MENAWARA

WP3. ACTIONS TO INCREASE THE QUALITY OF NON CONVENTIONAL WATER USED IN AGRICULTURE

Output 3.5. Report on the efficiency of the implemented pre and post treatments and MAR systems

A 3.5.1 Evaluation of the efficiency of MAR systems. Nitrate Vulnerable Zone of Arborea, Italy

Responsible partner: NRD-UNISS

26/01/2024

Menawara is a project funded by the EU unded the ENI CBC Med programme. Its total budget is €2.901.546,93 out of which €2.611.392,23 as EU funding (90% contribution).

This document has been produced with the financial assistance of the European Union under the ENI CBC Mediterranean Sea Basin Programme. The contents of this document are the sole responsibility of the LB, NRD-UNISS and can under no circumstances be regarded as reflecting the position of the European Union or the Programme management structures.

The 2014-2020 ENI CBC Mediterranean Sea Basin Programme is a multilateral Cross-Border Cooperation (CBC) initiative funded by the European Neighbourhood Instrument (ENI). The Programme objective is to foster fair, equitable and sustainable economic, social and territorial development, which may advance cross-border integration and valorise participating countries' territories and values. The following 13 countries participate in the Programme: Cyprus, Egypt, France, Greece, Israel, Italy, Jordan, Lebanon, Malta, Palestine, Portugal, Spain, Tunisia. The Managing Authority (JMA) is the Autonomous Region of Sardinia (Italy). Official Programme languages are Arabic, English and French. For more information, please visit:

www.enicbcmed.eu.

The European Union is made up of 28 Member States who have decided to gradually link together their know-how, resources and destinies. Together, during a period of enlargement of 50 years, they have built a zone of stability, democracy and sustainable development whilst maintaining cultural diversity, tolerance and individual freedoms. The European Union is committed to sharing its achievements and values with countries and peoples beyond its borders.

TABLE OF CONTENT

ABBREVIATIONS AND ACRONYMS

Acronym	Description
NRD-UNISS	Desertification Research Centre, University of Sassari
DNRA	Dissimilatory Nitrate Reduction to Ammonium
FIA	Forested Infiltration Area
HPLC	High-Performance Liquid Chromatography
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ISE	Ion-Selective Electrode Method
MAR	Managed Aquifer Recharge
O&M	Operation and Maintenance
PTS	Passive Treatment System
TWW	Treated wastewater
WP	Work Package

1. Background

This technical report has been written in the context of the third Work Package (WP3) of the MENAWARA project on *Non-conventional Water Re-use in Agriculture in Mediterranean countries* and more specifically for **Output 3.5 "Reports on the efficiency of the implemented pre and post treatments and MAR systems"** and **Activity 3.5.1 "Evaluation of the efficiency of MAR systems"** as described in infographic below (Fig. 1).

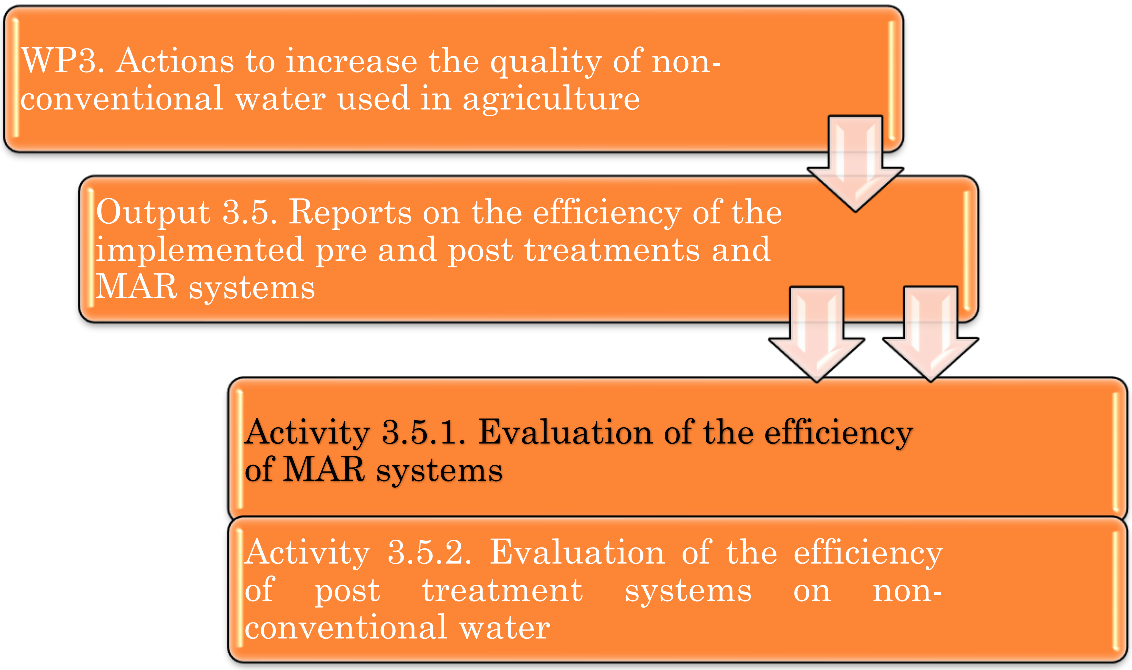

Figure 1. Infographic on the context of this technical report

More specifically the Output 3.5 is described as follows: "Technical reports on the assessment of the efficiency of the implemented treatments and MAR systems will be produced by all involved partners supervised by CENTA. They will include all monitoring data related to the quality of the inlet water and TWW coming out from the post-treatment systems, the recharge water used for the FIA systems and groundwater of the sandy aquifer in Arborea as well as the Operation and Maintenance (O&M) activities carried out and the lessons learned".

This document details the quality of drainage water, deep drainage, and groundwater coming out from the FIA system implemented at the pilot site of Arborea, Italy; the monitoring and a preliminary evaluation of the FIA efficiency through bulk analytics, infiltration rate, soil moisture content and GHG emission over the period from June 2023 to September 2023, as part of Activity 3.5.1 "Evaluation of the efficiency of MAR systems".

The results of this report are complementary to the technical aspects of outputs 3.3 "Pre and post-treatments and MAR systems designs" and output 3.4 "No. of pre and post-treatment and MAR systems realized".

The document is structured as follows:

1) an introduction and general overview of the FIA system in Arborea (section 2);
2) the methodology including material and methods (section 3);
3) main results of the first 4 months of the *post-operam* monitoring after the FIA implementation (section 4);
4) some concluding remarks (section 5).

2. Area of intervention

The area of intervention is located in the Arborea farming district which represents one of the most productive agricultural sites in Italy. It is located on a plain surrounded by marsh wetlands which are protected under the EU Natura 2000 directive and the Ramsar convention. There are two aquifers connected to each other: a sandy aquifer and an alluvial one. The agricultural district of Arborea, characterized by intensive dairy cattle farming, was declared a Nitrate Vulnerable Zone (NVZ) in 2005 following the application of Directive 91/676/EEC.

A Managed Aquifer Recharge (MAR) was implemented through the Forested Infiltration Area (FIA) technique (Figs. 2 and 3) to reduce nitrate contamination in the phreatic sandy aquifer.

