be clearly influenced by the TWW (Figure 2.31), the presence of aluminium and iron in the groundwater (Figure

2.32) is likely due to water percolation and the longer residence time in the sandy aquifer, which contains some clay. Similar graphics could be seen for lead (not presented here).

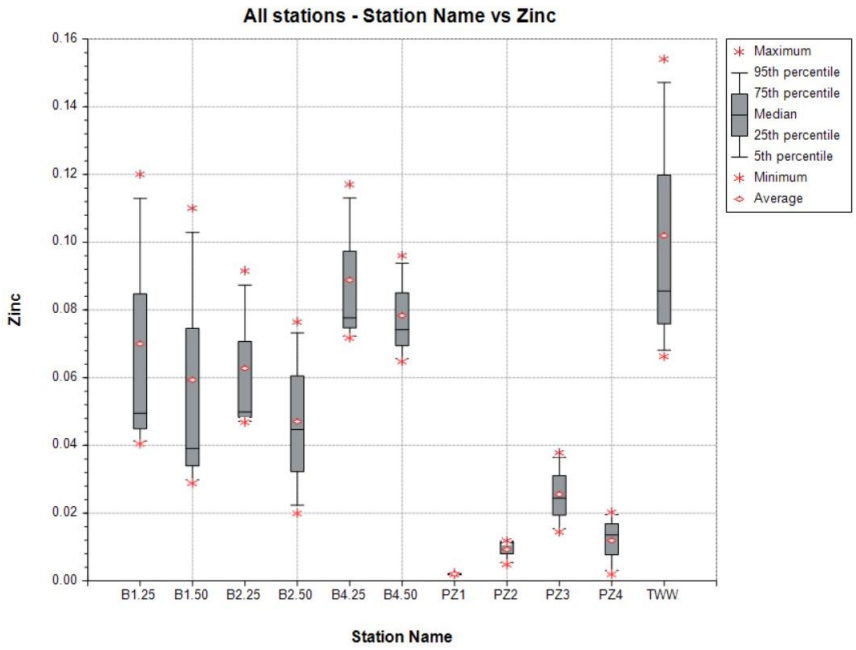

Figure 2.31 Box-plot diagram of the zinc concentrations in the water samples at Comporta WWTP_SAT-MAR

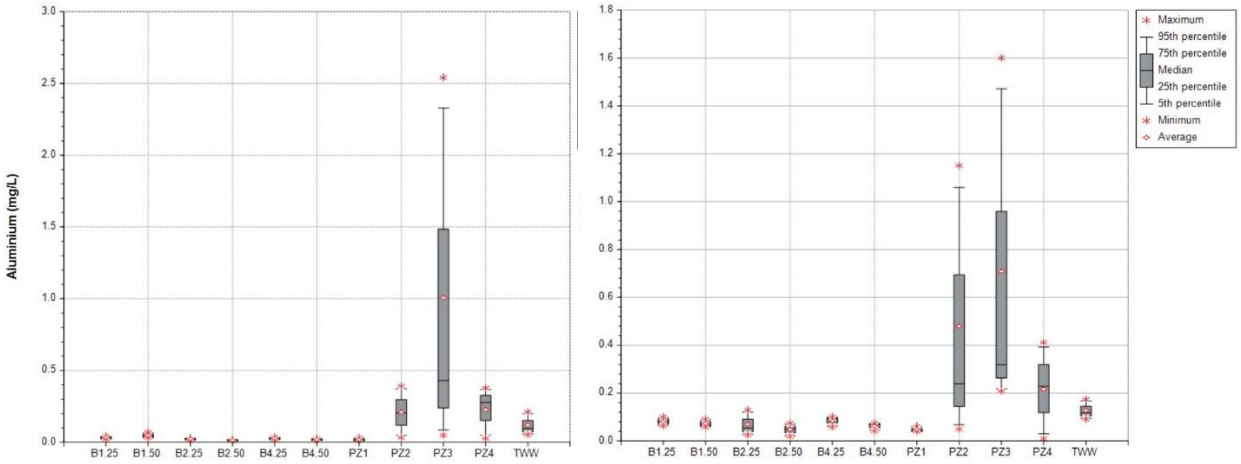

Figure 2.32 Box-plot diagram of the aluminium (left) and iron (right) concentrations in the water samples at Comporta WWTP_SAT-MAR

In summary, none of the metals or metalloids present in the TWW appear to contribute to concentrations exceeding regulatory limits in the receiving groundwater body. The physico-chemical conditions provided by the SAT-MAR system seem to favour precipitation rather

that metals or metalloids mobilization. Further analysis will be conducted following the results from the next five sampling periods.

Pharmaceutical compounds

The results presented below refer to the first three sampling campaigns.

A total of 55 pharmaceutical compounds (PhCs)[2] were analysed in the water samples collected at the Comporta WWTP SAT-MAR facility. They were selected based on the characteristics of the TWW and to cover different physicochemical properties of the PhCs, as these factors indicate their expected behaviour in terms of sorption or biodegradation.

According to the laboratory analysis results, only 16 PhCs were detected above their Limit of Quantification (LoQ) in, at least, one campaign. Therefore, there are 39 PhCs that were not detected above their LoQ. A spatial and temporal visualization of the PhCs concentrations, measured in the 11 sampling points, can be seen in Figure 2.33 for each of the three sampling campaigns. Except for sulfamethoxazole (1 µg/L represent contamination), the same classes of concentrations have been chosen, where above 2.5 µg/L values represent contamination.

[2]Anastrozole, Atenolol, Azathioprine, Bezafibrate, Buprenorphine, Butorphanol, Caffeine, Capecitabine, Carbamazepine, Chloramphenicol, Citalopram, Ciprofloxacin, Clofibric Acid, Cyclobenzaprine, Cyclophosphamide, Diazepam, Diclofenac, Enalapril, Fluoxetine, Flutamide, Furosemide, Gabapentin, Gemfibrozil, Hydrochlorothiazide, Ifosfamide, Indomethacin, Iohexol, Iomeprol, Iopamidol, Iopromide, Ketoprofen, Lincomycin, Loperamide, Metoprolol, Metronidazole, Mycophenolate Mofetil, Naproxen, Oxazepam, Paclitaxel, Paracetamol (Acetaminophen), Piroxicam, Propranolol, Salbutamol, Sertraline, Sotalol, Sulfamethazine, Sulfamethoxazole, Terbutaline, Thebain, Tramadol, Trimethoprim, Valsartan, Warfarin, and Zolpidem.

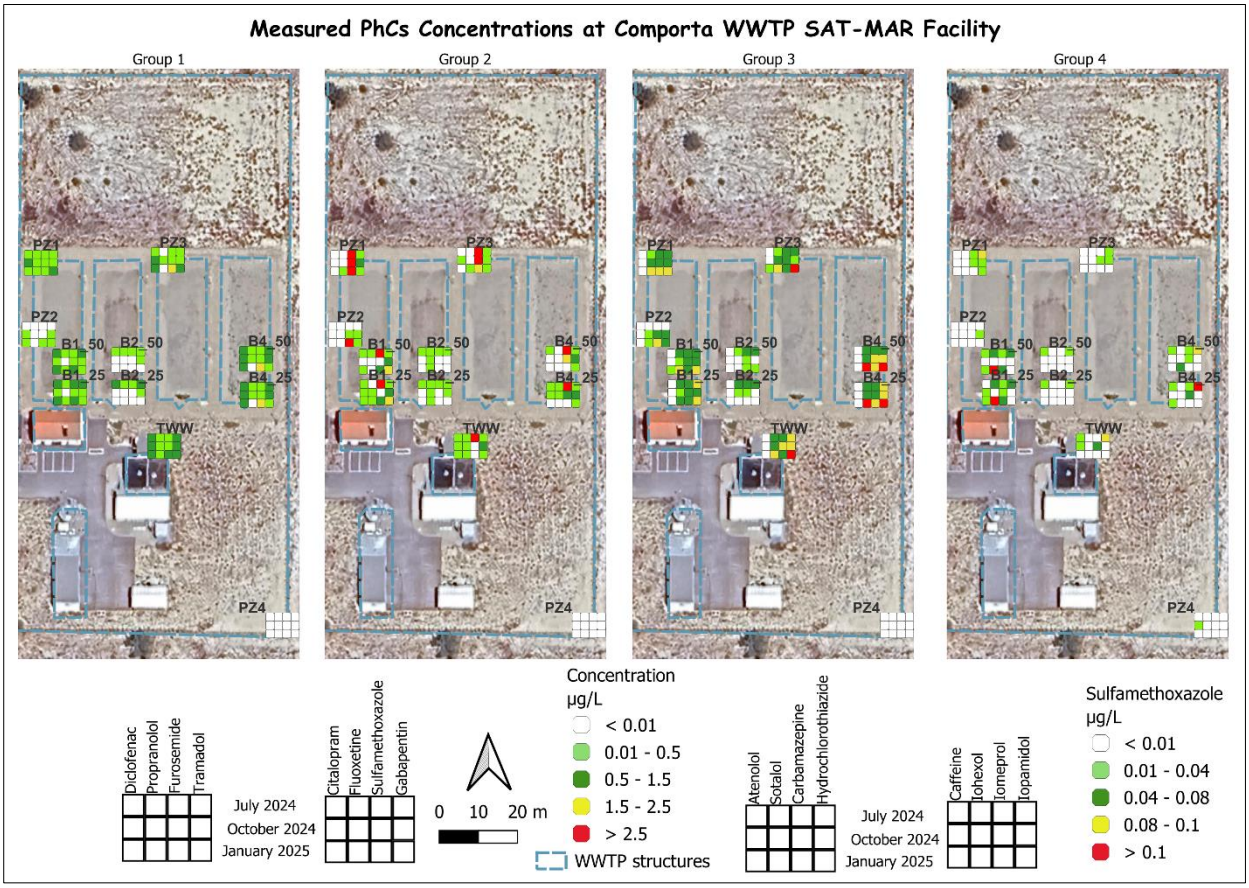

Figure 2.33 Measured Pharmaceutical Compounds (PhCs) concentrations in each sampling point for 3 Different Sampling Campaigns at Comporta WWTP SAT-MAR Facility

Only Sulfamethoxazole and Hydrochlorothiazide, from the 55 PhCs analysed, have shown concentrations above the contamination target value considered (1.0 µg/L and 2.5 µg/L), in all the three compartments (TWW, vadose zone, and groundwater), at least once. Sotalol, Iohexol and Iopamidol have also appeared above target once, but only in the vadose zone.

To better understand the fate of the PhCs analysed, Table 2.4 presents the main physico-chemical properties of the PhCs detected at Comporta. Together with their drug categories and LoQ, the following properties are presented: acid dissociation constant (pKa), n-octanol/water partition coefficient (logKow), organic carbon partition coefficient (Koc), and n-octanol/water distribution coefficient (logD).

Table 2.4 Categories, LoQ values and relevant physicochemical parameters with coloured indicators of the measured PhCs in Comporta WWTP SAT-MAR Facility

Group	Pharmarceutical	Category	LoQ (µg/L)	pK_a *	$logK_{ow}$	K_{oc}	LogD
1	Diclofenac	Analgesic	0.01	4 [a]	4.26 [b]	53.7 [b]	1.37 [b]
	Propranolol	Cardiovascular/ β-blocker	0.01	9.42 [d]	3.48 [d]	-	-
	Furosemide	Blood-vessel dilator	0.01	4.25 [e]	2.03 [c]	302 [f]	-0.94 [e]
	Tramadol	Analgesic	0.01	9.23 [e]	3.01 [c]	616 [c]	0.24 [e]
2	Citalopram	Antidepressive	0.01	9.8 [e]	1.39 [c]	427000 [c]	1.14 [e]
	Fluoxetine	Antidepressive	0.01	10.05 [g]	3.93 [g]	-	1.15 [g]
	Sulfamethoxazole	Antibiotic	0.01	6.16 [b]	0.79 [b]	72 [f]	0.14 [b]
	Gabapentin	Antiepileptic	0.01	4.63 [b]	-1.1 [c]	53 [c]	-1.27 [b]
3	Atenolol	Cardiovascular/ β-blocker	0.01	9.67 [b]	0.43 [b]	0.81 [b]	-2.14 [b]
	Sotalol	Cardiovascular/ β-blocker	0.01	8.2 [h]	0.2 [h]	0.02 [h]	-2.6 [h]
	Carbamazepine	Antiepileptic	0.01	13.9 [h]	2.45 [h]	510 [c]	2.4 [h]
	Hydrochlorothiazide	Cardiovascular	0.01	9.09 [b]	-0.58 [b]	5.25 [b]	-0.58 [b]
4	Caffeine	Stimulant	0.01	14 [c]	0.16 [i]	71 [c]	-0.63 [i]
	Iohexol	Contrast media (ICM)	0.03	11.73 [b]	-1.95 [b]	1.02 [b]	-1.95 [b]
	Iomeprol	Contrast media (ICM)	0.03	11.73 [b]	-1.45 [b]	1.86 [b]	-1.45 [b]
	Iopamidol	Contrast media (ICM)	0.03	11 [b]	-0.74 [b]	4.37 [b]	-0.74 [b]

* pKa values in pH≈ 7 environment

"-" in the data table indicates no data.

References: [a]Richard et al. (2024), [b]Sallwey et al. (2020), [c]PubChem NIH (2025), [d]Barbieri et al. (2012), [e]Hermes et al. (2019), [f]He et al. (2016), [g]Schaffer et al., (2015), [h]Ternes et al. (2007), [i]Alidina et al. (2014),

In short, a compound with low pKa value corresponds to a strong acid with a higher ionization potential, being more likely to be biodegraded. Typical values range between –10 and +50. Higher logKow value of a compound implies a higher adsorption affinity to the soil organic matter (SOM) or to the sediment due to the low affinity for water (hydrophobicity), and typical ranges vary between 0 and 6.5. A low Koc value reflects a compound that is more likely to be mobile in the soil and unlikely to be adsorbed to the SOM, therefore having higher mobility and bioaccumulation potential. Finally, logD is a measure of a compound's distribution between a lipophilic (e.g., octanol) and aqueous phase at a specific pH. A higher logD value indicates increased lipophilicity, while a lower value suggests greater hydrophilicity.

