GOOD PRACTICES HANDBOOK ON GROUNDWATER NETWORKS AND MODELS IN PILOT SITES

https://clepsydra.interreg-euro-med.eu/

Deliverable 1.2.1.

March 2025

Project title:

GROUNDWATER MONITORING & DECISION SUPPORT SYSTEM DEVELOPMENT TO OPTIMISE DECISION MAKING IN SENSITIVE AND WATER-SCARCE AGRICULTURAL ENVIRONMENTS IN MEDITERRANEAN CONTEXT

Mission:

Strengthening an innovative sustainable economy

Programme priority:

Smarter MED

Specific objective:

RSO1.1: Developing and enhancing research and innovation capacities and the uptake of advanced technologies

Deliverable:

1.2.1. Good practices Handbook on groundwater networks and models in pilot sites

Work Package:

1. Assessment of monitoring capacities in pilot areas and identification of key gaps

Activity:

1.2. Activity name: Comparative analysis of the control and monitoring of existing networks in pilot sites

Partner in charge:

IGME-CSIC

Partners involved:

IGME-CSIC, CRCC, CUADLL, IRD, AQUA-VALLEY, ISALEAF, EWA, FORTH / ICE-HT, UNICAS

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EXECUTIVE SUMMARY

The document “Good Practices Handbook on Groundwater Networks and Models in Pilot Sites” has been developed within the framework of the European CLEPSYDRA project, funded by the Interreg Euro-MED programme of the European Union. The project aims to design and test an intelligent and integrated system for monitoring and interpreting hydrogeological data related to aquifer behaviour, with particular emphasis on groundwater quality in agricultural and irrigation contexts.

This handbook provides a comprehensive overview of the instruments and datasets available from existing monitoring networks—including meteorological stations, saturated and unsaturated zone monitoring systems, and water sampling—across four pilot sites: Campo de Cartagena (SE Spain), Llobregat Delta (NE Spain), Aluviões do Tejo (Central West Portugal), and Malta Mean Sea Level (Malta).

The assessment of these networks revealed significant variability in data availability and development. While some sites benefit from well-established systems, others show notable deficiencies. Given the complexity of implementing specific and feasible improvements, especially when such actions fall outside the direct control of stakeholders and require coordination among multiple authorities, this document outlines a set of best practices to enhance monitoring efforts.

The national meteorological networks of Portugal and Spain provide the most complete and reliable datasets. Expanding the number of stations could further improve spatial coverage and data representativeness in all the study cases.

In Campo de Cartagena, pairs of soil moisture probes have been installed to control every irrigation events. Although these do not support hydrochemical analysis, they offer valuable quantitative insights of infiltration rates. Moreover, by monitoring water crops consumption, these tools allow to optimise the available resources, and minimise the risk of leachate percolation into the groundwater.

At the Malta Mean Sea Level site, 16 stations have been deployed to enable both real-time monitoring of vertical water flow, and punctual sampling for assessing contaminant transport through the unsaturated zone at several depths. Malta is the only pilot site with an unsaturated zone monitoring network well developed, highlighting to the other partners the necessity to implement a tool/probe/station with similar purposes to have a comprehensive understanding of the groundwater bodies.

Llobregat Delta and Malta Mean Sea Level sites feature a higher density of piezometers, while Campo de Cartagena offers more remote data access points. In all cases, careful consideration must be given to the characteristics of each monitoring water point due to several reasons. The main issue is related with the origin of the observation wells because not all of them were drilled expressly for monitoring purposes. Consequently, very often, building characteristic such as depth of the borehole, screen pipe locations and so on, are unknown influencing the reliability of the measure, as well as the lack of information about pumping periods (transient or steady state condition).

Sampling frequencies and procedures vary across pilot sites according to regional and local protocols. However, the limited representativeness of the data reduces its reliability, making it difficult to identify consistent best practices. Aimed by this concern, the activity 2.1 will design a protocol for the data collection and the deliverable “D.2.1.1 Groundwater monitoring protocol for the pilot sites” will be redacted.

The software programs used for hydrogeological models are widely adopted and scientifically validated. Nevertheless, the limited availability and representativeness of observational data constrain model performance. Despite satisfactory calibration and low uncertainty, further improvements are needed. These findings underscore the importance of enhancing data acquisition strategies to strengthen model robustness. The aquifers of the Llobregat Delta are the best modelled of all the pilot sites.

The Clepsydra project aims to conduct comprehensive aquifer monitoring, focusing on both quantity and quality. This effort will integrate meteorological data, moisture measurements from the root zone, unsaturated zone, and saturated zone ensuring the collection of reliable and consistent data.