The FIA technique is applied in a pilot site of about 0.5 hectares, where groundwater usually presents a nitrate concentration beyond the legal threshold value of 50 mg L^{-1}. Non-conventional water (drainage water) characterized by an average nitrate concentration of 60 mg L^{-1} is pumped from the adjacent dewatering pumping station of Luri and used as recharge water to supply the FIA system. Infiltration takes place in six recharge trenches with a total length of 300 m filled with a mixture of eucalyptus wood chips (49% by volume), inert material (sand and gravel, 50% by volume), and a small percentage of clay (1%) and iron oxides (0.1%). This mixture, called a "Passive Treatment System" (PTS) promotes the action of denitrifying bacteria that reduce nitrate (NO_3) to atmospheric nitrogen (N_2). The goal is to reduce nitrate concentrations in the drainage water introduced into the trenches and then use the same water to recharge and dilute the underlying contaminated aquifer. Normally, in a FIA system, the depurative action occurs in the rhizosphere, in conditions of almost oxygen-free soils and the presence of abundant organic matter provided by the woody plants. The denitrifying bacteria living in symbiosis with the roots have a very effective action to promote nitrate attenuation. In the Arborea pilot site, this function will be ensured in the medium-long term when the forested area, which includes eucalyptus and poplar trees planted along the edges of the trenches, will be fully developed. Considering that in this case, drainage water characterized by low quality is used for the aquifer recharge, the depurative action in the short term is ensured by the innovative PTS installed within the recharge trenches.

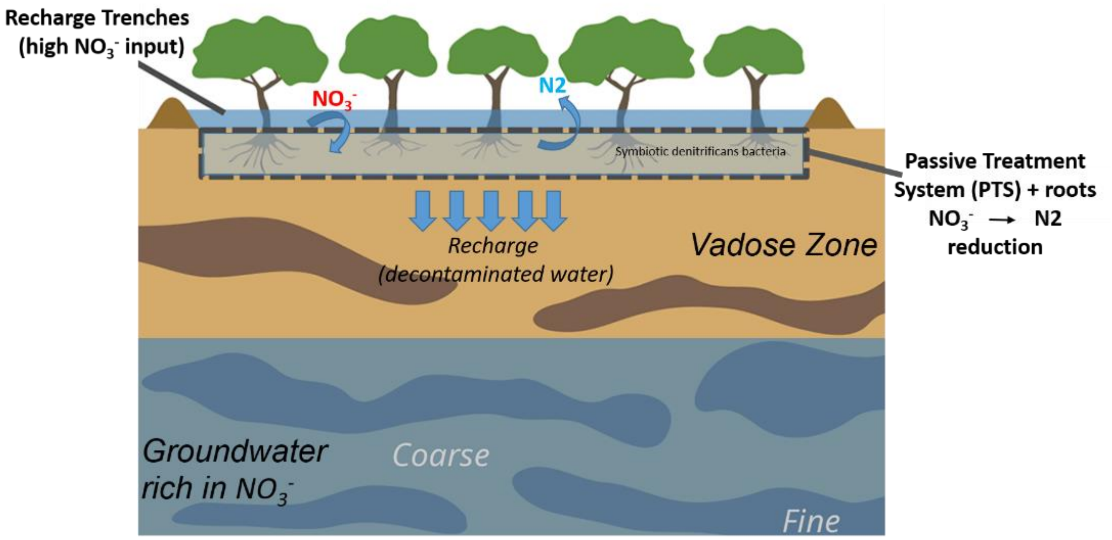

Figure 2. Scheme of the functioning of a FIA technique, with representation of the main involved processes

Figure 3. View of the FIA pilot system of Arborea

3. MATERIALS AND METHODS

The *post-operam* monitoring aims to assess the effectiveness of the FIA technique in reducing nitrate concentrations in contaminated groundwater. Table 1 provides an overview of the monitored variables, laboratory analytical methods, field instrumentation, and sampling strategies. However, based on the data results, the monitoring scheme is continuously adjusted to better observe the involved processes and dynamics.

The effectiveness of the FIA technique in reducing nitrate concentrations is evaluated through a complex monitoring network (Fig. 4), by monitoring several chemical and hydrological parameters, by laboratory analytical methods and field instrumentation. The monitoring started in June 2023 and is still ongoing. The activities were carried out until the end of September 2023 within the MENAWARA project and continued so far under the new project “NATMed - Nature-based Solutions on existing infrastructures for resilient Water Management in the Mediterranean”, funded by the PRIMA Programme, of which NRD-UNISS is a partner (2023-2026).

Water quality samples (including the pumped drainage water, ponding water in the trenches, deep drainage, and groundwater) are collected about once a week, while greenhouse gas emission monitoring started on September 15th, 2023. All automated instruments, such as a weather station, pressure transducers, and soil moisture probes, measure data every 10 minutes. Data from these instruments are downloaded every two weeks during field visits using a notebook. The inflow rate, which is equivalent to the infiltration rate as the system does not have surface water output, is measured by a flow meter. This data is transmitted remotely through an IoT system every hour and can be accessed via a cloud connection. However, based on the data results, the monitoring scheme is continuously adjusted to better observe the involved processes and dynamics.

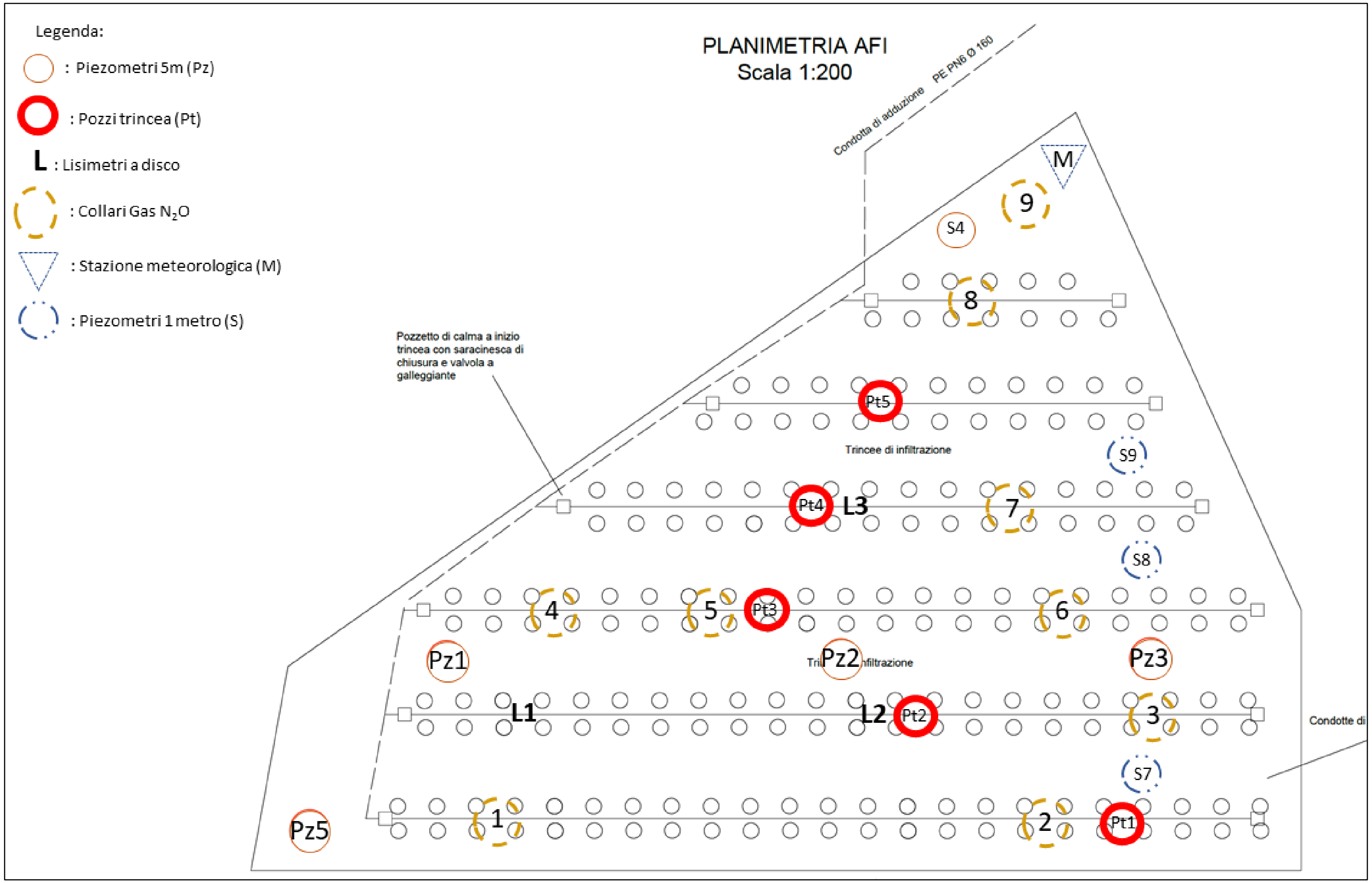

Figure 4. *Post-operam* monitoring scheme

Table 1: monitored variables, methods, sampling approaches.