Based on the criteria described above, green, yellow, and red colours were assigned to the physicochemical parameters of each PhCs to indicate high, moderate, and low likelihood of adsorption or biodegradation, respectively (Table 2.4). This classification was deployed to the PhCs characteristics and aimed to understand the relevant PhCs primary attenuation and/or removal mechanisms as well as their environmental fate in the SAT-MAR system. So, the measured PhCs were clustered into the four groups shown in Figure 2.33, according to their pKa and logKow values, where the transition from group 1 to group 4 implies good biodegradation potential / adsorption tendency to very poor biodegradation potential / adsorption tendency, respectively.

Besides the objective of analysing if PhCs with similar properties behave in an equivalent fate, another objective was to evaluate whether compounds with similar characteristics exhibit comparable behaviour in terms of environmental fate, particularly within the vadose zone, where the SAT-MAR system is influenced by the presence of different reactive organic layers (ROLs), placed in mid-September 2024, in two of the four infiltration basins (cf. section 2.4).

Group 1

In the TWW, all PhCs have shown concentrations between 0.01 and 1.5 µg/L, with similar values among the three campaigns, i.e., very consistent source values.

In the basins, it is possible to see that PhCs are more effectively removed in B2 compared to B1 and B4. In fact, for similar TWW concentrations, the measured concentration in both B2_25 and B2_50 during the July 2024 sampling campaign and the subsequent two campaigns clearly demonstrate the efficacy of the contaminant attenuation capacity of the Granular Activated Carbon (GAC) reactive organic layer (ROL), which was installed between the first and second campaigns. This improvement is not so clear for B1, and for B4 one can see that results are similar among campaigns (no improvement since there is no ROL). Besides, in some situations on B1 and B2, improvements can be seen from -25 cm samples (B1_25 and B2_25) when compared to the -50 cm depth (B1_50 and B2_50), the latter exhibiting slightly lower concentrations due to further treatment during infiltration. The conventional infiltration B4 exhibited no notable concentration reduction in vadose zone compared to the enhanced SAT-MAR infiltration at B2 and B1.

The reference piezometer (PZ4) showed no detectable PhCs concentrations across the three campaigns, as expected. PZ1 and PZ2 exhibited PhCs concentrations ranging from < 0.01 µg/L to 1.5 µg/L. PZ3 showed moderately high concentration, 2.34 µg/L for Furosemide in one of the campaigns, like the concentrations observed in B4_25 and B4_50 for that same campaign.

As expected, based on the properties of Group 1 PhCs, they can be retained within the basins, with retention performance enhanced by the addition of a suitable reactive organic layer (ROL).

Group 2

As for Group 1, also in Group 2 the PhCs concentrations in the TWW have shown similar values among campaigns, ranging between < 0.01 µg/L to 1.5 µg/L, except for sulfamethoxazole showing higher values in one of the campaigns. Sulfamethoxazole is an antibiotic.

In the basins, the additional GAC ROL in B2 showed significant removal capacity for several PhCs, namely sulfamethoxazole (cf. Figure 2.33). However, no significant attenuation was observed for sulfamethoxazole in the other basins. Besides, in some occasions it is possible to observe the decrease in PhCs concentrations from -25 cm and – 50 cm samples, but the opposite also happens in B4.

Sulfamethoxazole more persistent behaviour in aquatic environment can be seen in

Figure 2.34, particularly as it exhibits higher concentrations in the piezometers with a wider range quantities, indicating the compound's mobility and recalcitrance in SAT-MAR systems. It exhibited high concentrations at some period in all piezometers except PZ4 (the reference one). These findings are consistent with literature, where sulfamethoxazole's persistent behaviour and high mobility is also reported by Schaffer *et al*. (2015) in plain sand column test whereas the oxic conditions, hydraulic retention time, SOM are reported to enhance the compound's attenuation (He *et al*., 2016; Schaffer *et al*., 2015; Hernández *et al*., 2012). Furthermore, it is among the most common pharmaceutical residues detected in groundwater (Schaffer *et al*., 2015). This highlights the compound's logKow and moderate Koc values, indicating negligible adsorption potential, high mobility, and a hydrophilic behaviour. Nevertheless, its low pKa value shows that there is some biodegradability ability, which was achieved for B2 conditions.

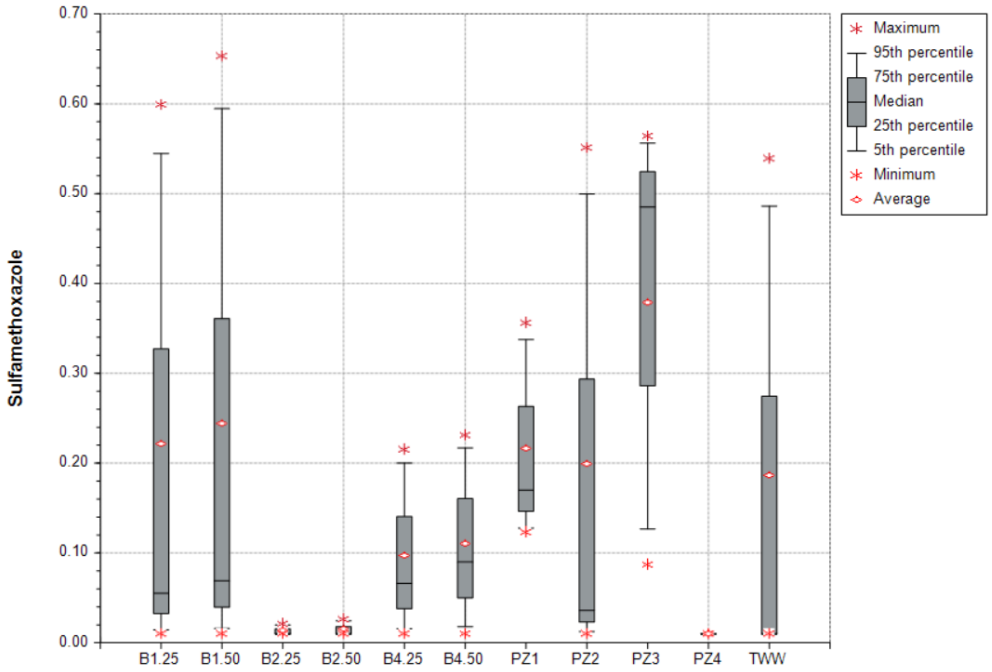

Figure 2.34 Box-plot diagram of the Sulfamethoxazole concentrations in the water samples at Comporta WWTP_SAT-MAR

PhCs concentration ranges are similar between the TWW and the conventional infiltration B4, with no organic barrier. This finding indicates limited attenuation and/or removal capacity in B4.

Group 3

Atenolol exhibited no concentrations higher than the LoQ across the three sampling campaigns in the TWW, and therefore most of the remaining samples, as the compound's biodegradability can be enhanced by oxidation-coagulation in the secondary treatment process for the wastewater (cf. Park and Lee, 2018). However, sotalol, carbamazepine and, especially, hydrochlorothiazide have shown elevated concentrations in the TWW, at least in one sampling campaign.

While one can see the positive attenuation effect of the PhCs concentrations in the basins B2 and B1, with the additionally installed GAC ROL in B2 and to some extent in the biochar ROL in B1, B4 (without any additional organic barrier) showed very low attenuation of the concentrations measured for these three compounds (even it looks like an increase of sotalol, but this is probably due to changes in the TWW concentrations, being the TWW sample only the concentrations measured discretely at one time).

At least in one of the three sampling campaigns, elevated concentrations of sotalol, carbamazepine, and hydrochlorothiazide were observed in piezometers PZ1, PZ2, and PZ3. Persistent behaviour is widely reported for Carbamazepine in column tests and SAT-MAR systems (Hellauer *et al*., 2018; He *et al*., 2016; Regnery *et al*., 2015; Arye *et al*., 2011) as well as for Hydrochlorothiazide (Sallwey *et al*., 2020; Hermes *et al*., 2019). In line with the literature, Figure 2.35 shows the persistent behaviour of these two PhCs in the saturated zone (piezometers). These findings are supported by the moderate to low logKow, which indicates higher mobility and lower chemical adsorption potential. The reference PZ4 exhibited no detectable PhCs concentrations for the relevant group as can be seen in Figure 2.33.

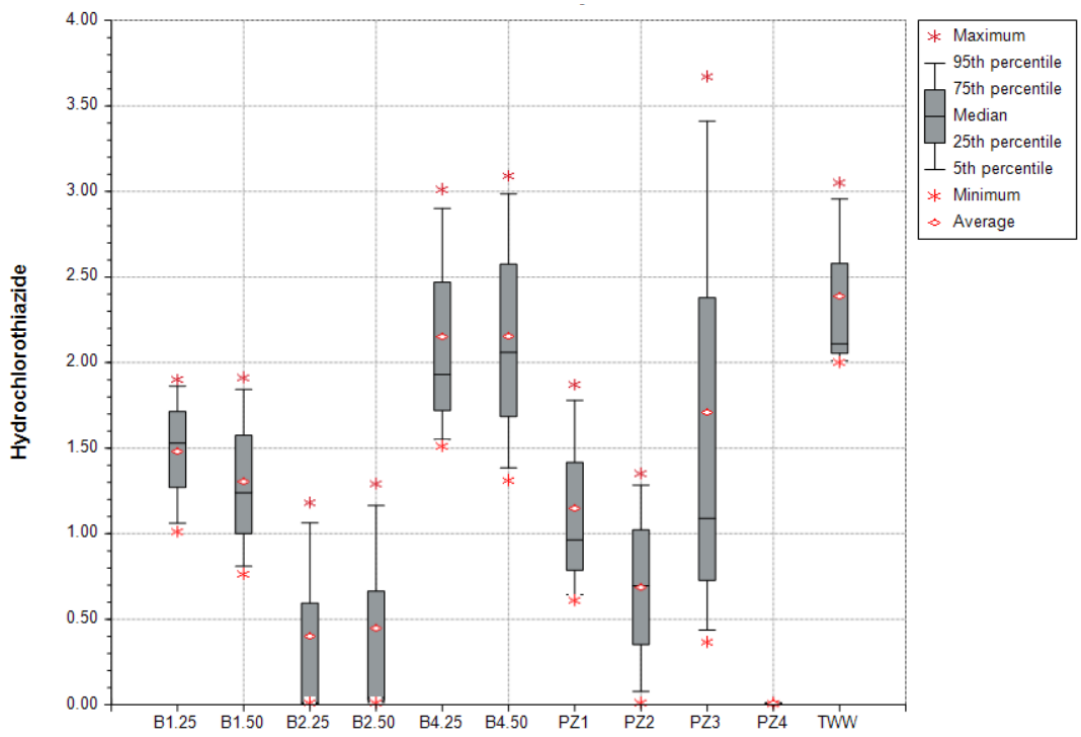

Figure 2.35 Box-plot diagram of the Hydrochlorothiazide concentrations in the water samples at Comporta WWTP_SAT-MAR

Group 4

The PhCs in group 4, namely Caffeine, Iohexol, Iomeprol and Iopamidol, are assumed to have poor biodegradation potential / adsorption tendency, according to their pKa and logKow values (cf. Table 2.4).

Caffeine in TWW exhibited low concentrations ranged between < 0.01 µg/L to 0.5 µg/L across three sampling campaigns. The contrast media agents, namely Iohexol, Iomeprol and Iopamidol exhibited concentrations ranging from < 0.01 to 2.5 µg/L.

In the basins, caffeine typically showed lower concentrations in B2, compared to B1 and B4. Iomeprol and Iopamidol show more efficient removal in B2 and in B1, compared to the conventional B4. Iohexol worse behaviour was observed in B1. In some situations, the concentrations in the basins appear to be higher than in the TWW, but the TWW sampling corresponds to a specific period, while the basin samples integrate the concentrations over a week.

Caffeine was not detected in the downgradient piezometers. The contrast media agents exhibited from no detectable to moderate concentration in the piezometers.

Overall, according to the findings, it may be suggested that the PhCs with similar characteristics behave similarly in the context of their environmental fate, particularly in the three different vadose zone conditions where most of the quality improvements occurs.

It was demonstrated that the PhCs which have similar characteristics have been biodegraded or adsorbed at similar concentration ranges, under the same conditions.

To resume, Figure 2.36 represents the sum of the average concentration values of the PhCs measured in the water samples collected at each sampling point. B2 is the most efficient system to attenuate the PhCs concentrations in the infiltration water (TWW), having in the last campaign concentrations equivalent to the reference piezometer (PZ4). B1 showed less pronounced attenuation than B2 but generally outperformed B4 (however, the high concentrations of iohexol observed in one campaign may give the impression that B1 performed worse than B4). Furthermore, Figure 2.36 shows some improvements during the vadose zone passage, between -25 cm and -50 cm depths, for most PhCs. Finally, the average concentration values of the PhCs in the piezometers show that PZ4 has no PhCs (with one exception) (the existing values correspond to half of the LoD), and PZ3 has the highest PhCs concentrations sum. This may be attributed to its proximity to B4, where no additional ROL was installed, as well as to its downgradient position. PZ2, which is located western side of the infiltration basins, seems to be the least influenced.