INTRODUCTION

This document, titled “Good Practices Handbook on Groundwater Networks and Models in Pilot Sites”, has been developed within the framework of the European CLEPSYDRA project. This is the WP1 deliverable (WP1. Assessment of monitoring capacities in pilot areas and identification of key gaps). It aims to provide a comprehensive overview of the existing monitoring networks in four pilot areas located in the partner countries: Spain (two sites), Portugal, and Malta.

The assessment is focussed on the reliability, representativeness, and potential for improvement of these networks, which include meteorological stations, saturated and unsaturated zone monitoring systems, and groundwater quality control tools. Each CLEPSYDRA partner has characterized and inventoried the tools available in their study site.

In addition, each partner has provided one or more hydrological models at varying stages of development and accuracy. These models have been tested to assess their ability to represent aquifer/s behaviour, with the primary goal of simulating groundwater flow and predicting pollutant transport.

1. CAMPO DE CARTAGENA (SPAIN)

In the following sections, all monitoring networks that provide data for the hydrological and hydrogeological characterization of the Campo de Cartagena groundwater body are described.

Campo de Cartagena is a plain covering 1,440 km² (1,600 km^2 watershed), located in the SE of Spain (Region of Murcia). It is bordered to the east by the Mar Menor and the Mediterranean Sea, while inland it is surrounded by low mountain ranges.

Campo de Cartagena groundwater body include the sedimentary infill of this basin, mainly composed of detrital, low-permeability sediments (clays and marls) with permeable interlayered material (limestones, sands and conglomerates).

The Clepsydra project involves two partners in this area, the IGME-CSIC (research institute) and the irrigation community of Campo de Cartagena (CRCC).

1.1. Meteorological data collection networks

IMIDA[1] Institute, has 56 stations distributed throughout the region of Murcia, and in particular those available for the study area (7) are presented in *Figure 1*.

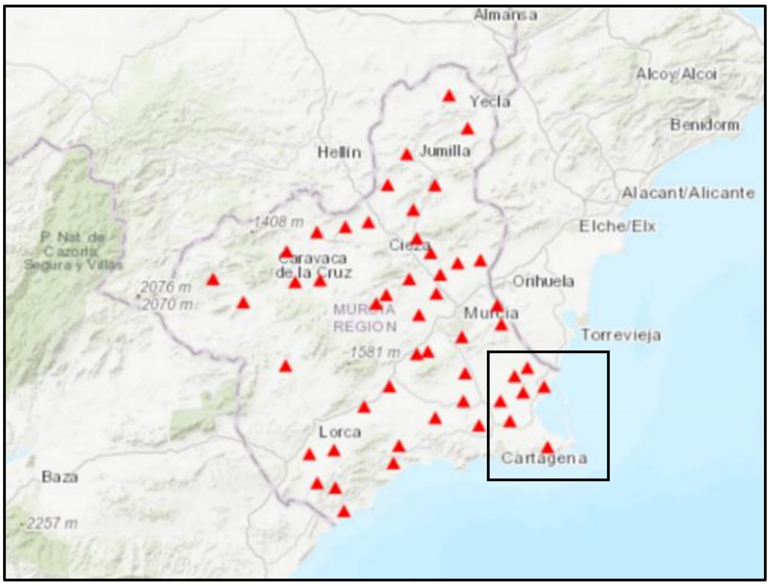

Figure 1: IMIDA web viewer with the location of weather stations.

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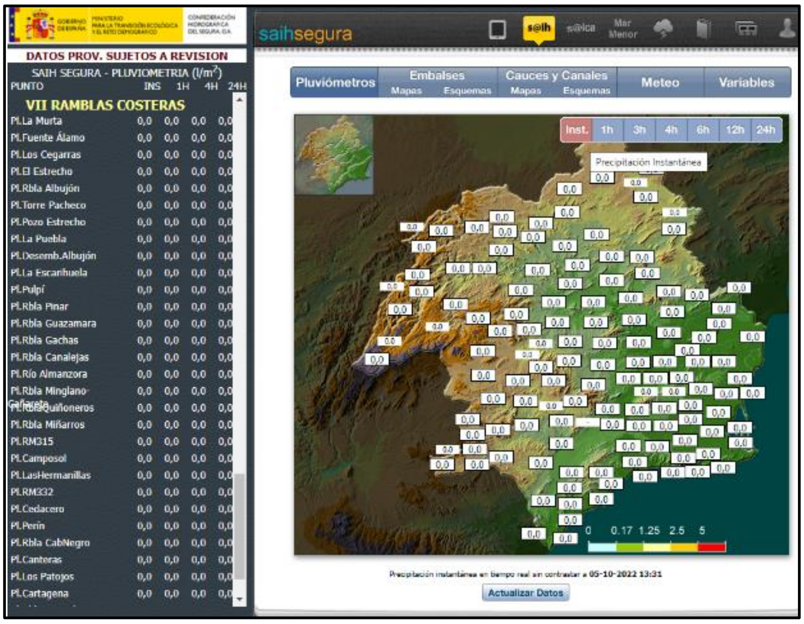
[1] IMIDA (Institute for Agricultural and Environmental Research and Development of Murcia Region).