Variable	Incoming flow (drainage water)	Ponding water in trenches	Deep Drainage	Groundwater	Weather	Soil	Gas emission
nutrient load (NO_3, NH_3, PO_4)	HPLC* ISE*** (NH_3)	HPLC*	HPLC* Sampling performed with 3 disk lysimeters placed below PTS https://www.soilmoisture.com/S OIL-WATER-SAMPLING- PLATE/	HPLC*	-	-	-
BOD, COD, SST	Respirometric Method for BOD; Titration Method for COD						
major anions and cations (HCO_3, Cl, CO_3, SO_4, NO_2, Na, Mg, K, Ca, NH_3, Fe, B)	HPLC* & ICP-MS** ISE*** (NH_3)	-	HPLC* & ICP-MS** Ion-selective electrode method (NH3)	HPLC* & ICP-MS**Ion-selective electrode method (NH_3)	-	-	-
some heavy metals of interest (As, Mn, Al, Cu, Hg, Pb, Zn, Cd, Cr)	ICP-MS**	-	ICP-MS**	ICP-MS**	-	-	-
Isotopes (^{15}N and ^{18}O in NO_3)	IRMS Cd method		IRMS Cd method	IRMS Cd method			

pH, Redox potential, Dissolveld Oxigen, Temperature	-	-	-	Measured in the field with flow-through cell and electrodes	-	-	-
Water flow and volumes	Flow meter with remote data transmission	-	This flow is equivalent to the incoming flow	-	-	-	-
P, T°, RH, Wind, Rad, Pressure	-	-	-	-	Automatic wireless station https://www.specmeters.com/weather-monitoring/weath	-	-

*HPLC = High Performance Liquid Chromatography

**ICP-MS = Inductively Coupled Plasma Mass Spectrometry (for cations)

***ISE= Ion-selective electrode method

4. Assessment of the FIA efficiency

This section shows details related to the dynamics of the most important parameters among those monitored (Table 1), observed during the monitoring period. The interpretation of these trends allows us to evaluate the efficiency of the FIA system, even if preliminarily taking into account the short monitoring period under consideration.

4.1. Precipitation

Precipitation is measured by a tipping gauge bucket in a weather station located in the FIA area. Measuring this parameter is important to define the water balance in the FIA area. Fig. 5 reports the precipitation observed from June 2023, when the monitoring started. Due to the semi-arid characteristics of the Mediterranean climate, precipitation was almost absent during the last summer period, with only a few rain events, sometimes of high intensity.

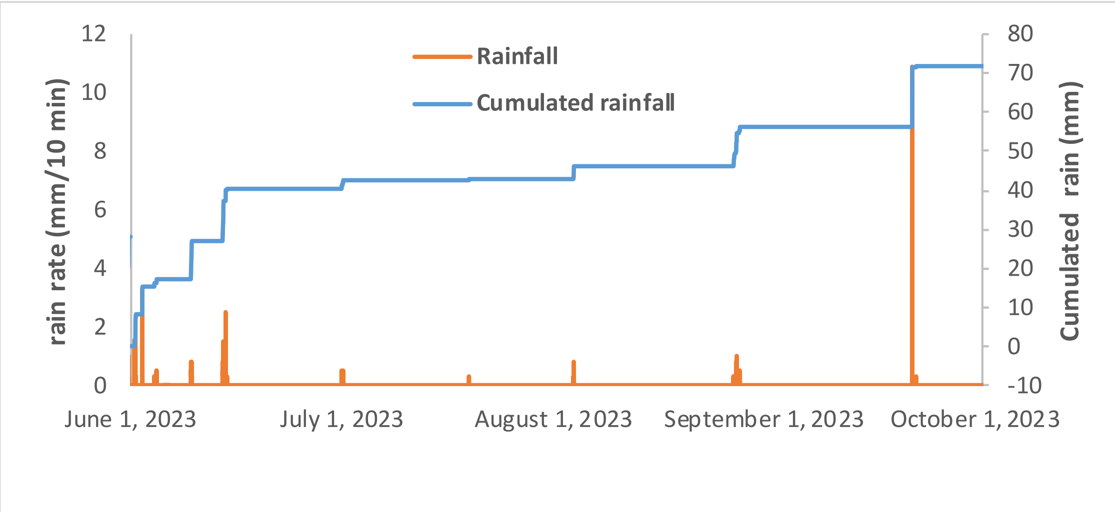

Figure 5. Observed rainfall from June to October 2023.

4.2. Water level in aquifers

The piezometric levels are observed in six piezometers installed in the FIA area, five piezometers are within the FIA plot (from Pz 1 to Pz 5) and one is outside the plot (Pz 6) (Fig. 4). These piezometers were done to evaluate the impact of the managed aquifer recharge on groundwater. The levels are monitored and stored by automatic DIVER pressure transducers (https://www.royaleijkelkamp.com/products/monitoring/sensors-and-probes/water-sensors/td-diver/) every 10 minutes and downloaded during field visits to a notebook by a dedicated application.

Fig. 6 shows the results of groundwater monitoring from June to October 2023. Piezometers Pz1, Pz2, and Pz4 were the most affected by the trench recharge, with piezometric levels increasing by about 2 m after the FIA activation at the beginning of June. Piezometer PZ5, situated at the border of the area, showed an increase of about 1 m after the start of the recharge. Finally, PZ3 was only slightly affected by the recharge, probably because its piezometric level is constrained by the proximity to a channel. Pz6, located about one hundred meters away from the trenches, was not affected by the recharge.

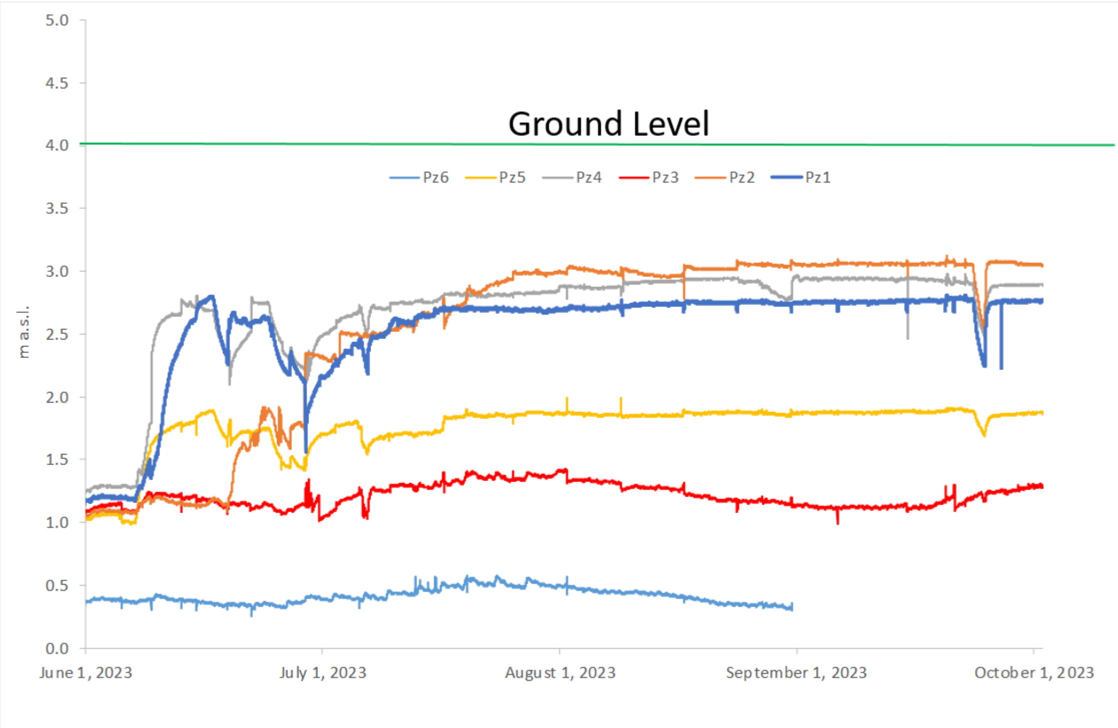

Figure 6. Water table levels observed in the FIA plot.