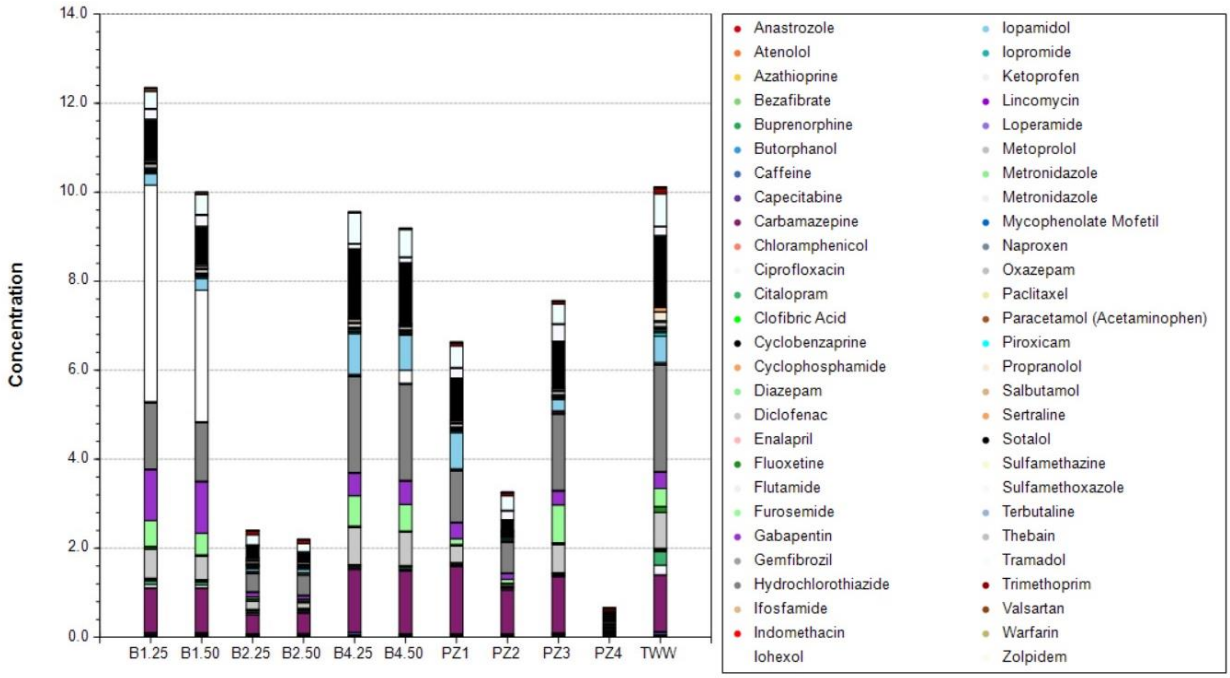

Figure 2.36 Sum of the average concentration of PhCs compounds (µg/L) in the water samples at Comporta WWTP_SAT-MAR

2.6 MARCLAIMED IDST implementation

2.6.1 MARCLAIMED tools implementation

Extensive details on application of each of the MARCLAIMED tools in DS2 and associated first results are provided in the WP1 deliverables:

- D1.1 – Predictive Models for MARVIS, PREDMAR and MARAISER
- D1.2 – MAR with AWR impact at municipal scales for OASIS FLOW
- D1.3 – Economic and financial aspects for MARINSURE and RECOVER

At this stage of the project, the integration of the tools within the IDST is still in progress. Therefore, no other details regarding the site-specific implementation of each tool in DS2 can be provided at this time.

2.6.2 Input data integration

Two different input data gathering processes were set up for two different types of data: real time measurements from online sensors, and Excel files containing the laboratory analysis results.

S::can sensors online analysis

Two online ICP sensors spectro::lysers v3, from the s::can, are installed in Comporta with a data logger, the con::cube v3, which is configured to automatically transmit the collected data to an FTP server in the form of CSV files. These files contain multiple measurements from the TWW (inflow) and groundwater (PZ1) (cf. section 2.5.2) and are received by an FTP server set up within the project's infrastructure. The data collection module of the Integrated Decision Support Tool (IDST) regularly monitors the FTP server for new files. Upon detecting new files, it fetches them, converts the data into the relevant format specified by the NGSI-LD model used in the project, and then sends the converted data to the IDST database for storage and further processing.

This process is actively retrieving data to the IDST since M6 of the project. The automation is functional and reliable, based on the assumption that the format of the files will remain consistent.

Laboratory analysis results

For the laboratory analysis results, the data transfer process is only semi-automated. As DS2 receives new Excel files from the laboratory by email every few months, a folder was created within the project's Google Drive, in which the results files are manually deposited. Then, the following process is fully automated, as it is the same as the one for online sensors: the

data collection module of the IDST regularly checks for new files, converts the one that is found to NGSI-LD and sends it to the IDST. This process works and is automated based on the assumption that the format of the files will remain consistent.

This process is actively retrieving data to the IDST since M6 of the project, the automation is functional and reliable, based on the assumption that the format of the files will remain consistent.

2.6.3 Visualization dashboards

Some simple dashboards were developed and provided for the project's partners to be able to visualize the retrieved data (cf. Figure 2.37 and Figure 2.38). It also includes a dynamic schema of the DS2 infrastructure, which shows the latest measurement of the chosen variable at each of the sensors' / sampling points' locations (cf. Figure 2.39).

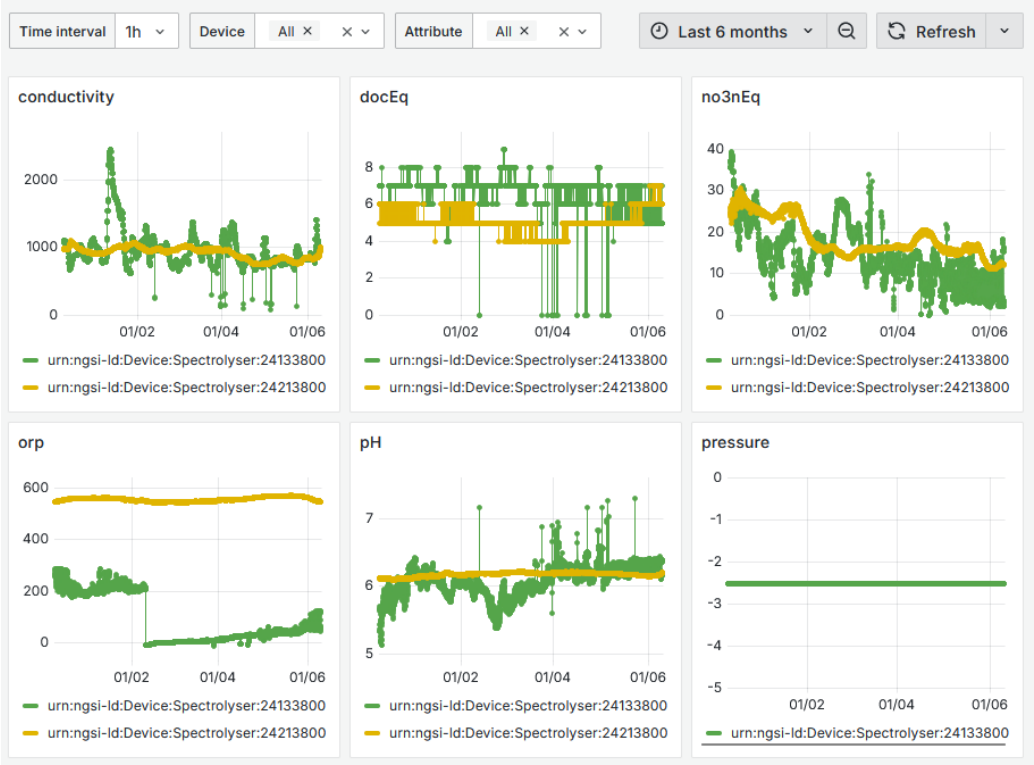

Figure 2.37 Basic dashboard for s::can sensors online analysis

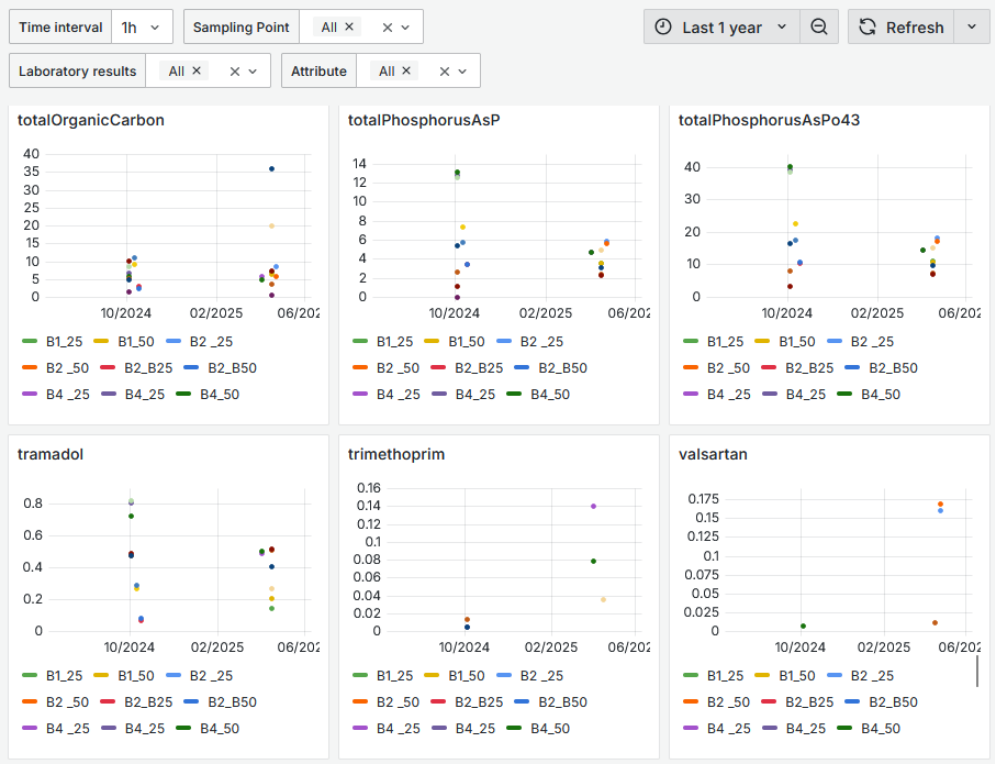

Figure 2.38 Basic dashboard for laboratory results analysis

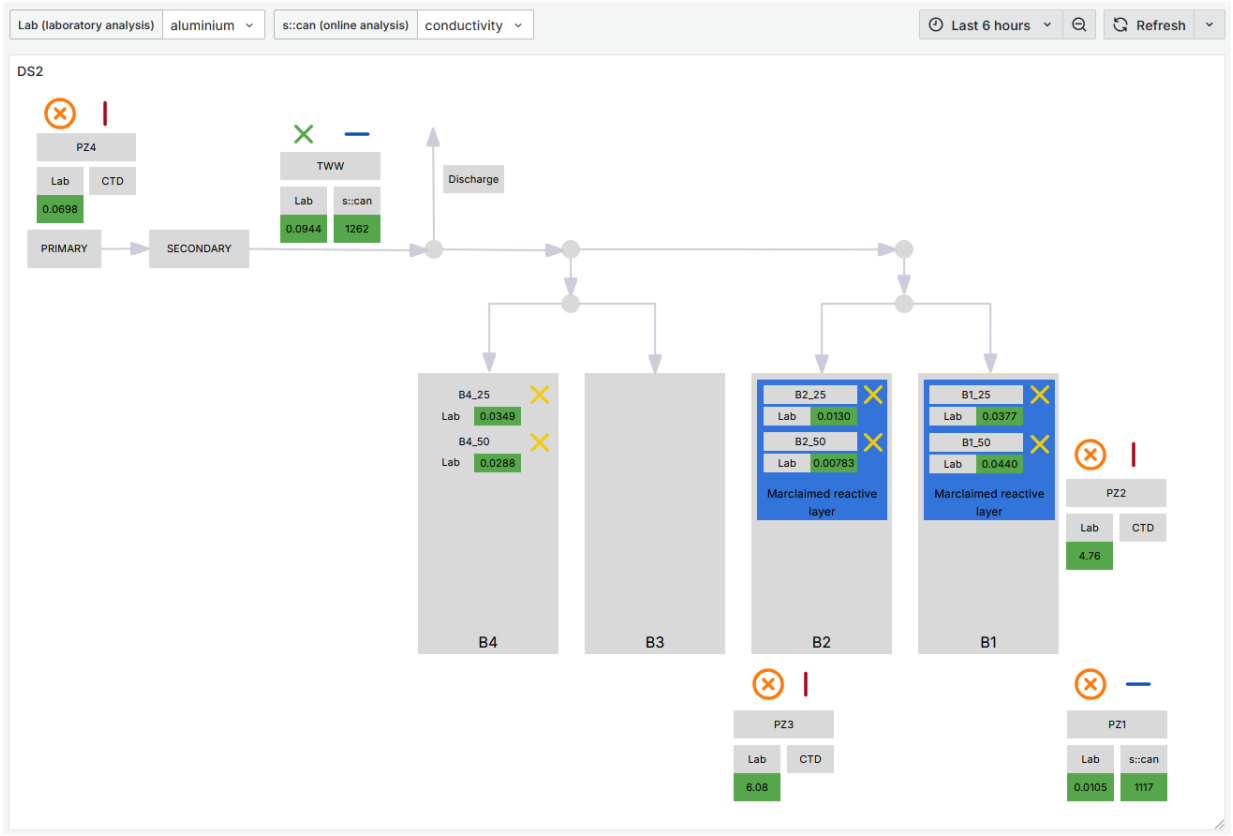

Figure 2.39 Dynamic schema of the DS2 infrastructure with example of the results

2.7 Conclusions

The DS2 developments have followed what was initially planned, with several improvements (e.g., more monitoring piezometers) made during the monitoring and sampling programming stage.

As a summary of key findings, the results obtained so far indicate no clear contamination by heavy metals nor pharmaceutical compounds in the groundwater, with few punctual exceptions. This is a significant finding, particularly considering that the latter was a primary concern since wastewater treatment plants (WWTPs) are not typically designed to remove such compounds.

However, the issue of nutrient pollution - specifically nitrogen (N) and phosphorus (P) - emerges as a critical concern. Very high concentrations of these nutrients were detected at the WWTP outflow (i.e., at the entry point into the basins). This passive system is not capable of effectively addressing this situation, indicating that treatment must be implemented at the WWTP itself, as recommended by the new Urban Wastewater Directive guidelines.

Another key finding is the excellent performance of Basin B2, which contains 15% Granular Activated Carbon (GAC), in improving water quality. This suggests that the incorporation of GAC can significantly enhance treatment effectiveness.

Concerning the way forward, all the analysis done in this report needs to be updated and revised considering the results of the following five sampling campaigns and the continuous sensors data retrieved. Recommendations and lessons learned may lead to consider extending the treatment approach used in Basin B2 to the remaining basins, given its demonstrated effectiveness in improving water quality, particularly with the inclusion of 15% Granular Activated Carbon (GAC) as well as evaluate the feasibility of designating one of the basins as a retention basin (rather than an infiltration basin) to serve as a buffer during occasional malfunctions of the WWTP.