These stations provide daily data on: precipitation, temperature, hours of sun, relative and absolute humidity, dew point, accumulated and reflected radiation, wind speed and direction, medium vapour pressure deficit and evapotranspiration.

The CHS rainfall network[2] (Segura River Basin Authority), whose data can be directly downloaded from the official website *(Figure 2)* and report data of rainfall volume per hour.



DATOS PROV. SUJETOS A REVISION

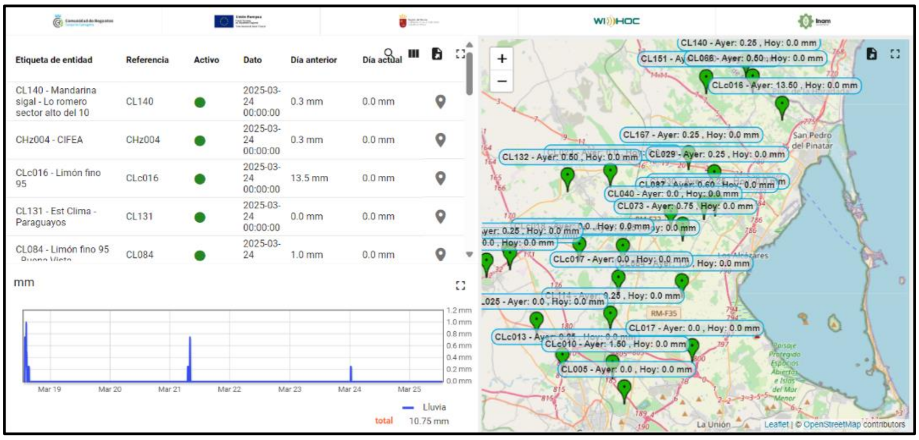
SAIH SEGURA - PLUVIOMETRIA (l/m²)

PUNTO	INS	1H	4H	24H
VII RAMBLAS COSTERAS				
Pl.La Murta	0,0	0,0	0,0	0,0
Pl.Fuente Álamo	0,0	0,0	0,0	0,0
Pl.Los Cegarras	0,0	0,0	0,0	0,0
Pl.El Estrecho	0,0	0,0	0,0	0,0
Pl.Rbla Albujón	0,0	0,0	0,0	0,0
Pl.Torre Pacheco	0,0	0,0	0,0	0,0
Pl.Pozo Estrecho	0,0	0,0	0,0	0,0
Pl.La Puebla	0,0	0,0	0,0	0,0
Pl.Desemb.Albujón	0,0	0,0	0,0	0,0
Pl.La Escarihuela	0,0	0,0	0,0	0,0
Pl.Pulpí	0,0	0,0	0,0	0,0
Pl.Rbla Pinar	0,0	0,0	0,0	0,0
Pl.Rbla Guazamara	0,0	0,0	0,0	0,0
Pl.Rbla Gachas	0,0	0,0	0,0	0,0
Pl.Rbla Canalejas	0,0	0,0	0,0	0,0
Pl.Río Almanzora	0,0	0,0	0,0	0,0
Pl.Rbla Minglano-Cañareta	0,0	0,0	0,0	0,0
Pl.Rbla Quiñoneros	0,0	0,0	0,0	0,0
Pl.Rbla Miñarros	0,0	0,0	0,0	0,0
Pl.RM315	0,0	0,0	0,0	0,0
Pl.Camposol	0,0	0,0	0,0	0,0
Pl.LasHermanillas	0,0	0,0	0,0	0,0
Pl.RM332	0,0	0,0	0,0	0,0
Pl.Cedacero	0,0	0,0	0,0	0,0
Pl.Perín	0,0	0,0	0,0	0,0
Pl.Rbla CabNegro	0,0	0,0	0,0	0,0
Pl.Canteras	0,0	0,0	0,0	0,0
Pl.Los Patojos	0,0	0,0	0,0	0,0
Pl.Cartagena	0,0	0,0	0,0	0,0

Precipitación instantánea en tiempo real sin contrastar a 05-10-2022 13:31

Figure 2: Data viewer of the Segura River Basin Authority.