4.3. Infiltration capacity/rate

The infiltration rate is assessed at the field spatial scale by determining the stationary inflow to the FIA plot. Essentially, the infiltration rate is equivalent to the inflow rate, as the system lacks surface water output. The inflow rate is measured by a flow meter located in the main pipeline, encompassing data from all six infiltration trenches comprising the FIA system. Inflow measurements are obtained during field visits. The inflow rate varied over the monitoring period, primarily due to changes in water level management within the trenches. In the initial phase of FIA system activity, from the 4th of June till to 17th of July, water levels in the trenches were maintained at approximately 5 cm above the PTS. The stationary inflow rate was around 6 $m^3 h^{-1}$ (equivalent to 1.2 mm h^{-1} of infiltration rate).

On July 17th, water levels in the trenches were raised from 5 cm to 10 cm above the PTS. This increase amplified the vertical hydraulic gradients and the portion of water infiltrating through the sloping walls of the trenches. Consequently, the inflow rate rose to 10 $m^3 h^{-1}$, corresponding to a stationary infiltration rate of 2 mm h^{-1}. These values will serve as a reference for the future, especially when addressing clogging processes at the infiltrating surface, which are expected to significantly reduce the infiltration rate. Thus, the changes in infiltration rates over time enable us to evaluate the hydraulic performance of the system, a critical factor in determining the lifespan of the FIA.

4.4. Soil moisture content

Soil moisture dynamics are observed in three locations within the FIA plot. Specifically, a soil moisture probe is positioned midway between two trenches (SENTEK 1 in Fig. 7), while the other two probes (Figs. 8 and 9) are situated 0.5 m from the trench border. Sentek soil moisture probes utilizing capacitance-based technology are employed for measurements. (https://sentektechnologies.com/products/soil-data-probes/drill-drop/). For each probe, twelve soil moisture measurements are taken along a vertical profile, spaced 10 cm apart, starting from 5 cm below ground level. Measurements are collected at 10-minute intervals and stored in a CR1000 data logger.

In general, the surface soil exhibited drier conditions compared to the deeper layers, attributed to surface evapotranspiration processes. Consequently, more pronounced temporal fluctuations are observed in the superficial soil. As soil depth increases, moisture levels become relatively constant over time, indicating the sensors are in the capillary fringe. Consequently, changes in groundwater levels, driven by water table fluctuations within the trenches, result in rapid variations in soil moisture values. These variations are more noticeable in probes near the trenches (SENTEK 2 and 3) compared to the probe positioned midway between the trenches (SENTEK 1). The observations align with expectations based on hydrological processes, such as the presence of the capillary fringe and evapotranspiration. This suggests that the measurements provided by the soil moisture probes are reliable, which is a fundamental condition for the continuation of monitoring.

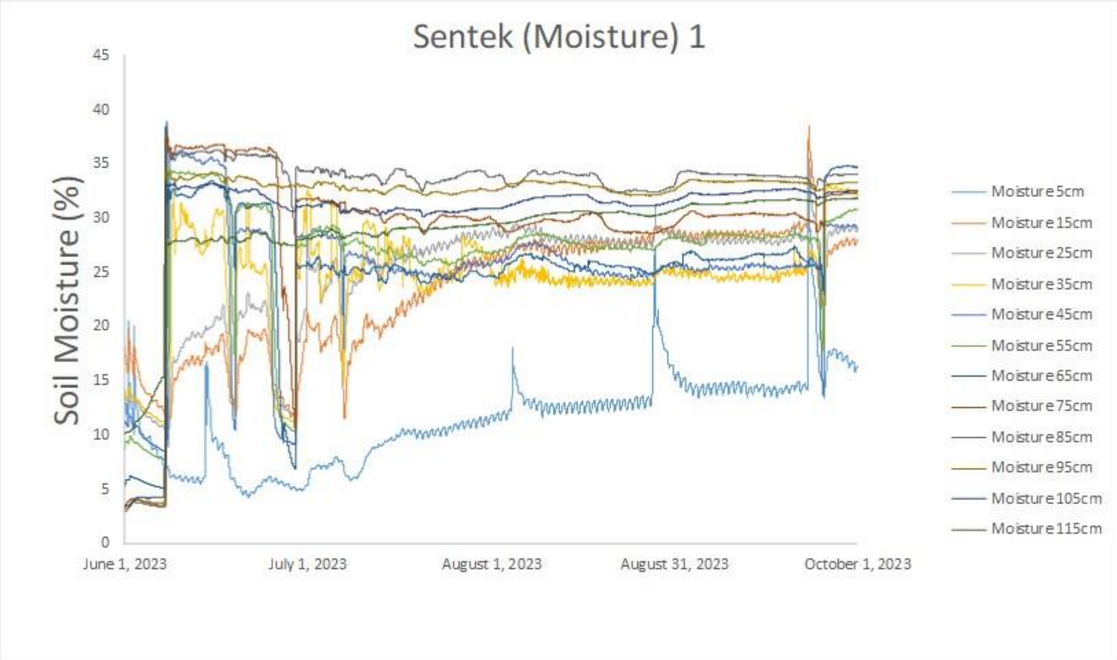

Figure 7. Soil moisture vertical profile observed by the Sentek soil moisture probes located midway between the trenches

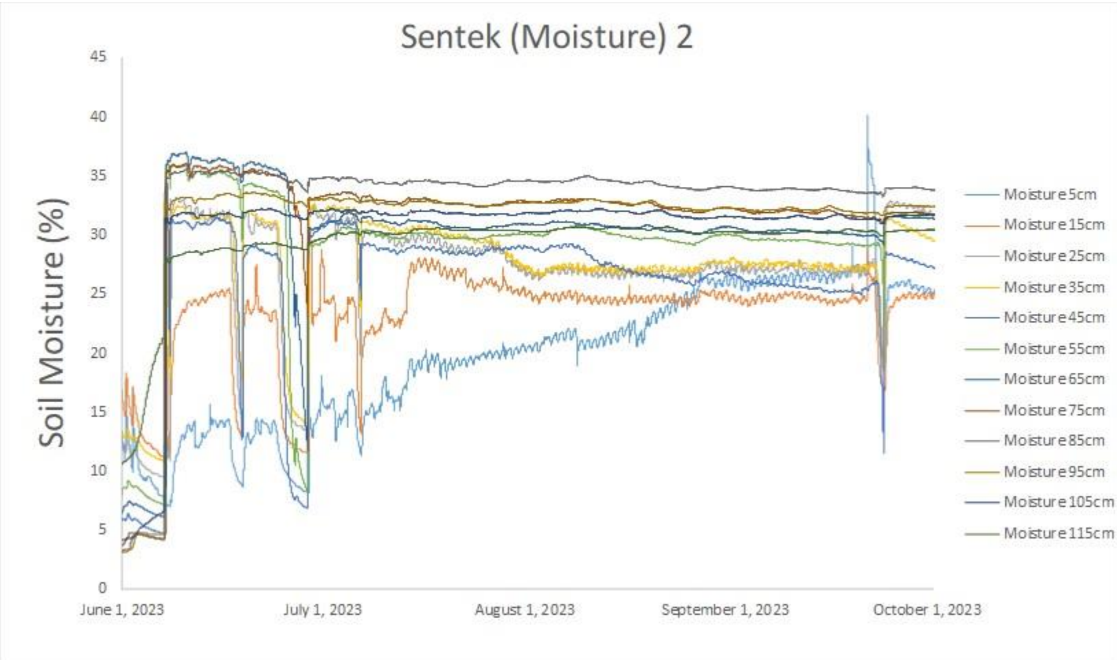

Figure 8. Soil moisture vertical profile observed by the Sentek soil moisture probes located at the border of the trench