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3 DS3: Texel (NL)

3.1 Introduction and objectives

The third MARCLAIMED Demo Site (DS3) is located on Texel, one of the Dutch Wadden islands in the province of North Holland, the Netherlands (Figure 3.1). The island consists mainly of farmland surrounded by sand dunes and dykes along the coasts. The municipality of Texel encompasses the whole island, which is approximately 586 km^2. Texel is entirely dependent on freshwater from rain and from a drinking water pipeline with the mainland. Agriculture is the major water-demanding function on Texel. As climate change exacerbates extreme precipitation and drought, the ability to store freshwater, when abundant, and utilize it during dry periods is of utmost importance. Currently, Texel discharges about 44 million m^3 of water per year to the adjacent Wadden Sea, indicating a great potential for aquifer storage projects.

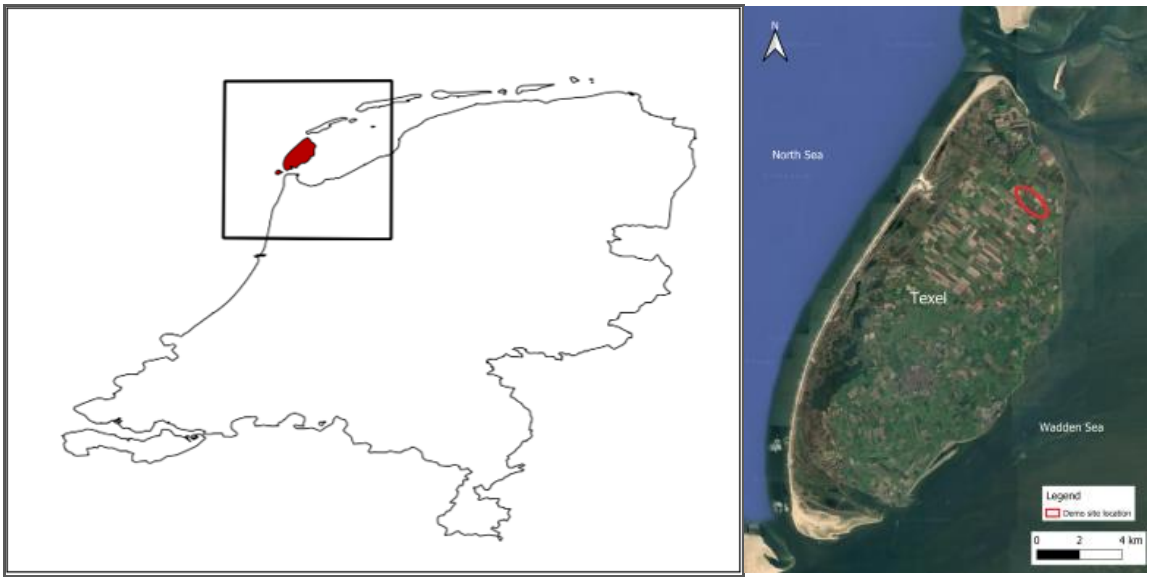

Figure 3.1 Location of DS3: Texel, The Netherlands

The goal of the MAR system at DS3 is to store water from agriculture runoff that accumulates in the wet season (October – April) in the deep aquifer. In the dry season (May - September), the stored water is recovered and used for subsurface irrigation. Securing freshwater availability in the area is of great importance for the economic position of the agricultural sector. Furthermore, groundwater is considered highly vulnerable to pollution, needing to be protected in this agricultural area.

Specific MARCLAIMED objectives are to: 1) preserve the aquifer water quality via nutrient and pesticide control in the Tail Drainage Water (TDW); 2) make TDW available for large-scale ASTR-MAR scheme, improving its cost-effectiveness, optimising the maintenance, and

achieving a small footprint; 3) prolong the lifetime of the infiltration wells by reducing the clogging potential of infiltration water; 4) increase the reliability and acceptance of MAR with TDW in the agricultural and water sector, and thus contribute overall feasibility and sustainability; 5) promote farmers' engagement to recognize the necessity of MAR with TDW and willingness to invest in these systems, knowing how to operate them for the sake of potentially more stringent future requirements on the quality of TDW.

3.2 Motivation for the site selection

Unlike DS1 and DS2, which process treated wastewater from WWTPs with a focus on drinking water and ecosystems, DS3's goal is to optimize MAR systems for agricultural uses. The demo site aims to develop self-sufficient fresh irrigation water with underground storage in a highly salinized area. This will reduce dependency on external freshwater supplies and improve crop production conditions.

3.3 Geological/hydrogeological setting

3.3.1 Hydrogeological context and interaction with the tile drain system

DS3 is in the Eijerland Polder region of Texel, meaning that the land is reclaimed and is about 0 to -0.6 m below sea level. DS3 consists of two plots: the northwestern plot, "Broekman", and the southeastern plot, "Slot". From the surface to approximately 6 m below ground level (bgl) are Holocene tidal deposits consisting of sand, clayey sand and peat. Based on a hand drilling at the Slot plot performed in 2020, the Holocene deposits can be further described as the following:

- 0 to 20 cm: topsoil - moderately fine clayey sand
- 20 to 45 cm: moderately fine clayey sand
- 45 to 65 cm: moderately coarse clay-poor sand
- 65 to 80 cm: moderately coarse clay-poor sand, small shell fractions, moist from > 70 cm
- 80 to 95 cm: moderately fine clayey sand
- 95 to 105 cm: moderately fine clayey sand, small shell fractions
- 105 to 135 cm: light loam, alternating with organic material
- 135 to 210 cm: light loam, fully saturated
- 210 cm to 6 m: fine clayey sand, light loam, and organic material

From 6 m to 12 m bgl is an unconfined aquifer consisting of fine sand. At about 12 m bgl is a confining clay layer, below which is the confined aquifer that the ASR system uses for storage. The confined aquifer is brackish with an electrical conductivity of about 20 to 25 mS/m. The confined aquifer extends from about 12-13 m bgl to approximately 22 m bgl, where an extensive clay layer begins. These soil layers are shown in Figure 3.2.

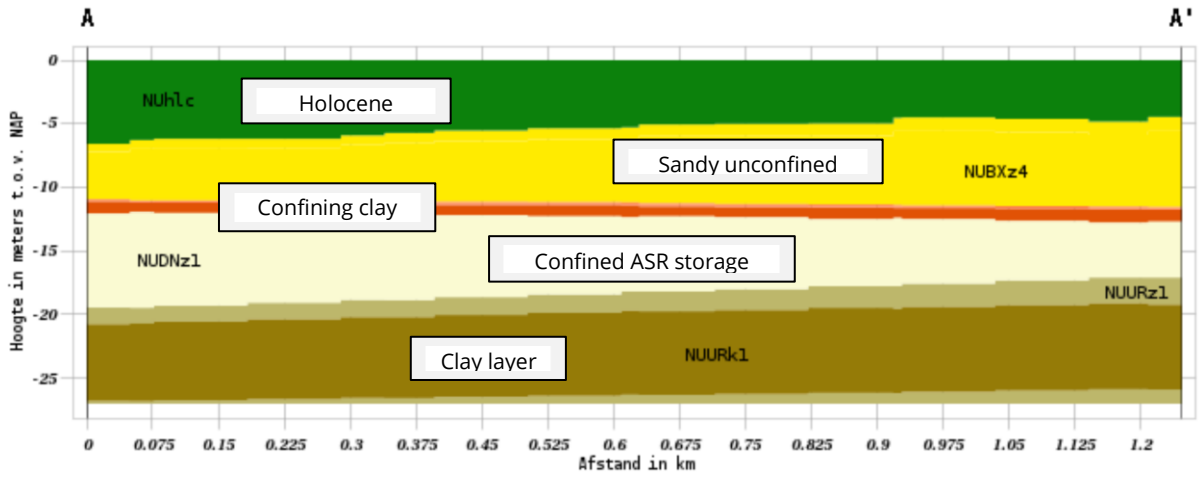

Figure 3.2. Soil layers at DS3 from 0 to -27 m bgl in a ~1.2 km cross section. Source: TNO – GDN, 2025

At approximately 0.8 m depth, there is a system of tile drains. Tile drains are used throughout the polder areas of the Netherlands to drain agricultural fields to allow for grazing or crop growth. In these systems, piping with filter screens (the tile drains) are distributed in a network across the fields. These pipes flow directly to ditches that run between the plots. When groundwater rises to the level of the pipes, it drains to the ditches and eventually to the sea, rather than flooding the cropland. The schematic in Figure 3.6 also shows the tile drainage system.

Because these tile drains are approximately 11 m above the confining clay layer, they will not immediately begin to drain water when it rains. First, the unconfined aquifer must fill so that the level of the groundwater table reaches the tile drains. When the groundwater table reaches -0.8 m, then the tile drains begin to drain water to the ditches. In the winter months, the combination of higher precipitation and lower evaporation (<1 mm/day) creates a water surplus in the soil, such that the tile drains begin to drain water. This is important to note in the functioning of the MAR system because water is only introduced via the collection wells when the groundwater table reaches the tile drains, which is not necessarily during every rain event.

3.3.2 Climate

Texel's climate is characterized by mild summers with average maximum temperatures of 20 °C and relatively mild winters with average maximum temperatures of 6-7 °C. Rainfall is highest in October and November and lowest in April and May (Figure 3.3). The mean annual rainfall is approximately 700 to 900 mm.

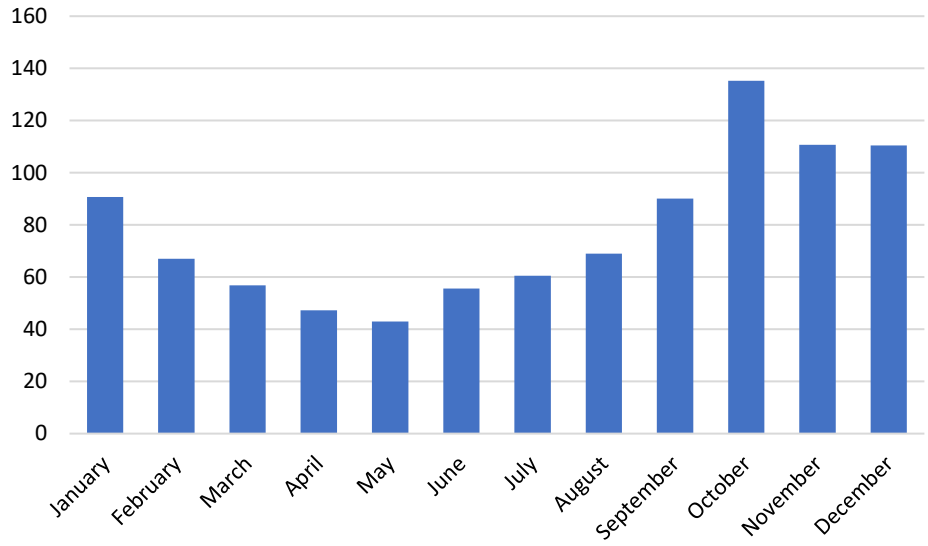

Figure 3.3. Mean monthly precipitation, Den Burg, NL, 1991-2023. Source: KNMI

From December 2024 through May 2025, the Netherlands experienced the driest winter and spring since 1976. The precipitation deficit, or the difference between precipitation and evaporation, was up to 129 mm on 23 May (Figure 3.4) (KNMI, 2025). This drought was especially pronounced on the western half of the country, including Texel.

With climate change, the climate extremes, such as the very dry weather experienced in the first half of 2025, will increase. As rainfall becomes less stable, the importance of systems such as ASR is emphasized.

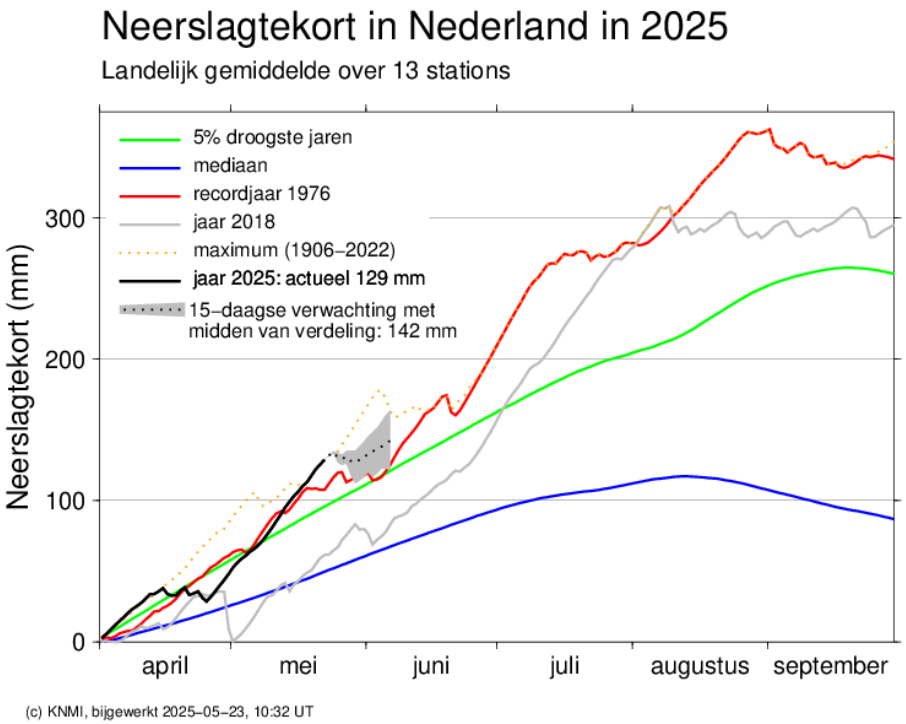

Figure 3.4. Precipitation deficit in The Netherlands in 2025 in mm, averaged over 13 stations. 5% driest years (green), median (blue), record dry year 1976 (red), very dry year 2018 (grey), maximum precipitation deficit 1906-2022 (orange dashed), year 2025 (black), and 15-day predicted deficit with an average of 142 mm (grey shaded)

3.3.3 Water quality considerations: historical measurements

Water quality at DS3 has been recorded as a part of initiation of the MAR system since 2020. The water quality is measured at four main points: the water of the receiving water body, i.e., the confined aquifer; the water that enters the collection wells via the tile drainage system; the water that exits the SSF/GAC system; and the water that is recovered for irrigation.

Electrical conductivity

Prior to MAR system installation, the water quality of the confined aquifer was tested by Acacia Water in 2020. Electrical conductivity (EC) was recorded at 22 mS/cm in the groundwater. The EC of the water in the ditch was measured at the Slot plot at 3.7 mS/cm and at the Broekman plot varying between 6.5 mS/cm and 19.0 mS/cm. A soil moisture pin on the Slot plot measured EC in the surface soil after a rain event at 4.2 to 5.0 mS/cm.