Finally, the CRCC, within the "Execution project for the implementation of precision agriculture technologies and aquifer control in the irrigation community of the Campo de Cartagena (Murcia)" set up a network of 24 pluviometers distributed as shown in *Figure 3*, with data recording every five minutes, operative since the second quarter of 2022.



Etiqueta de entidad	Referencia	Activo	Dato	Día anterior	Día actual
CL140 - Mandarina sigal - Lo romero sector alto del 10	CL140	●	2025-03-24 00:00:00	0.3 mm	0.0 mm
CHz004 - CIFEA	CHz004	●	2025-03-24 00:00:00	0.3 mm	0.0 mm
CLc016 - Limón fino 95	CLc016	●	2025-03-24 00:00:00	13.5 mm	0.0 mm
CL131 - Est Clima - Paraguayos	CL131	●	2025-03-24 00:00:00	0.0 mm	0.0 mm
CL084 - Limón fino 95 Buena Vista	CL084	●	2025-03-24	1.0 mm	0.0 mm

Figure 3: Network of rain gauges of the Community of Irrigators of the Campo de Cartagena.

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[2] *Segura River Basin Authority rainfall network website (https://saihweb.chsegura.es).*

1.2. Monitoring of the unsaturated zone

1.2.1. Soil moisture probes (root zone)

To quantify the effects of irrigation, the CRCC installed probes to detect soil moisture and observe its evolution with depth. Since 2022, accurate monitoring of irrigation runs has allowed for minimizing the infiltration rate, thereby preventing excess water from entering the aquifer due to over-irrigation.

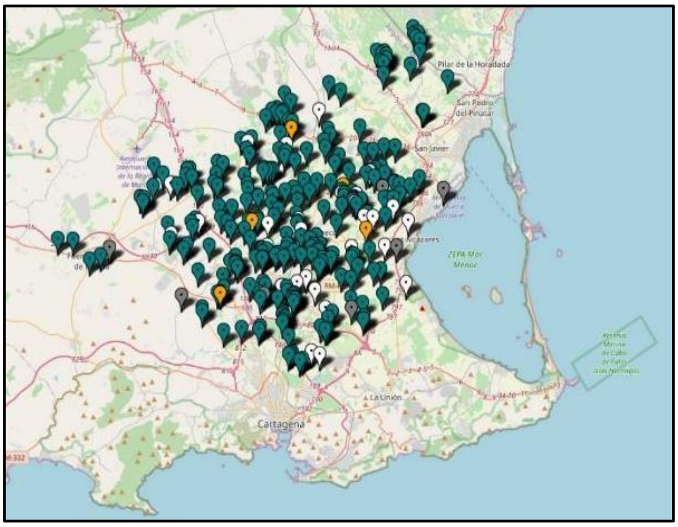


Figure 4: Map of installed probes in Campo de Cartagena (CRCC network).

In 500 farming plots, a pair of probes have been installed, their spatial distribution is shown in *Figure 4*. The shallow probe is 20-30 cm depth and the second is 60 cm for horticultural crops or 90 cm for trees. Those pairs of probes are able to measure volumetric humidity and electrical conductivity of the soil. A mobile application allows stakeholders to visualize the data. It also has a series of alerts that provide information on the need for water of the crop, taking into account the soil moisture and according to thermo-rainfall data of weather forecast. When the humidity reaches a threshold value, it warns for the interruption of irrigation.