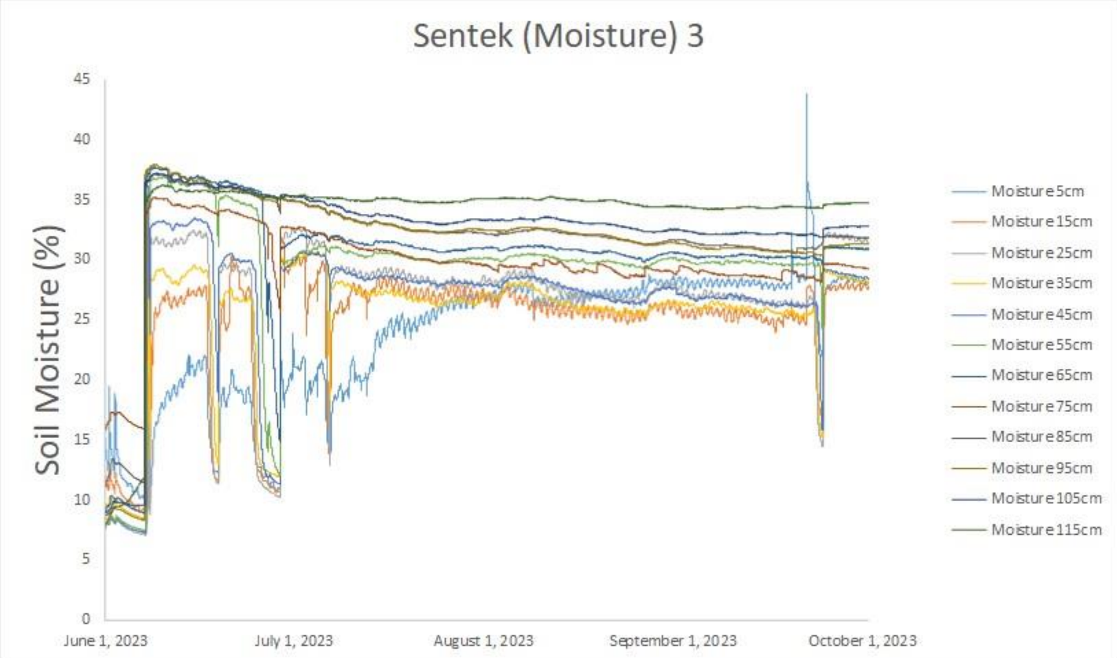

Figure 9. Soil moisture vertical profile observed by the Sentek soil moisture probes located at the border of the trench

4.5. Water temperature

For the denitrification process within the PTS, water temperature is a fundamental parameter, as microbiological processes depend on the temperature of the medium. Temperature fluctuations in the PTS are observed at two locations within a trench by two T107 soil moisture probes (data stored every 10 minutes in a CR1000X datalogger). Fig. 10 shows the mean PTS temperatures in comparison with the time series of the air temperature observed at the weather station. While the air temperature reached very high values, exceeding 40°C at the end of July, the PTS temperature was dampened, showing maximum values of 31°C, with the minimum observed being 19°C. Hence, the PTS had water temperatures that seem to fall within the optimum range for the activity of denitrifying bacteria.

4.6. Calculation of evapotranspiration

Potential evapotranspiration (ETo) is calculated on a daily timescale using the Penman-Monteith formula, incorporating temperature, relative humidity (RH), wind speed, and solar radiation data observed at the weather station located at the FIA plot. The calculated ETo will be utilized in the future for water balance calculations. Fig. 11 illustrates the ETo values for the period between June and October 2023, ranging from 4.5 to approximately 8 mm day^{-1}. These values align with the potential evapotranspiration usually observed in summer for the Arborea area.

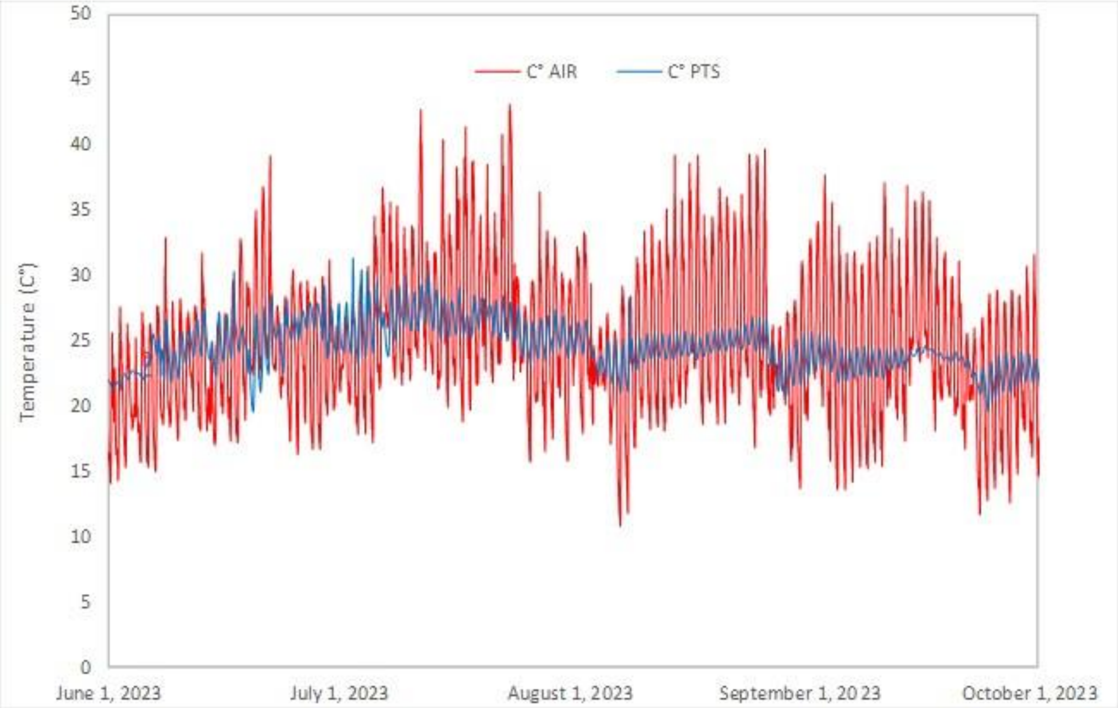

Figure 10. Time series of the temperatures of the PTS and of the air.