Nutrients

The water that enters the collection wells via the tile drains generally contains increased concentrations of nitrogen and phosphorous due to leaching of fertilizers. Concentrations of nitrate measured in water at the SSF/GAC influent ranged from 0.2 mg/L to 28.5 mg/L

from 2022-2024. Phosphate concentrations were lower, ranging from 0.83 mg/L to 1.97 mg/L.

Water samples at the SSF/GAC inlet and outlet have been collected by Acacia Water and TU Delft via the AGRICOAST project to confirm the SSF/GAC filter functionality. As of May 2025, there have been three infiltration seasons. Concentrations of nitrate and phosphate are measured at the influent and the effluent of the SSF/GAC to monitor the extent to which degradation of nutrients takes place in the upper sand layer. In the 2022-2023 infiltration season, the efficiency of nitrate purification was approximately 80% and for phosphate approximately 50%. However, nitrate removal in the SSF/GAC can be highly variable. In the 2023-2024 infiltration season, purification removed approximately 35% to 60% of nitrate, and 10% to 50% of phosphate.

The nitrate remaining in the effluent water, which is infiltrated into the aquifer via the horizontal injection wells, is no longer found in groundwater samples taken from the deep aquifer near the horizontal wells. The anoxic aquifer allows denitrification to occur, so that nitrate is naturally removed. There is no nitrate recorded in the aquifer just prior to the infiltration season, during the infiltration, or during the recovery period.

Pesticides

Pesticides and herbicides were identified in the drainage water above the detection limit. Of the 64 active substances mapped in the products used by the participating farmers, 51 substances were selected to be measured and can be considered representative in terms of substance behaviour for the total group of 64 active substances. The substances found with concentrations above the detection limit were azoxystrobin, dichlorobenzamide (BAM), diethyltoluamide (DEET), dimethenamid, fluopicolide, flutolanil, glyphosate, metobromuron, phthalimide and thiamethoxam. It should be noted that only fluopicolide (applied in 2015, 2017, 2019 and 2021), BAM, glyphosate, and DEET (n,n-diethyl-m-toluamide; not applied) were found in concentrations higher than 0.1 µg/L , and that the concentrations of the other substances were just above the detection limit of 0.01-0.05 µg/L.

BAM (2,6-Dichlorobenzamide) is a metabolite of Fluopicolide and Dichlobenil (1,5-dichlorobenzonitrile) and is widely found in groundwater in the European Union. Even at high concentrations, the safety risks of this substance are considered low (Bjorklund *et al*., 2011). Since Dichlobenil was not used, BAM will be a product of the degradation of fluopicolide.

DEET has not been applied to the plots and has human origin (Cirkel *et al*., 2017). Its origin in drainage water from the plots in Texel is unknown. Possible origin is from (purified) wastewater (STOWA, 1997) that ended up on the plots via irrigation with surface water.

Glyphosate was used in 2013, 2014, 2015 and 2019 in the cultivation of maize and seed potatoes. Despite degradation processes in soil, glyphosate is regularly found in groundwater and surface water (Kanissery *et al*., 2019).

In the 2022-2023 infiltration season, seven monitoring rounds of influent and effluent from the SSF/GAC were completed for pesticides. Except for one substance (phthalimide), during the first monitoring round, the effluent from the SSF/GAC system did not contain pesticides in concentrations above the detection limit (0.01 – 0.07 µg/L). In the 2023-2024 infiltration season, no pesticides were found in any effluent samples.

Salinity

As fresh water is less dense than salt water, the infiltrated fresh water forms a "bubble" at the top of the confined aquifer around the horizontal well. Some mixing occurs at the edges of this approximately ellipsoid shape, such that at the end of the infiltration season, the freshest water occurs at the center of the bubble where the horizontal well is, and salinity increases with horizontal and vertical distance from the horizontal well. During the recovery period, salinity is monitored in the water that is abstracted from the horizontal well. When the salinity reaches some threshold determined by the farmers, the recovery stops. This threshold depends on the water stress levels of the crops and the type of crops planted, as salinity tolerances differ between crops. In this way, the entire freshwater bubble is not abstracted every year. Therefore, every infiltration season, the freshwater bubble grows as more freshwater is infiltrated.

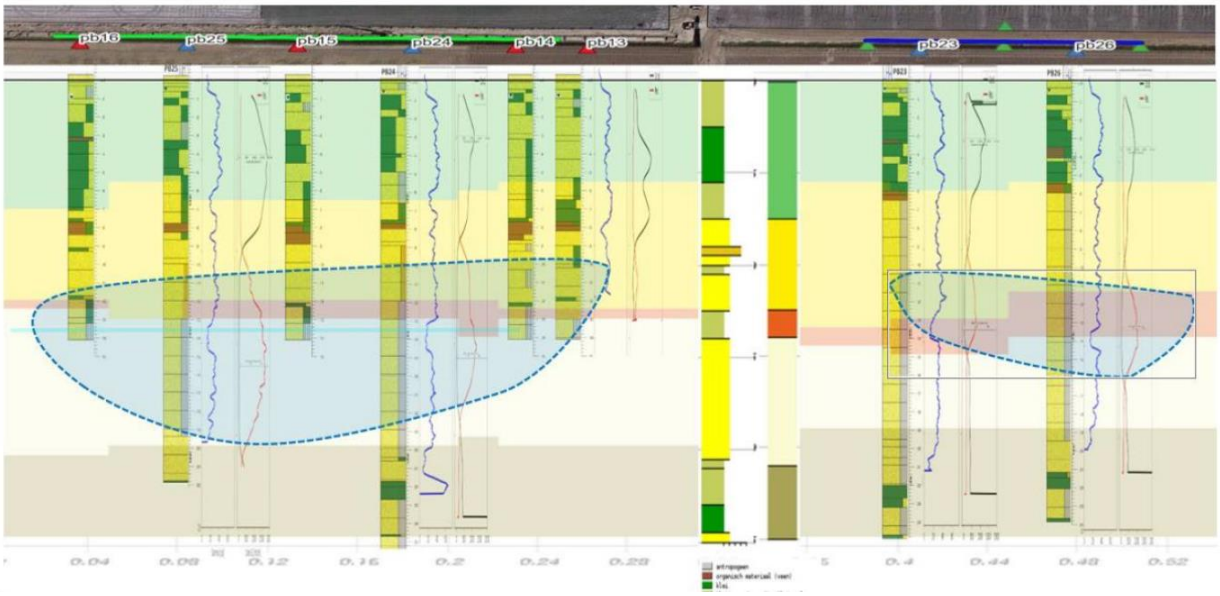

Figure 3.5. Freshwater bubbles at the Slot (left) and Broekman (right) plots, 2024. Note that the bubble penetrates upwards to the lower 203 meters of the covering layers due to infiltration taking place under pressure. SOURCE: TU Delft – Agricoast

Due to soil heterogeneity, there are places where the horizontal or vertical conductivity may be greater than others. This means that in the recovery period, each piezometer along the horizontal injection well will read different salinity values. More information on the piezometers will be provided in Section 3.4. For example, one well may suddenly see an

increase in salinity to the background aquifer levels, while the others read nearly freshwater. Because all the water is mixed as it is abstracted from the horizontal well, the salinity reading taken following abstraction is the one that is considered when determining when water recovery should stop for the season.

Infiltration water has an EC of approximately 1.2 to 1.3 mS/cm. During infiltration, the EC of the aquifer near the horizontal wells quickly drops to the level of the infiltration water. During recovery, the EC value increased slightly from 1.4 to 1.8 mS/cm during the 2023 recovery period. While abstraction may have continued longer, the goal during this first season was to grow the freshwater bubble.

3.4 Existing infrastructures and MARCLAIMED contributions

3.4.1 MAR conceptual model

DS3 is an Aquifer Storage and Recovery (ASR) MAR system which collects water from a tile drainage water (TDW) network approximately 1 m below a 30-ha agricultural parcel. This drainage network normally discharges water to the surface water, but in this system all tile drains end up in one of three collection wells, which discharges into the MAR system, a Slow Sand Filtration (SSF) in combination with Granular Activated Carbon (GAC) schema running through two horizontal injection wells into a confined sandy aquifer (Figure 3.6).

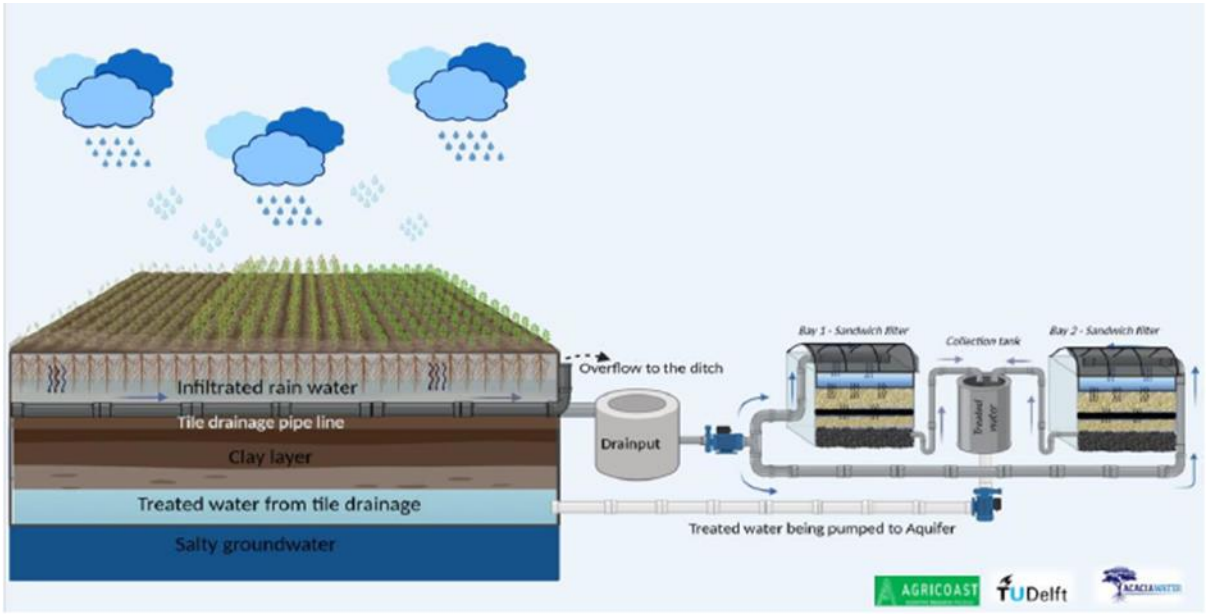

Figure 3.6. Conceptual scheme of MAR system at DS3

The two separate plots that provide water to the MAR system, Broekman and Slot, contribute with water through tile drains and collection wells, which is combined before entering the SSF/GAC filtration system in the rainy season. Water is injected into two

horizontal wells at about 13 m bgl one in each plot. Along these horizontal wells there are a series of piezometers that measure piezometric head and salinity of the aquifer (Figure 3.7).



Figure 3.7 Horizontal ASR wells and piezometers at the Slot plot (Well 1) and Broekman plot (Well 2)

During the dry season, the pump direction is reversed so that the freshwater is recovered through the same horizontal wells and re-introduced to the plots as subsurface irrigation.

3.4.2 System operation

A schematic of the current system operation is provided in Figure 3.8. There are two collection wells on the Broekman plot, though only one of these was selected for sensor installation along with the one collection well from the Slot plot. The water collected from all three collection wells is combined before it enters one of two SSF/GAC systems. Degradation of nitrates and phosphates occurs in the SSF/GAC to some extent. The GAC serves as a material to which the pesticides adsorb to, removing them from the water. The water is then injected into two horizontal infiltration wells. The horizontal well on the Slot plot is 100 m long and has 100 mm in diameter. It was installed in April 2021. The horizontal well on the Broekman plot is 180 m long, with a diameter of 100 mm, and was installed in February 2022. Both were installed at a depth of -13.5 m bgl. Due to some issues with the Slot horizontal well construction that were discovered following preliminary testing, the Slot well

was not operational during the first infiltration season, 2022-2023. Improvements were made so that both wells were operational during the second (2023-2024) and third (2024-2025) infiltration seasons. In early 2024 some additional adjustments were made to the Broekman plot to ensure that the level sections connected better to the drainage system.

In September 2022, four piezometers were placed along each of the horizontal infiltration wells. Two new piezometers were installed along each horizontal well in November 2023 with three filters each: at the bottom of the covering layer (-6 to -8 m bgl), at the level of the horizontal well, and at the bottom of the confined aquifer at -22 to -24 m bgl. This allows for better monitoring of the vertical extent of the freshwater bubble.

During water recovery period (May to September), water is pumped out from both horizontal wells, mixed together, and analysed to ensure that EC does not exceed crop tolerance. Water is then immediately used for irrigation via a sub-surface and/or drip irrigation system.