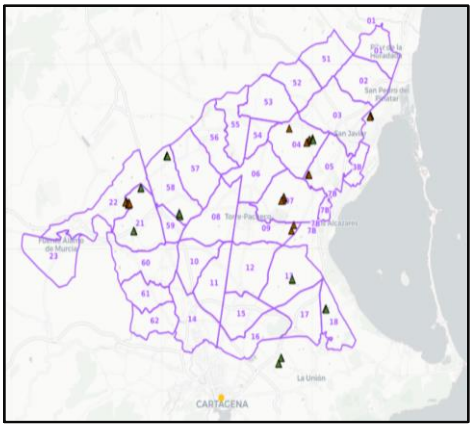


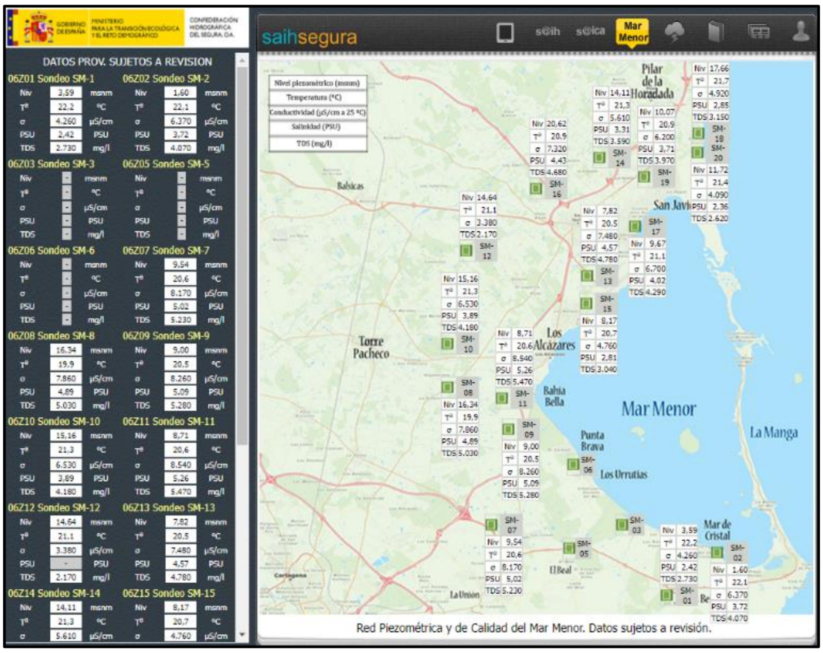
Figure 5: Map with moisture probes project CRCC-UPCT.

Finally exist another network (*Figure 5*) of 50 humidity probe installed by the UPCT (Polytechnic University of Cartagena) in collaboration with the CRCC. It measures soil humidity, electrical conductivity and temperature every 10 cm to a depth of 60 cm.

1.3. Monitoring of the saturated zone

1.3.1. Groundwater level networks

Piezometric level databases have recorded data with annual or monthly frequency for decades. In recent years, these records have been supplemented by several monitoring networks that provide continuous data recording. The main of these was implemented by the CHS in December 2019, with 19 points located in the coastal zone of the Mar Menor (*Figure 6*) with records every five minutes. The database is public and available for download at the SAIH website[3]. Those probes record: temperature, piezometric level, electrical conductivity, salinity and total dissolved solids.



DATOS PROV. SUJETOS A REVISION

06Z01 Sondeo SM-1			06Z02 Sondeo SM-2		
Niv	3,59	msnm	Niv	1,60	msnm
Tª	22,2	ºC	Tª	22,1	ºC
σ	4.260	µS/cm	σ	6.370	µS/cm
PSU	2,42	PSU	PSU	3,72	PSU
TDS	2.730	mg/l	TDS	4.070	mg/l

06Z03 Sondeo SM-3			06Z05 Sondeo SM-5		
Niv	-	msnm	Niv	-	msnm
Tª	-	ºC	Tª	-	ºC
σ	-	µS/cm	σ	-	µS/cm
PSU	-	PSU	PSU	-	PSU
TDS	-	mg/l	TDS	-	mg/l

06Z06 Sondeo SM-6			06Z07 Sondeo SM-7		
Niv	-	msnm	Niv	9,54	msnm
Tª	-	ºC	Tª	20,6	ºC
σ	-	µS/cm	σ	8.170	µS/cm
PSU	-	PSU	PSU	5,02	PSU
TDS	-	mg/l	TDS	5.230	mg/l

06Z08 Sondeo SM-8			06Z09 Sondeo SM-9		
Niv	16,34	msnm	Niv	9,00	msnm
Tª	19,9	ºC	Tª	20,5	ºC
σ	7.860	µS/cm	σ	8.260	µS/cm
PSU	4,89	PSU	PSU	5,09	PSU
TDS	5.030	mg/l	TDS	5.280	mg/l

06Z10 Sondeo SM-10			06Z11 Sondeo SM-11		
Niv	15,16	msnm	Niv	8,71	msnm
Tª	21,3	ºC	Tª	20,6	ºC
σ	6.530	µS/cm	σ	8.540	µS/cm
PSU	3,89	PSU	PSU	5,26	PSU
TDS	4.180	mg/l	TDS	5.470	mg/l

06Z12 Sondeo SM-12			06Z13 Sondeo SM-13		
Niv	14,64	msnm	Niv	7,82	msnm
Tª	21,1	ºC	Tª	20,5	ºC
σ	3.380	µS/cm	σ	7.480	µS/cm
PSU	-	PSU	PSU	4,57	PSU
TDS	2.170	mg/l	TDS	4.780	mg/l

06Z14 Sondeo SM-14			06Z15 Sondeo SM-15		
Niv	14,11	msnm	Niv	8,17	msnm
Tª	21,3	ºC	Tª	20,7	ºC
σ	5.610	µS/cm	σ	4.760	µS/cm

Red Piezométrica y de Calidad del Mar Menor. Datos sujetos a revisión.

Figure 6: Web viewer of CHS dataloggers in real time.