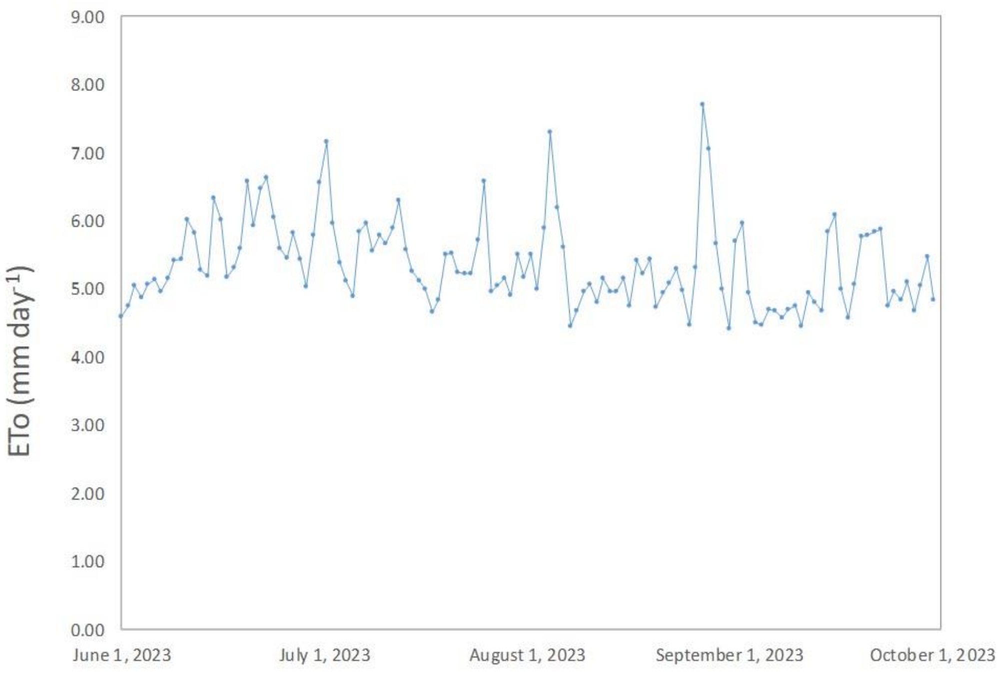

Figure 11. Daily potential evapotranspiration in summer 2023

4.7. Nutrient parameters in water (NO_3, PO_4)

Nitrate (NO_3) concentration is determined in several monitoring points within the FIA plot. Specifically, NO_3 is evaluated in the incoming flow (IN), in three porous disk lysimeter placed at the base of the PTS (LIS1, LIS2 and LIS3), and in groundwater (in piezometers, from Pz1 to Pz6) (Fig. 4). The sampling procedure always includes a first phase of purging, consisting in removing the water accumulated within the measurement point (disk or piezometer), and then collecting the sample fresh water.

The analytic determinations are done in the laboratory using HPLC standards methods (HPLC = High Performance Liquid Chromatography). Sampling is performed every six-ten days.

Fig. 12 compares the nitrate concentration detected in the supply water to the FIA and the three disk lysimeters below the recharge trenches. After an initial phase of adaptation, it can be noted that the PTS realized an effective removal of the nitrate dissolved in the inflowing water, as the concentration immediately below the trenches was around 10-20% of that of the water used for the aquifer recharge.

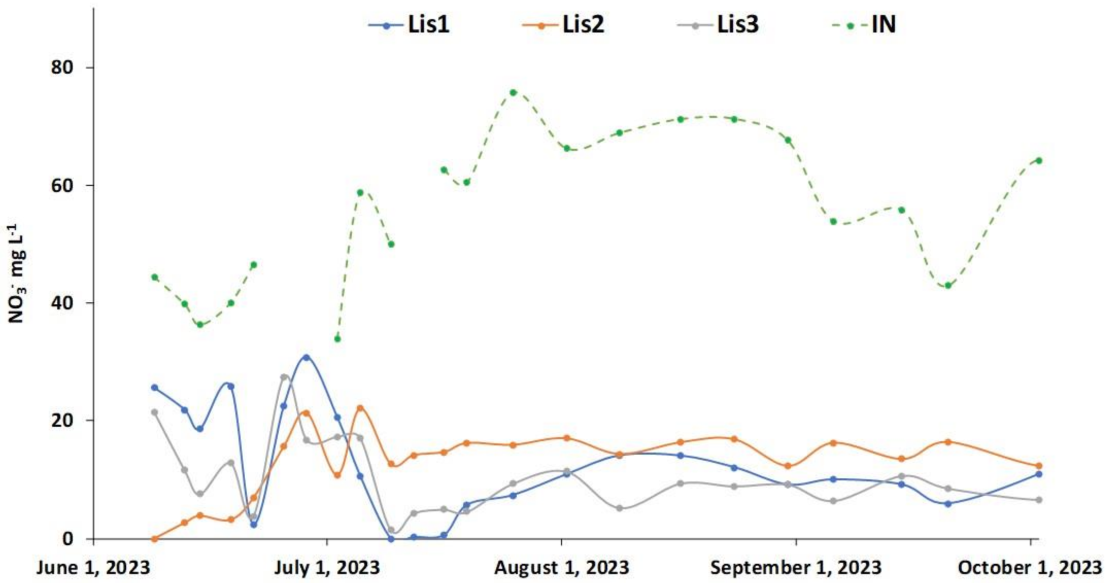

Figure 12. Nitrate concentration in the supply water (IN) to the FIA and the three disk lysimeter (LIS) below the recharge trenches

Regarding the groundwater monitored in the piezometers within the FIA (Fig. 13), contrasting data were obtained. In fact, piezometers 2 and 3 showed nitrate concentrations much lower than the other piezometers, and a clear descending trend from June to October. Conversely, PZ1, Pz4 and Pz5 exhibited nitrate concentration in line with the supplied water, indicating that here the water quality was less affected by the trench recharge. The piezometer PZ6, not shown in the graphs, located outside the FIA plot, during the monitoring period always showed a negligible nitrate concentration. This can be attributed to its positioning within a patch of trees of poplar, probably guaranteeing natural denitrification processes.

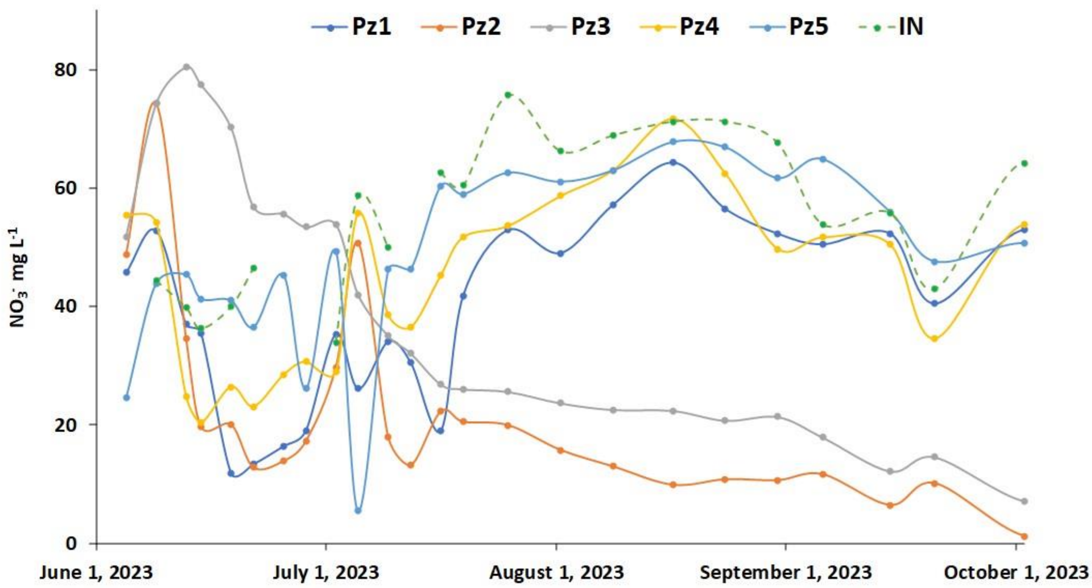

Figure 13. Nitrate concentration in the supply water to the FIA (IN) and in the five piezometers (PZ) within the FIA plot

Figs 14 and 15 show the phosphate concentration detected in the supply water, in the three disk lysimeters and the piezometer network. Note that results come from the first period of activation of the FIA and the monitoring period included between September and November 2023, while, unfortunately, there are 3 months of missing data due to an issue in the laboratory instrumentation in that period.