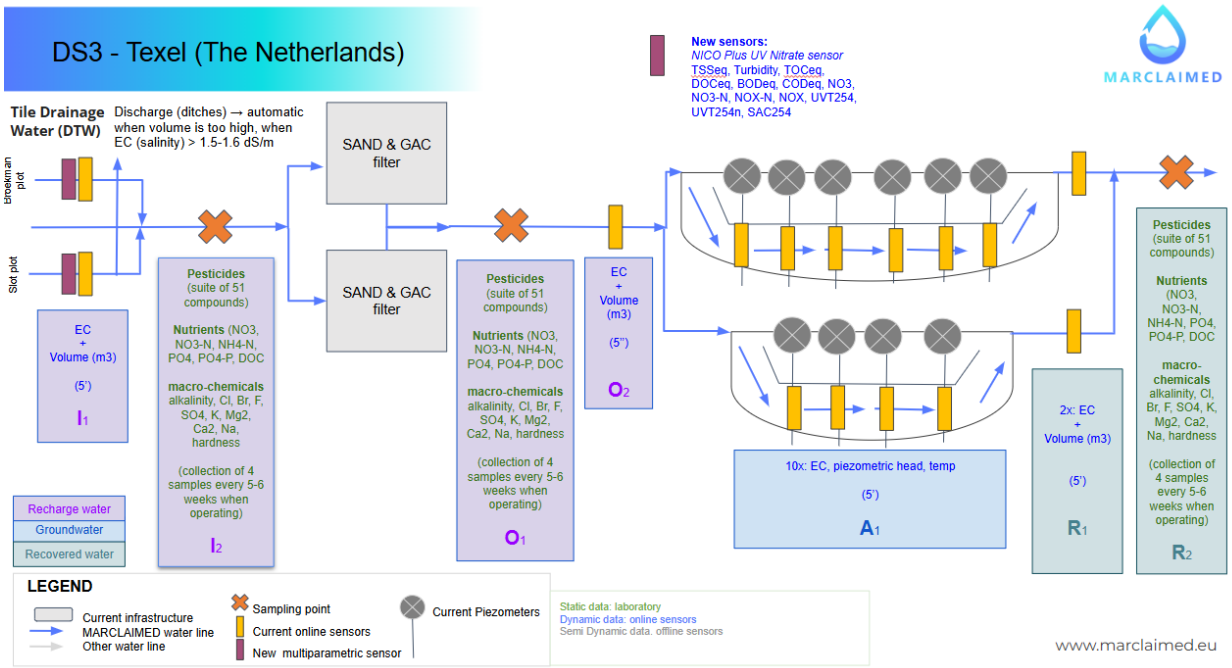

Figure 3.8. Schematic of the DS3 MAR system operation and sampling points

Storage Summary

Table 3.1 shows a summary of the volumes of water stored and recovered in the aquifer in the first three seasons of the operation of the MAR system at DS3. Water re-use from the Slot well did not occur in 2023-2024 to grow and stabilize the freshwater bubble before recovery begins. Note that even with less precipitation in the 2024-2025 season, the total volume of water infiltrated between the two horizontal wells (19,500 m^3) was comparable to the total volume in the second infiltration season (19,400 m^3). This is due to improvements

in system operation surrounding clogging and leakage to the ground surface. Recovery is still in progress at the time of this report (July 2025). It has been recommended that 13,000 m^3 of water are recovered during summer 2025. This would be approximately 67% of the water infiltrated. With the percent water recovered every year growing from 15% to 30% and to 67%, it is clear that the system's efficiency is improving as the freshwater bubble grows.

Table 3.1 Summary of water storage volumes at DS3

Plot	Season 1: 2022-2023			Season 2: 2023-2024			Season 3: 2024-2025		
	Infiltration [m^3]	Recovery [m^3]	% Recovery	Infiltration [m^3]	Recovery [m^3]	% Recovery	Infiltration [m^3]	Recovery [m^3]	% Recovery
Slot	-	-	-	2,990	-	-	19,500	13,000 (advised)	67%
Broekman	21,000	3,200	15%	16,410	8,000	30%			

3.4.3 Challenges

Beyond challenges that occurred during the first infiltration season that have since been addressed, there are ongoing challenges surrounding clogging of the horizontal wells during infiltration, and infiltration water leakage to the ground surface.

Clogging

During the second infiltration season (2023-2024), there were frequent problems with clogging. The drainage water from the Broekman plot contained floating organic material and iron precipitation. To solve this problem, a paper band filter was added before the water is pumped into the SSF/GAC at the beginning of the 2024-2025 infiltration season. This removes all particulate matter from the water and reduces clogging issues at the surface of the SSF as well as the horizontal wells.

Clogging in the SSF occurs as organic matter builds up on the top of the sand layer. Therefore, the top of the sand layer is scraped off periodically to reduce clogging. The lifetime of the GAC filter is expected to be between 10-15 years, as the surface area of the activated carbon grains is very large, so its capacity for pesticide adsorbance is high. Maintenance of the SSF/GAC is therefore only required for the surface of the sand filter.

It is possible that clogging in the horizontal wells and in the pore space of the aquifer surrounding the horizontal wells also occurs due to hydrochemical interactions between the infiltration water and the aquifer water. For example, suspended particles of organic matter in the infiltration water can lead to algae growth in the horizontal wells. It remains largely unknown what is the main driver in clogging in the subsurface.

Leakage to Ground Surface

In the first infiltration season, after approximately 3.5 months of operation with an average infiltration pressure of approximately 0.5 bar, several leaks to the ground surface were observed. This was caused by infiltrated water rising almost vertically to the ground surface near the piezometers. The confining layer of clay is not homogenous over the length of the horizontal infiltration well. As a result, the vertical permeability of the top layer varies and thus so does the resistance to infiltration pressure.

The piezometers were re-sealed with grout in April 2023, and the infiltration began again with a pressure of 0.3 bar.

3.4.4 New MARCLAIMED solutions

The following technological monitoring improvements and environmental sampling scopes have been implemented at DS3 within the MARCLAIMED project:

- Two TriOS NICO plus sensors installed in two of the collection wells along with two TriOS G2-Interface Boxes for data logging.
- Dissolved oxygen, pH, ORP and EC sensors, also installed in two of the collection wells (see Table 3.2 for more details).
- Ongoing efforts for implementation of telemetric data transmission by a SIAP MicroSUM datalogger.
- Weekly water sampling from two collection wells and accompanying environmental analysis (see Section 3.5.2 for more details).

These solutions will reduce the contamination risk through early detection of contaminants, specifically nitrates, above the threshold value (KPI_6.1). In addition, early detection of contaminants can reduce system shut-down time that may be required later on. This improves the MAR system's performance and increases its recovery efficiency (KPI_1.4).

3.5 Data collection progress and results

3.5.1 Sensor installation

Four different kinds of sensors were placed in two collection wells (eight in total), measuring various parameters. See Table 3.2 for an overview.

Table 3.2 Overview of sensors

Sensor	Brand, product	Parameters
Nitrate sensor	TriOS, NICO plus sensor	N-NO3, N-NOx, CODeq, BODeq, DOCeq, TOCeq, TSSeq, turbidity, SAC254, UVT254
DO sensor	Aqualabo, OPTOD sensor	DO, temperature
pH-ORP sensor	Aqualabo, digital sensor PHEHT	pH, ORP, temperature
EC sensor	Aqualabo, digital sensor CTZN	EC, temperature

The nitrate sensor was coupled with the TriOS G2-Interface Box for datalogging. The other three sensors were connected to a SIAP MicroSUM datalogger. Initially, it was intended to ensure both dataloggers would be able to send their data telemetrically. However, preparing the SIAP MicroSUM datalogger for telemetric data transmission turned out to be more time consuming than expected. To ensure data collection was started on time, it was opted to place the sensors without the option for telemetric transmission. Instead, the site would be visited regularly to obtain the data manually (roughly once a month). Each time the data was retrieved, it was uploaded to the MARCLAIMED Google Drive folder.

The sensors were placed in two collection wells named 'Slot' and 'Broekman', collecting agricultural tile drainage water, on December 10th, 2024. On the Texel demo site there are three collection wells in total: two for the Broekman field and one for the Slot field. In Figure 3.9, these three collection wells are indicated by a blue dot. The two collection wells closest to each other were chosen to place the sensors in. In between these two wells is the filter installation (an orange rectangle in the figure).



Figure 3.9 An overview of the Texel Demo Site at the Hoofdweg

The infiltration period for ASR started on October 15th, 2024. In the early period, however, the infiltration was on and off because of little rainfall and clogging issues. It was decided to replace the upper layer of sand in the SSF by iron coated sand to combat this clogging, which took some weeks. The infiltration could truly start up in the second half of November 2024 (see Figure 3.12 and Figure 3.13 for the flow data).

3.5.2 Sampling procedures

In the two locations where the sensors were installed, water samples have been collected from the wells for laboratory analysis to confirm the sensor readings. One 100 mL sample was collected by the farmer from each well at a frequency of once per week for the duration of the infiltration period. Immediately following each sampling event, the samples were placed in the freezer on site. Samples can be stored in the freezer for up to 28 days until

they need to be analysed in the laboratory. Therefore, samples were collected from the site once every four weeks. The samples were transported in a cooler with ice to the laboratory.

At the Acacia Water laboratory, the following analyses were performed on the samples:

- pH
- EC
- Alkalinity (HCO_3^-)
- Cations (Li^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+) and anions (F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2-},) using an ion chromatographer
- TOC

These parameters (partially resulting from agriculture pressures) were selected because they will allow us to corroborate the sensor measurements. The results of these analyses were uploaded to the MARCLAIMED Google Drive folder.

During field visits, additional measurements were performed with a portable pH, DO and EC sensor.

3.5.3 Results: nitrate sensors

The results of the nitrate sensors are given in Figure 3.10. Unfortunately, Acacia found that the nitrate sensors had become very dirty while they were in the wells, so that the optical lenses of the sensors had become too dirty for reliable measurements. The sensors provide the user with a Spectral Quality Index (SQI), which should be near 1. An SQI of larger than 0.8 is acceptable, while an SQI between 0.5 and 0.8 requires caution. An SQI of lower than 0.5 indicates the sensor does not provide reliable data. The SQI values of both sensors are also plotted in Figure 3.10. As becomes apparent from this figure, for a large portion of the measurements, the SQI was not sufficiently high for reliable data. From March 2025 onwards, Acacia performed regular sensor maintenance to ensure that the data would remain reliable (Figure 3.11). However, as is also clear from the KNMI data (Figure 3.4), precipitation has been extremely low this wet season and after March 1st very little water has run through the collection wells.

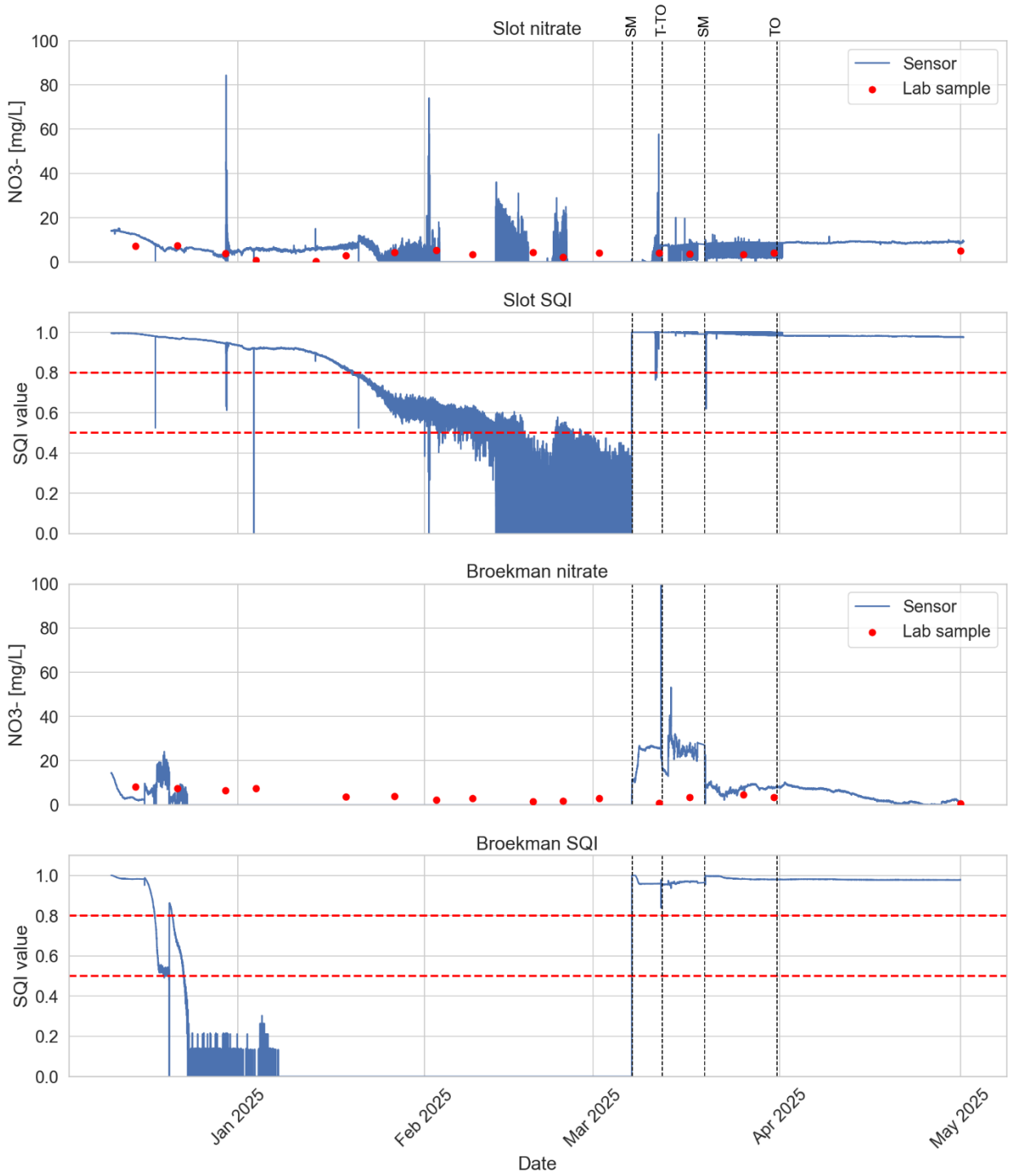

Figure 3.10. Sensor data from the Slot well (upper two graphs) and the Broekman well (lower two graphs)

Note: The first and third graph show the nitrate sensor measurements along with the nitrate concentrations from the laboratory samples that were taken weekly. The second and fourth graph show the spectral quality indices with two

dotted red lines at SQI = 0.8 and SQI = 0.5. The vertical dotted lines indicate important events: SM = sensor maintenance; T-TO = temporary turn-off of installation; TO = turn-off of installation



Figure 3.11. Acacia colleagues cleaning the Broekman sensors covered in a red-brown sludge on March 7th, 2025

The SQI data shows that the Broekman sensor became too dirty much quicker than the Slot sensor. This was confirmed by in-field observations by Acacia colleagues and the farmer. Namely, the Broekman field had been known by the farmer to leach extremely red-brownish water with a considerable amount of suspended solids. When analysing a tile drainage water sample, the water contained high amounts of Fe (223 mg/L). When cleaning the sensors in the field, Acacia found them covered in a red-brown sludge, which was not the case for the Slot sensors. The origin of the iron precipitation could be an iron-rich soil in combination with/or iron-oxidizing bacteria and oxygen, which can convert dissolved ferrous iron (Fe^{2+}) into solid ferric iron (Fe^{3+}) compounds, such as iron oxides or hydroxides, leading to very turbid water.