Additional datalogger networks were established by the previously mentioned CRCC project (soil moisture probes). This network includes 24 piezometers equipped with sensors to record temperature, conductivity, and piezometric level every 30 minutes. It has been operational since March 2022 *(Figure 7)*. In this case, 12 of the piezometers were drilled for this project (drilled in pairs with different depths) and remaining points are existing boreholes and wells (private owners).

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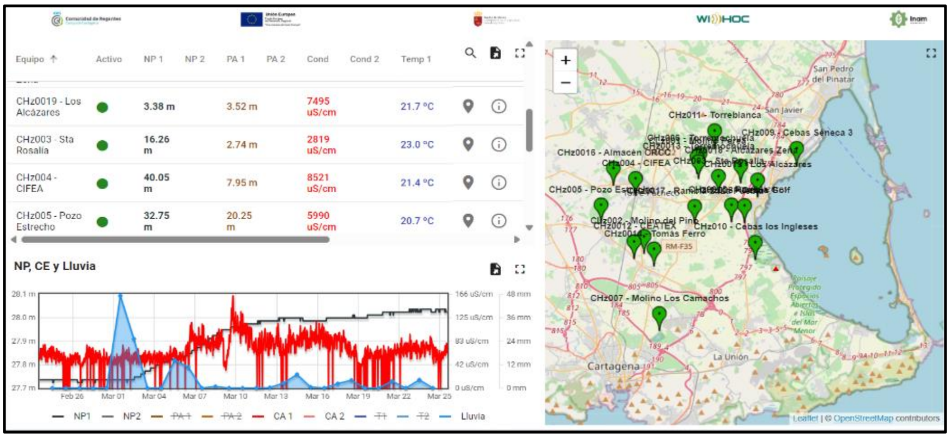
[3] Segura River Basin Authority network visor (https://saihweb.chsegura.es/apps/iVisor/index.php?salto=11).

The AQUIFER project has 6 data loggers in private wells *(Figure 8*) recording temperature, piezometric level and electrical conductivity, operational since March 2022 with hourly data recording. Data are automatically uploaded every 24 h on the Grafana server. Moreover, 12 more data loggers (LevelScout 2x; Diver) are installed whose data must be manually downloaded periodically by IGME-CSIC[4].



Equipo	Activo	NP 1	NP 2	PA 1	PA 2	Cond	Cond 2	Temp 1
CHz0019 - Los Alcázares	●	3.38 m		3.52 m		7495 uS/cm		21.7 °C
CHz003 - Sta Rosalía	●	16.26 m		2.74 m		2819 uS/cm		23.0 °C
CHz004 - CIFEA	●	40.05 m		7.95 m		8521 uS/cm		21.4 °C
CHz005 - Pozo Estrecho	●	32.75 m		20.25 m		5990 uS/cm		20.7 °C

Figure 7: Piezometric network of the project to implement precision agriculture technologies and control the aquifer in the Community of Irrigators of Campo de Cartagena.

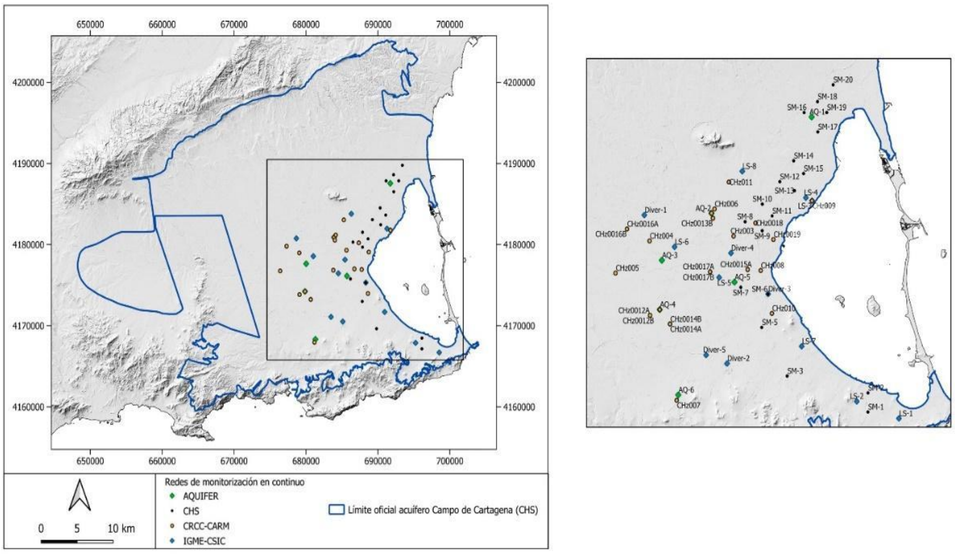


Figure 8: Continuously operational piezometric level log networks spreading in Campo de Cartagena groundwater body.