The PO_4 concentration observed in the supplied water was quite high and such as to justify the eutrophication phenomena observed in the water inside the trenches during the monitoring phase. At the beginning of the monitoring, the results indicate that a certain quantity of phosphate was released by the woody chips material in the PTS, as the lysimeter located within the trenches, in particular LIS2 and LIS3 showed PO_4 concentration significantly higher than that of the incoming water. This is confirmed in the last part of the monitoring for LIS3, while the PO_4 concentration in LIS2 decreased below the values measured for the incoming water (Fig. 14).

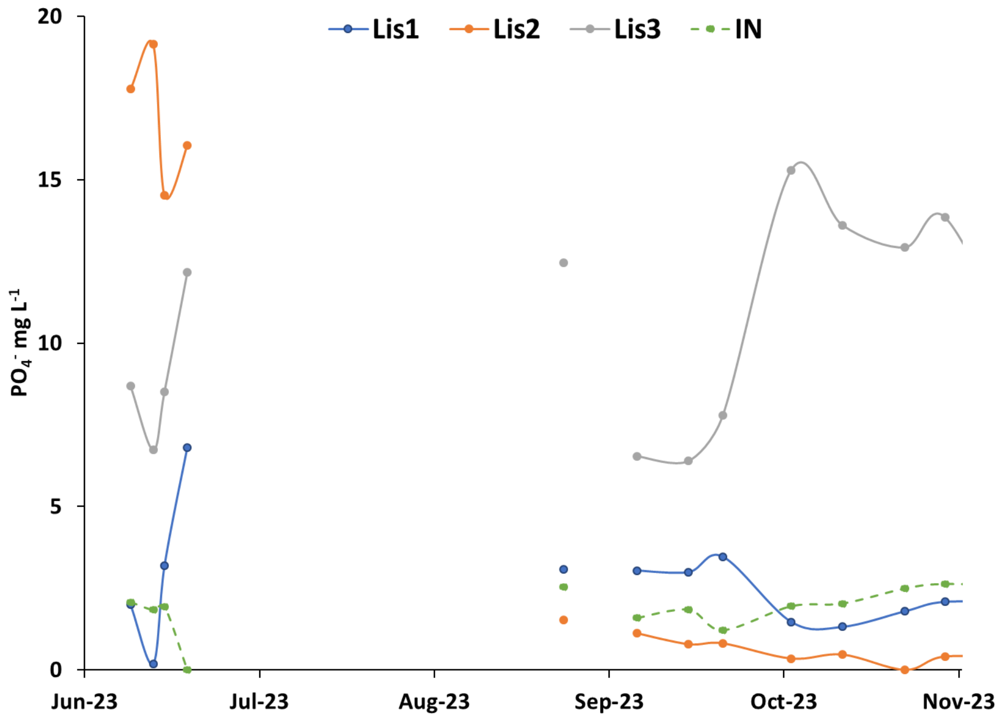

Figure 14. Phosphate concentration in the supply water (IN) to the FIA and the three disk lysimeter (LIS) below the recharge trenches

Compared to the data observed in the piezometers at the start of the period (5th of June, FIA not still activated), the concentration of PO_4 in the groundwater increased in PZ2 and PZ3, while did not change significantly in the remaining wells. This was in line with the results shown for the nitrate, as the water quality in PZ2 and PZ3 was the most affected by the managed aquifer recharge. This trend was confirmed also for the period between September and November 2023 (Fig. 15).

Overall, the results of PO4 monitoring suggest identifying solutions to attenuate the PO4 leaching from the PTS, in order to not worsen groundwater quality concerning this pollutant.

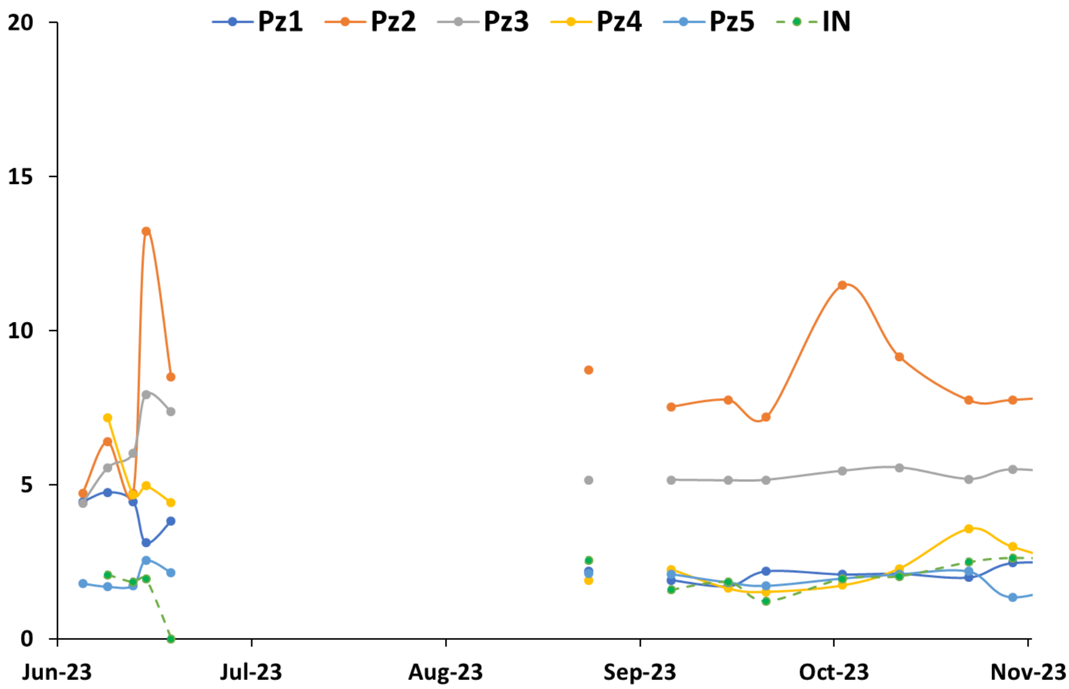

Figure 15. Phosphate concentration in the supply water to the FIA (IN) and in the five piezometers (PZ) within the FIA plot

4.8. Ammonia in water

Controlling the quality parameters in recharge water and groundwater is fundamental to understanding the dynamics of the denitrification process and detecting the potential release of undesirable products. Currently, several laboratory analyses are underway to determine the concentrations of anions and cations, and the results are not shown in this report. Among them, the concentration of ammonia (NH_3) in water samples collected from disk lysimeters and piezometers was determined. The dynamics are shown in Figs 16 and 17.

In the lysimeters below the trenches, the concentration of ammonia was greater than that introduced by the incoming flow. Additionally, an increasing temporal trend was detected in two lysimeters. Hence, there was a production of NH_3 within the PTS. The processes underlying this production could be attributed to the release of NH_3 initially stored in the PTS, then dissimilatory nitrate reduction to ammonium (DNRA) and oxidative nitrification occurring within the PTS.

Regarding the ammonia concentrations detected in the groundwater samples collected from the piezometer network, they were significantly lower than those observed in the disk lysimeters. This could plausibly be related to the dilution of recharge water in the groundwater or to some nitrification occurring during the recharge pathways. We planned to conduct further investigations, including microbiological and isotopic analyses, to clarify all these aspects.