While the SQI of the sensors is near to 1, the nitrate values correspond to the concentrations measured from the laboratory samples. Only for the two samples measured from the Broekman well in March do the values differ considerably from the sensor data. After the second round of sensor maintenance, the values correspond again. Turning off the installation has somewhat stabilized the nitrate data for the Slot sensor. The stabilization of the data might relate to the water being less turbulent while the installation is turned off. A similar effect is shown for the pH sensor of the Slot well.

3.5.4 Results: DO, pH-ORP and EC sensors

The DO, pH-ORP and EC sensors do not contain spectral quality indices as the nitrate sensor does, so the sensors cannot let us know when that data is poor. However, the DO sensors are optical sensors, similar to the nitrate sensors, and thus similarly sensitive to fouling. The pH-ORP and EC sensors are not optical sensors but are also sensitive to fouling. So, also for these sensors, the values are most reliable from March 7th onwards, i.e., the moment Acacia performed our first maintenance on the sensors.

DO results

The DO sensor values from March 7th onwards correspond well with the field measurements. It is not possible to accurately measure the DO in the laboratory from samples, so no laboratory measurement points are given here. Towards the end of the measurement period, the DO of both the Slot and Broekman well dips towards 0%, right after the installation has turned off (Figure 3.12 and Figure 3.13). This suggests that no new water or air has entered the wells, leading to a complete oxygen consumption by the microbes. A similar dip in DO is visible right after the temporary installation shut off.

pH-ORP results

The pH profiles of the Broekman well looks similar to the DO profiles (Figure 3.13). This can be expected as a decrease in DO due to biological activity corresponds with an increase in CO_2, which makes the water more acidic. For the Slot well, this relationship is less visible (Figure 3.12), which might mean that this water is more strongly buffered. The ORP values of both wells slightly differ, with Slot ranging between 200 and 300 mV and Broekman ranging between 300 and 330 mV, meaning that the Broekman well is more strongly oxidizing than the Slot well.

EC results

Before March 7th, the EC sensor values in the Slot well do not correspond to the laboratory values. While the accuracy of these sensors is ± 100 µS/cm (or 0.1 mS/cm), the values during the period of December to March exceed these accuracy thresholds. After March 7th, the laboratory and sensor values are generally within the accuracy thresholds. The EC values from the Slot well range between 1200 and 1400 µS/cm, while the values from the Broekman well range between 1400 and 1900 µS/cm, meaning that the EC from Broekman is generally considerably higher than from Slot. This is confirmed by the farmers and the project team's previous experience regarding the outflowing EC. The EC is an important threshold parameter for infiltration, as no water with an EC higher than 1.6 mS/cm can be infiltrated for a proper development of the freshwater bell.

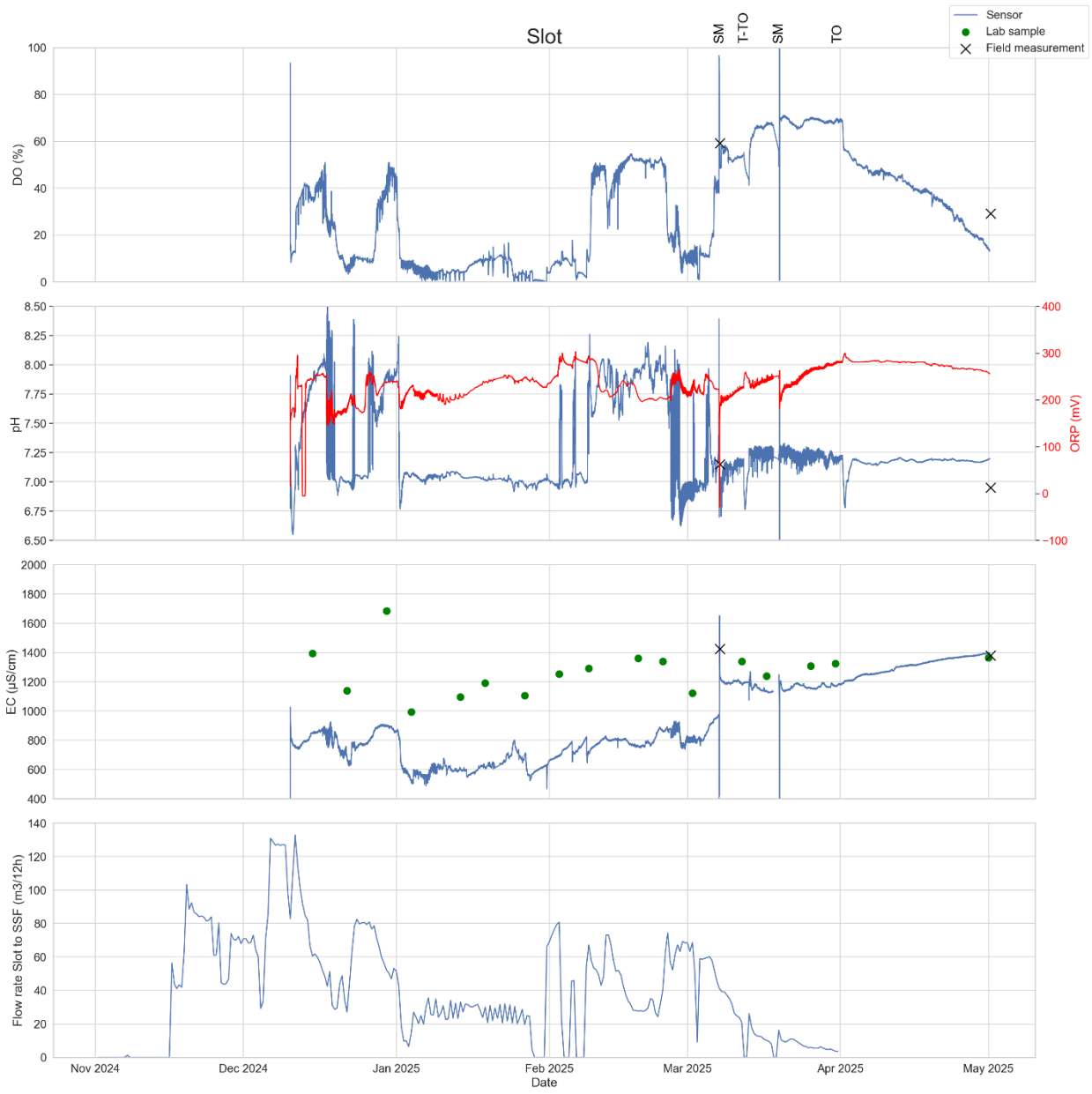

Figure 3.12 Results of the sensor data in the Slot well

Note: The upper figure shows the dissolved oxygen data, with two field measurements (x). The second figure shows the pH data (blue) with two field measurements (x) as well as the oxidation-reduction potential (red). The third figure shows the electrical conductivity of the water, together with two field measurements (x) and the results from the laboratory analyses (green dots). The fourth figure shows the flow rate of the water being pumped from this well to the Slow Sand Filter, to eventually be infiltrated. The letter codes above the plots indicate important events: SM = sensor maintenance; T-TO = temporary turn-off of installation; TO = turn-off of installation

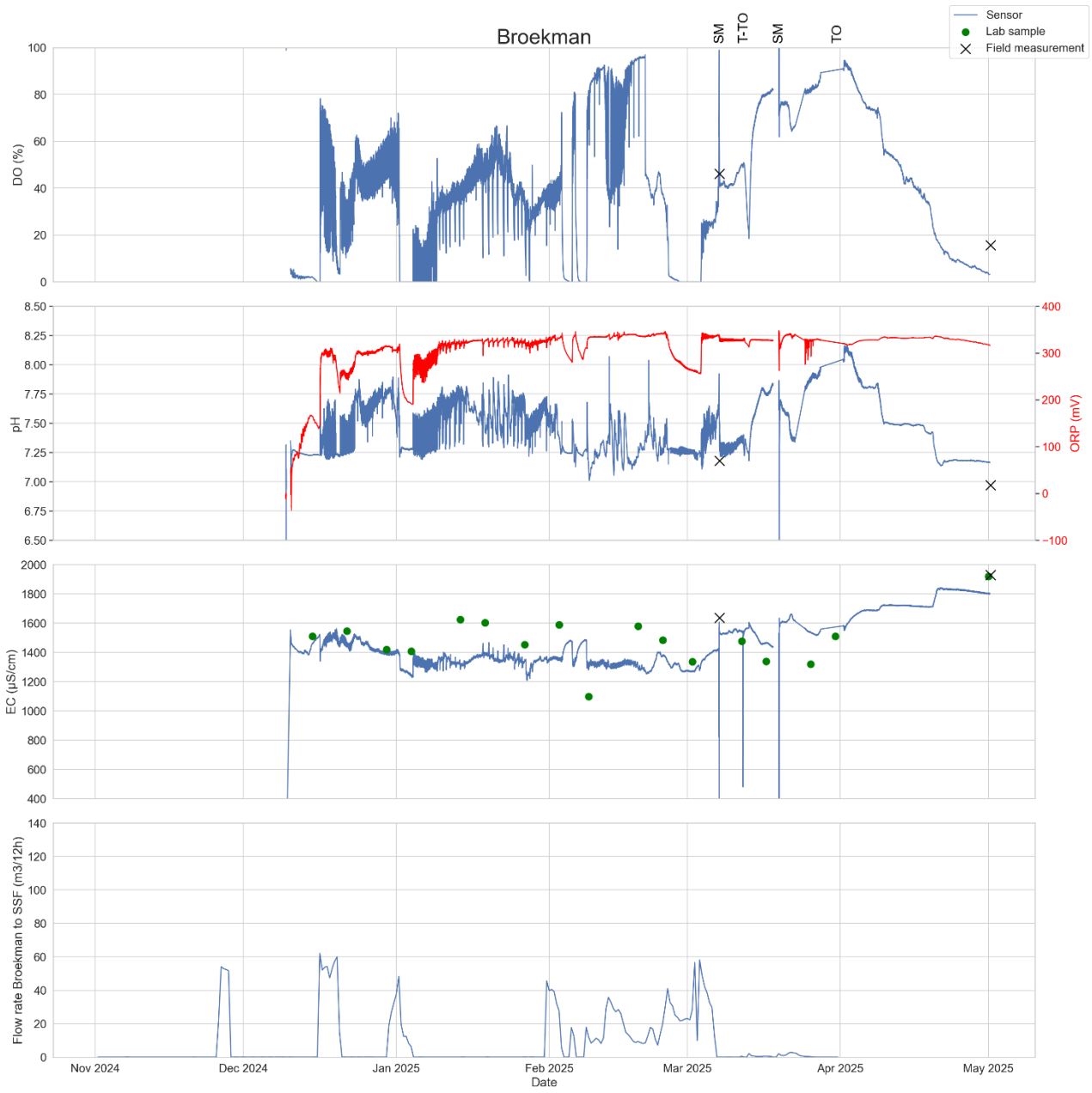

Figure 3.13 Results of the sensor data in the Broekman well

Note: The upper figure shows the dissolved oxygen data, with two field measurements (x). The second figure shows the pH data (blue) with two field measurements (x) as well as the oxidation-reduction potential (red). The third figure shows the electrical conductivity of the water, together with two field measurements (x) and the results from the laboratory analyses (green dots). The fourth figure shows the flow rate of the water being pumped from this well to the Slow Sand Filter, to eventually be infiltrated. The letter codes above the plots indicate important events: SM = sensor maintenance; T-TO = temporary turn-off of installation; TO = turn-off of installation

Flow rate data

The lower graphs in both Figure 3.12 and Figure 3.13 show the flow rate of the water being pumped from either collection well to the SSF. Figure 3.12 shows clearly the start of the infiltration period being halfway through November 2024. The infiltration period ended April 1st, 2025. Notably, from the Broekman well much less water has been pumped towards the SSF than from the Slot well. However, this does not necessarily mean that there was less tile drainage water entering the Broekman well. The water from the Broekman well has been of lower quality than that from the Slot well. As a result, it was occasionally discharged to surface water instead of being used for infiltration, due to insufficient quality. So, when there is a zero-flow rate, it does not necessarily mean that there was no new tile drainage water entering the well; it only means that no water was pumped from the well to the slow sand filter.

The data shows clearly when infiltration has started and stopped, but the data does not show when the drainage started and stopped running. Unfortunately, there is no data available on this latter point.

3.5.5 Laboratory samples

The laboratory samples were taken weekly by the farmer and picked up monthly by Acacia to its Water lab. Aside from measuring nitrate, TOC and EC to confirm sensor results, Acacia has also measured other cations and anions (the IC that measures nitrate automatically includes these as well). The results of these laboratory samples are plotted in the Piper diagram in Figure 3.14. This plot provides a visual representation of the chemical composition of the water samples, based on the major cations and anions. Three of the samples have raised some suspicions, as they were labelled either 'Slot' or 'Broekman', but their chemical composition appears more consistent with the other location. This becomes even clearer when looking at the sulphate concentration specifically in Figure 3.15. The samples might have accidentally been swapped on December 30th, and the farmer might have taken the Slot sample twice by accident on February 9th.