1.3.2. Quality networks

Quality networks over the groundwater body Campo de Cartagena managed by CHS, is shown in *Figure 9*. It is composed by 56 points (blue dots wells/borehole/piezometers with discrete sampling) and Mar Menor dataloggers network (red crosses).

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[4] *IGME-CSIC website Geological and Mining Institute of Spain. (https://www.igme.es/)*

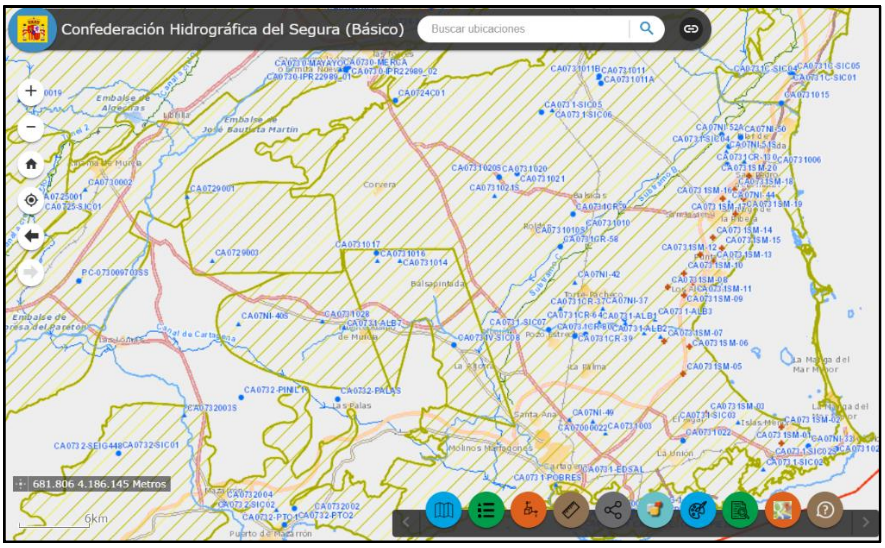

Figure 9: CHS web viewer with visible shapefiles of groundwater body boundaries (polygons) and quality network points.

Figure 10 shows the location of the 137 private wells and boreholes sampled monthly by CRCC from 2019. The sampling is carried out with the aim of measuring nitrate concentration, also electrical conductivity and water consumption are recorded for each one. The chemical analyses are carried out by a certified laboratory. These data are reported to CHS and available with his own data in the repository of water quality[5].

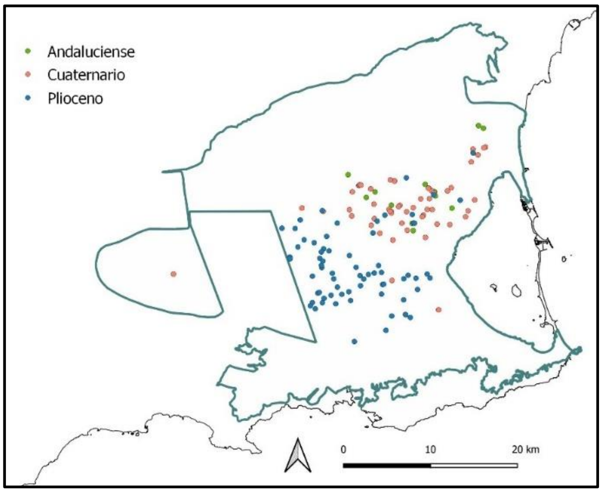

Figure 10: Distribution of CRCC monthly sampled wells/boreholes classified for each aquifer.

1.3.3. Hydrogeological models

Campo de Cartagena aquifers had been the subject of study for many years, attracting the interest of various research institutions focused on modelling the regional aquifer.

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[5] *www.chsegura.es/es/cuenca/redes-de-control/calidad-en-aguas-subterraneas/*

This basin, located in the eastern part of the Betic Cordillera, contains a sedimentary record that extends from the Miocene to the present, about 2000 meters of thickness (Aragón et al., 2011).

Several regional flow models have been developed to better understand groundwater dynamics. However, among these models, three numerical models stand out as the most reliable and widely referenced in current research.

1.3.3.1. Alcolea et al. (2019)

The study developed a three-dimensional model to analyse density-driven effects at the interface of unconfined aquifers and lagoon, using the SPHY (Spatial Processes in Hydrology) model. It quantifies daily surface water balance components and soil moisture dynamics at discrete layers. The root zone water balance is primarily influenced by soil moisture, precipitation inflows, and losses from interception and actual evapotranspiration, all affected by vegetation, root depth, water storage, and soil texture.