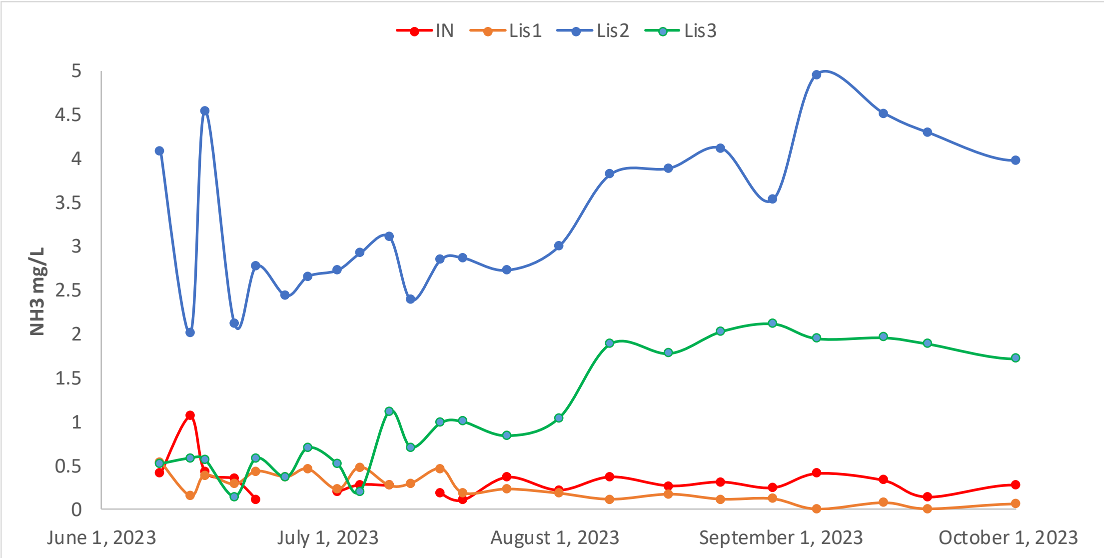

Figure 16. Concentration of ammonia detected in the recharge water collected by the disk lysimeters below the trenches

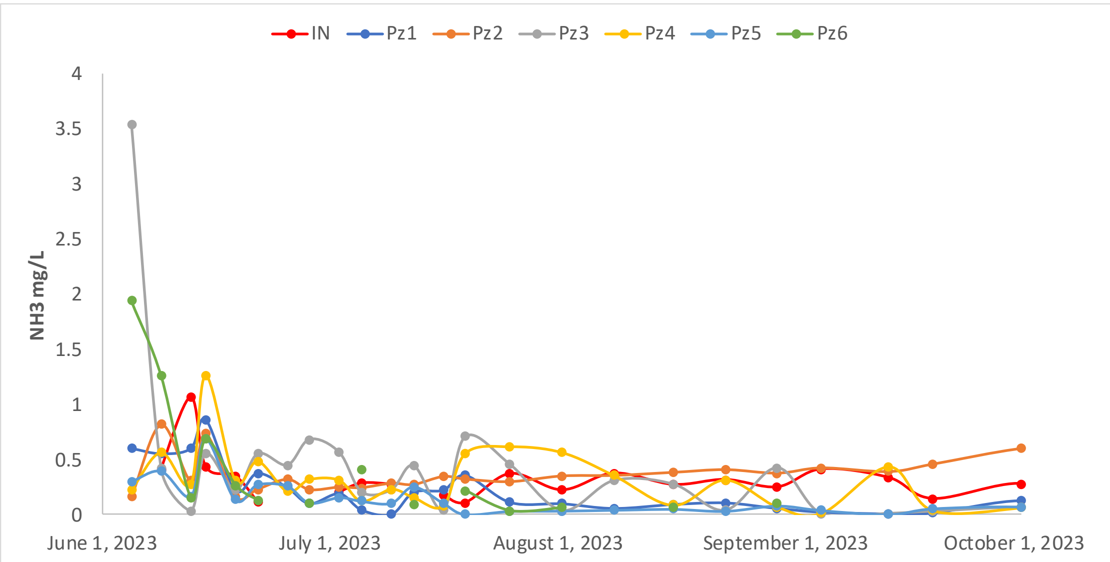

Figure 17. Concentration of ammonia detected in the groundwater collected in the piezometer network.

4.9. N_2O, CH_4, CO_2

Greenhouse gas emission was determined in 8 static chambers placed within the trenches, and one chamber placed on the soil. The monitoring was performed on two dates (15th and 20th of September 2023), following the sampling procedures illustrated in Parkin, T.B. and Venterea, R.T. (2010). Collected gas samples were analysed by gas chromatography. The results are reported in Table 2. The rates of N_2O and CO_2 emissions can be considered acceptable, considering that these were from one to two order of magnitude lower than the ones observed by Pulina et al. (2018) in the cultivated lands of Arborea. Conversely, CH_4 emission was significant, although the measures revealed very high variability. In general, all the GHG flow measurements showed a noticeable spatial variability, and these significantly changed between the two monitoring dates. This suggests the need for the future to increase both the spatial and temporal density of samplings.

Table 2: Gas emission measured in the FIA plot. CV is the coefficient of variation

	CO_2 flux ($g/m^2/h$)	**CH_4 flux ($g/m^2/h$)**	**N_2O flux ($g/m^2/h$)**
	15th September 2023 (n=8)		
Mean	1.19E-02	1.20E-04	1.92E-06
Std Dev	8.41E-03	9.80E-03	2.16E-06
CV	0.70	81.91	1.13
SOIL (1 sample)	*5.26E-02*	*-1.72E-04*	*4.63E-07*
	20th September 2023 (n=8)		
Mean	1.85E-02	2.02E-03	3.05E-06
Std Dev	1.14E-02	4.06E-03	1.85E-06
CV	0.62	2.01	0.61
SOIL (1 sample)	*6.21E-02*	*-3.52E-05*	*6.51E-06*

5. Conclusion

Four months of the FIA system environmental monitoring indicated points of strength and weakness, and suggested a road map for improving the effectiveness both of the system technique and of the monitoring network. Water quality analysis in the disk lysimeters indicated an almost complete removal of nitrate from the supplied water, indicating the effectiveness of the PTS. However, the indications coming from the piezometer network are sometimes discording, as after the start of the managed aquifer recharge, the nitrate concentration dropped in the two piezometers (PZ2 and PZ3), while remaining unaffected in the other ones. Phosphate and ammonia data indicated that some undesirable products are released by the PTS, which could deteriorate the quality of the groundwater, even if the PO_4 concentration is already quite high in the drainage water. The first data on greenhouse emissions indicates low gas release, so the FIA system could be considered a net absorber of greenhouse gases. Overall, the data collected suggested the existence of complex interactions among trench recharge, natural and induced (by PTS) denitrification processes that need to be analysed more in-depth. Moreover, considering the small size of the FIA, also the boundary conditions may have had a relevant impact on the observed concentrations. The heterogeneity of the observed response in groundwater levels and water and air quality parameters suggested that the recharge and denitrification are characterized by large spatial variability. Hence, our possibility to fully understand the denitrification dynamics will be increased by potentiating the monitoring network, by increasing the number of observation points of air and water quality. The continuation of monitoring in the coming years, through the funding of the NATMed project, will allow us to understand how the efficiency of denitrification in the PTS system may vary and evaluate the duration of its life cycle. The available analysis of PO_4 in the recharge water and also released by the PTS indicated the need to find technological solutions for reducing PO_4 leaching in groundwater. This is relevant in our environment, where groundwater and natural surface water bodies, i.e. wetlands and marshlands, are in strict communication. Future activities in the laboratory and the field will be directed to indicate how the PTS could be modified for PO_4 removal. Preliminary data for the GHG emissions indicate the need to realize a well-structured monitoring plan for evaluating gas emissions. From this point of view, considering that the trees in the FIA system are actively growing, it will be important to evaluate if the FIA system could be considered a net emitter of CO_2 and nitrogen gas by studying their full cycle.