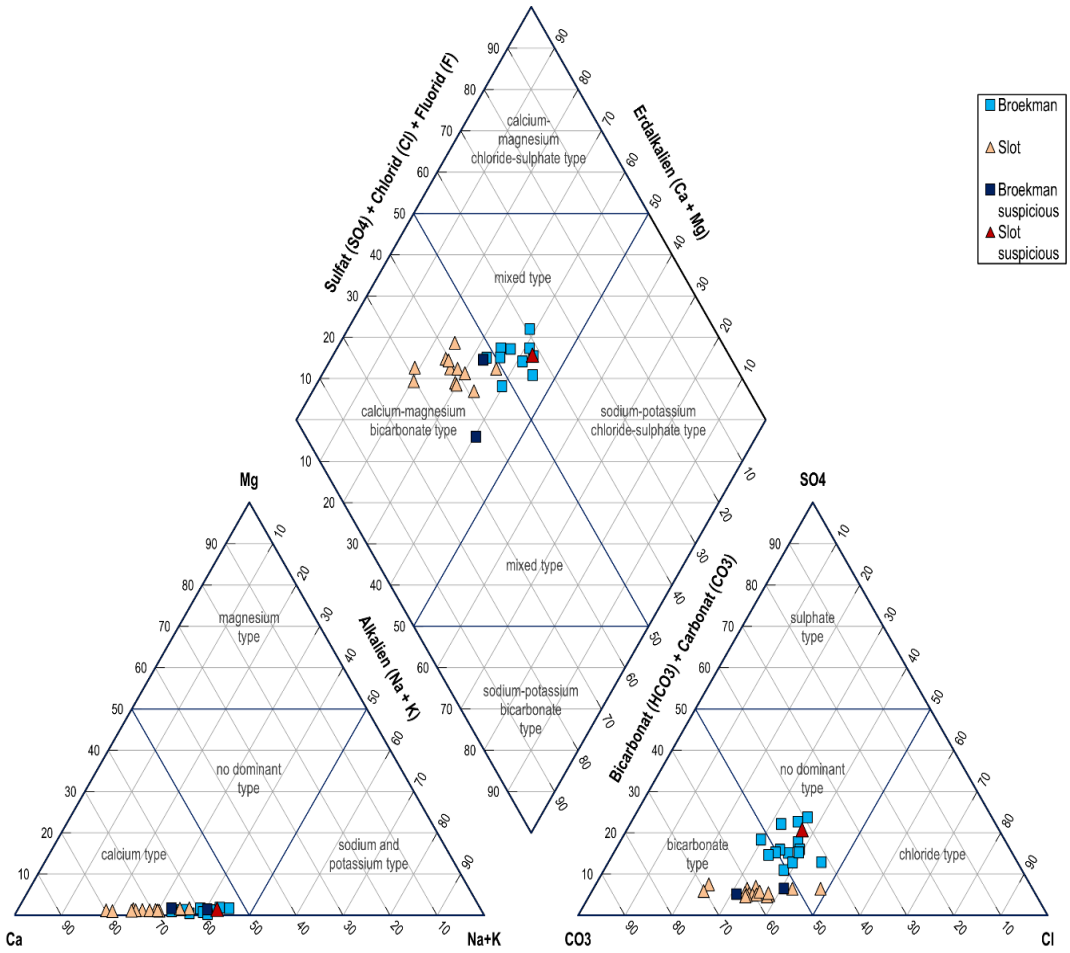

Figure 3.14 Piper diagram showing the chemical composition of the water samples from the Broekman and Slot wells. Three samples are highlighted which have raised suspicions on whether the samples have been labelled correctly

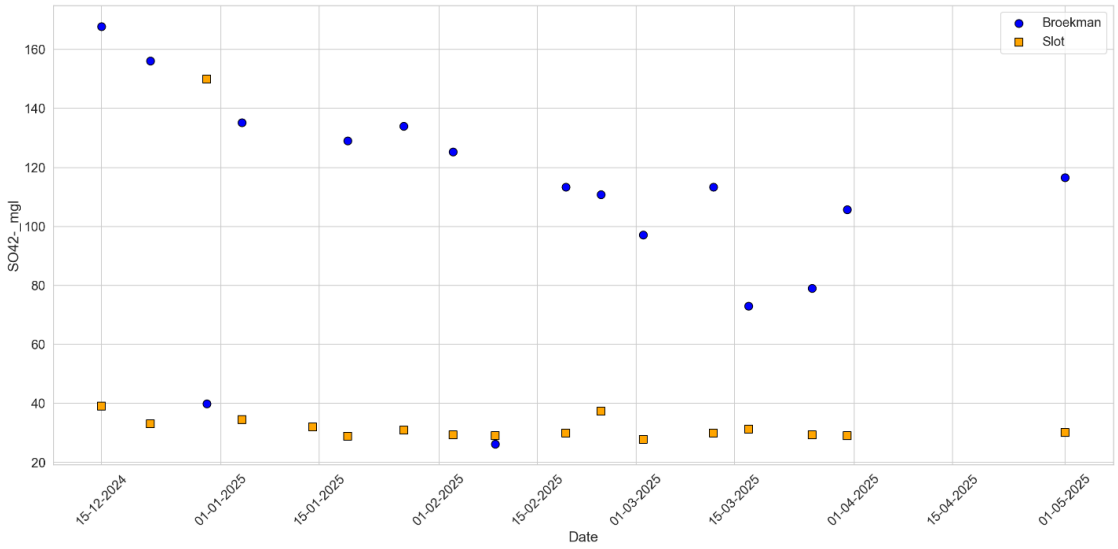

Figure 3.15 Sulphate concentrations from the laboratory samples. Three samples have raised suspicions on whether the samples have been labelled correctly (Broekman Dec 30th, Broekman Feb 9th, Slot Dec 30th)

3.5.6 Concluding the infiltration season

The infiltration season was concluded and the installation turned off on March 31st, 2025. No rainfall was to be expected for the coming weeks and because the season had already been dry for a long time, any water that would fall would be used to raise the moisture levels in the agricultural field first, before any water would be left for infiltration. Therefore, no more laboratory samples were taken after this date, except for the day the sensors were removed. The sensors were removed on May 1st, 2025, and brought to the Acacia Water offices for cleaning and maintenance.

3.5.7 Preparing for the upcoming rainy season

For the upcoming rainy season, expected to start in September 2025, Acacia wants to be fully prepared and have overcome the issues from last season. Of course, a precipitation deficit is not something that can be controlled (though Acacia is acquiring additional data from another project, see next section), but the fouling of the sensors will be addressed.

Firstly, Acacia team is working towards ensuring the availability of telemetric data transmission. This not only means that MARCLAIMED partners will be able to process data more easily for the development of MARVIS, but Acacia will also be able to see more quickly whether the sensors have gotten dirty. In the previous period, it would only become known after having retrieved the data manually, which meant that a period of data gathering would already have been lost. With telemetric transmission the SQI-value (which indicates the

quality of the data) can be reviewed much more frequently and sensor maintenance can be scheduled as quickly as possible.

Secondly, Acacia will install a TTrig device on the TriOS NICO sensor which automatically cleans the optical lenses and will reduce the need for manual cleaning considerably. The TTrig device will be tested in the months prior to the rainy season and sensor installment.

Acacia will re-install the sensors in August 2025 to ensure any issues encountered are handled before the rainy season and the sensors are 'ready-to-go' when the rain starts. Acacia will then continue with weekly sampling and monthly sample pick-ups. Manual maintenance of the sensors will be continued for the pH-ORP, DO and EC sensor, as these do not have TTrig-like devices to add on. Sensor calibration will be performed in August, ahead of the rainy season, as well, and will be repeated during each field visit.

A monitoring protocol has been developed to guarantee a smooth procedure while maintaining the Nitrate sensors in the field and collecting the samples for data validation

3.5.8 Integration of AGRICOAST data

At the same site, TU Delft has been collecting similar sensor data from the filter installation. Their sensors are installed in the standing water above the SSF representing the inlet concentration, and in the collection tank, where the water from both SSFs is collected, representing the outlet concentration. Their objective is to monitor the effectiveness of the SSF in removing nitrates. The sensors they have installed are a TriOS NICO nitrate sensor, pH sensor, DO sensor and turbidity sensor. They do not have an EC sensor installed. The TU Delft are willing to share their data with us to use possibly for the development of MARVIS, because the inlet water is very similar to the water in the field wells (Broekman and Slot). Notably, the differences are:

- Before the water from the field wells Broekman and Slot are passed through the SSF, they are mixed together. This means that the 'inlet' data from TU Delft represents the mixed water from Broekman and Slot.
- After the water is mixed and before the water is transported to the SSF, the water is passed through a paper band filter to remove particulate matter. Particulate matter leads to a lot of clogging in the Slow Sand Filter, which is why they installed it at the start of the 2024-2025 infiltration season. This means that the 'inlet' data from TU Delft will be of much cleaner water, with much less particulate matter, than the water from the field wells Broekman and Slot.

Acacia is expecting to receive the complementary data at the end of June 2025.

3.6 MARCLAIMED IDST implementation

3.6.1 MARCLAIMED tools implementation

Extensive details on application of each of the MARCLAIMED tools in DS3 and associated first results are provided in the WP1 deliverables:

- D1.1 – Predictive Models for MARVIS, PREDMAR and MARAISER
- D1.2 – MAR with AWR impact at municipal scales for OASIS FLOW
- D1.3 – Economic and financial aspects for MARINSURE and RECOVER

At this stage of the project, the integration of the tools within the IDST is still in progress. Therefore, no other details regarding the site-specific implementation of each tool in DS3 can be provided at this time.

3.6.2 Input data gathering

At this stage of the project, due to the technical difficulties encountered in DS3 to operate the online sensors, no clear data gathering process has been fully decided and the matter is still being discussed.

3.7 Conclusions

DS3 provides a test case for small-scale agricultural MAR systems. The MARCLAIMED improvements on the system aim to optimize water recharge and recovery by implementing new tools and monitoring systems. To date, improvements on the ASR system operation include adding filter band paper to reduce clogging at the surface of the slow sand filter, making improvements on the drainage of the plot, and recovering optimal volumes of water to grow the freshwater bubble. Water quality sampling during the first two infiltration seasons (2022-2023 and 2023-2024) indicated that pesticides are rarely found above detection limits in water post-filtration. Nitrates and phosphates are found at or above allowable infiltration limits prior to filtration, but the SSF/GAC combined with denitrification removes nitrates and phosphates to allowable concentrations.

The third season of infiltration from November 2024 to April 2025 is the first one to occur during the MARCLAIMED project. At the beginning of the season, the two new nitrate sensors were installed in two wells. During the winter of 2024-2025, rainfall was much less than expected due to drought conditions. This resulted in infiltration ending earlier than expected. Combined with fouling of the sensors due to iron precipitation, the amount of data collected from the nitrate sensors was limited. Additional weekly sampling from each of the two capture wells provided data back-up and confirmation. However, even with sub-optimal conditions, the system was able to infiltrate a total of 19500 m^3 of water, similar to the volume of the much rainier 2023-2024 season.

Tools incorporated to DS3 by MARCLAIMED will make improvements to system optimization. The MARAISER early-warning tool will also improve system optimization surrounding water quality and quantity. Water availability forecasting will be made possible by the PREDMAR tool to improve optimization of water infiltration and recovery volumes. The introduction of the two MARCALIMED nitrate sensors will be used for the MARVIS tool and allow for development of the IDST.

Looking forward to the next infiltration season in the winter of 2025-2026, improvements to the nitrate sensor operations will allow for better data collection. Namely, there will be automatic lens cleaning device installed on each sensor so that fouling doesn't result in loss of data. Additionally, the telemetric systems will be operational starting in August 2025, so that system operators can observe data at 5-minute intervals rather than relying on monthly data collection. This will also provide the ability to discover any issues in data collection early so that a solution can be implemented in a timely manner. In addition to issues with the nitrate sensors that will be addressed in 2025-2026, the ongoing challenge surrounding clogging of the horizontal wells will be better understood through MARCLAIMED improvements via improved data analyses.

3.8 References

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4 Conclusions

Deliverable D4.3 presents the progress made at the three Demo Sites (DS) of the MARCLAIMED project as it approaches the mid-term period.

Demo Site (DS1) is in the Mediterranean coastal aquifer of Baix Llobregat, in the region of Barcelona, northeast Spain, DS2 is located at Comporta, in the Alentejo region, Portugal, and DS3 is located on Texel, one of the Dutch Wadden islands in the province of North Holland, the Netherlands. The DS are facing different challenges, from increasing water stress due to climate change, to water quality improvement needs, and intensive land use water provision. Therefore, different MAR solutions were implemented and are being analysed: DS1 - MAR scheme using reclaimed water, aiming to enhance groundwater availability, improve water quality, and reduce dependency on conventional water sources; DS2 - SAT-MAR system composed of four infiltration basins that receive the wastewater treated effluent to further improve water quality; and DS3 – ASTR-MAR system to store water from agriculture runoff, that accumulates in the wet season in the deep aquifer, to be further retrieved in the dry season to be used for subsurface irrigation.

The project Demo Sites are therefore demonstrating the potential of MAR systems across diverse operational contexts (e.g., urban and agricultural) and for different MAR schemes (e.g., infiltration ponds/basins, ASTR). The developments in the three demonstration sites highlight a clear progress in enhancing groundwater quality and quantity (KPI_6.1 and KPI_6.3), optimizing recharge operations (KPI_6.2), and improving system resilience through technological innovation tools (KPI_6.4 and KPI_6.5) and results-based decision-making (KPI_3.2).

The main progress in each DS can be summarized as follows:

- At DS1, the integration of an infiltration pond and a deep injection well has resulted in a combined recharge of over 2.1 hm^3 by mid-2025, contributing significantly to local aquifer recovery and reduced exploitation pressure. Extensive monitoring confirms the effectiveness of natural attenuation, with high removal efficiencies for pathogens, CECs, and nutrients, particularly at the Sant Vicenç dels Horts pond. Operational adjustments, such as extended recharge cycles, have further improved nitrate removal, while Well 18 demonstrated stable performance under changing water qualities.

- At DS2, SAT-MAR infiltration basins have met expectations, showing no significant contamination from heavy metals or pharmaceuticals, an important reassurance given the limitations of conventional small WWTPs. However, persistent nutrient levels (N and P) at the TWW discharge underscores the need for further treatment at the WWTP, aligning with the updated Urban Wastewater Directive. Basin B2 (with 15% Granular Activated Carbon) has shown higher contaminants removal

performance, offering a promising example for scaling-up across other similar WWTP situations. Continued monitoring and adaptive management will guide decisions on basin adaptations and treatment upgrades.

- At DS3, the tile drainage combined with ASTR-MAR system showcases successful small-scale MAR applications tailored for water reuse in irrigation. System upgrades, including enhanced filtration and sensor integration, have sustained infiltration volumes even under drought conditions. Water quality remains compliant, with effective nitrate and phosphate removal. Despite some technical setbacks (such as iron-related sensor fouling), the planned improvements in sensor functionality and telemetric monitoring for 2025–2026 are expected to further enhance operational reliability and data quality.

Together, these findings affirm that MAR, when supported by robust monitoring, operational flexibility, and smart digital tools, can play a central role in addressing water scarcity in a climate change context (more extreme water-related situations), enhancing recharge efficiency, and safeguarding groundwater quality. The site-specific experiences from DS1, DS2, and DS3 offer valuable lessons for broader MAR deployment in diverse hydrogeological and regulatory contexts.

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.

MARCLAIMED

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