Due to the area’s gentle topography, where 90% of slopes are less than 1%, lateral fluxes in the vadose zone are ignored, making capillary forces the main driver of vadose flows. The study also calculates the portion of precipitation exceeding soil storage as potential recharge to the shallow aquifer (*Figure 11*).

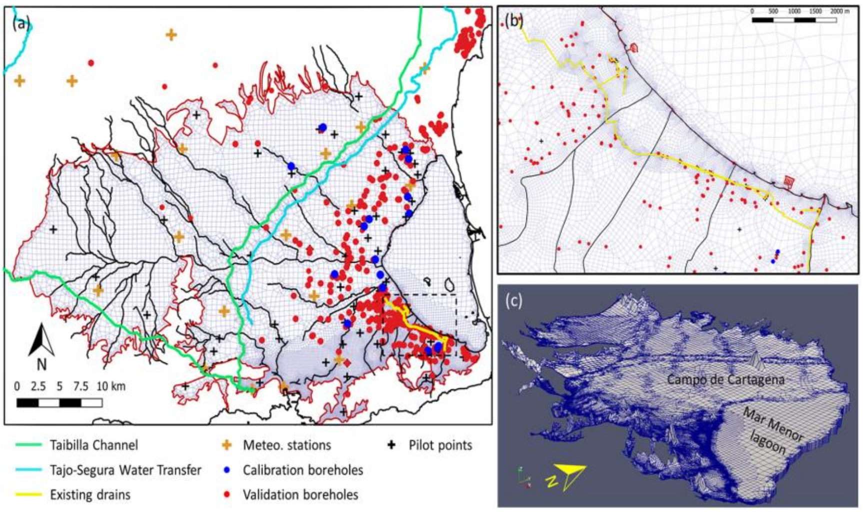


Figure 11 (a) The model set-up ; (b) Detail of the fine model discretization in the vicinity of existing drains; (c) 3D view of model discretization (vertical exaggeration factor ×10) (Alcolea et al., 2019).

The SPHY model incorporates both static (slope and soil hydraulic properties) and dynamic (climate data and satellite-based vegetation data NDVI) inputs. Outputs include evapotranspiration losses and aquifer recharge, feeding into the 3D variable-density model. Groundwater flow is analysed using the SUTRA finite elements code, with aquifer properties calibrated through the regularized pilot points method and PEST software.

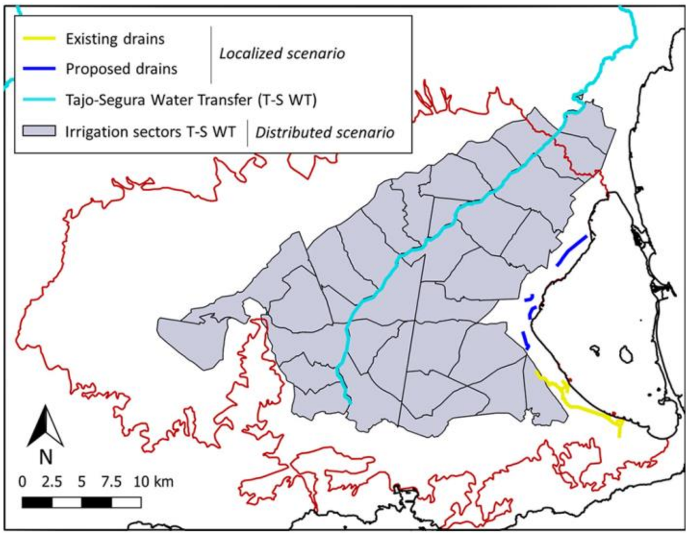


Figure 12: Localized and distributed management scenarios.

The Campo de Cartagena Quaternary aquifer covers 1,119 km² and it extends under the Mar Menor lagoon and it has been modelled in 3D with 500 × 500 m cells. It comprises sand, silt, clay, and conglomerates, with a thickness ranging from 50 to 150 m. An underlying aquitard is excluded from the model due to minimal natural fluxes to deeper aquifers.

The 3D model uses irregular finite elements for horizontal discretization, refining around areas with; steep topography, the coastline, and drainage networks. It consists of ten vertical layers based on aquifer thickness, totalising 8 million elements *(Figure 12).*

The model simulates a 16-year period (October 2000 to December 2016) that encompasses various hydro-meteorological conditions, including wet average, and dry periods.

Nitrate discharge into the lagoon is calculated by multiplying groundwater discharge by monitored concentrations, assuming stability along its path due to the oxic conditions of the aquifer not allowing for relevant denitrification processes (*Figure 13*).

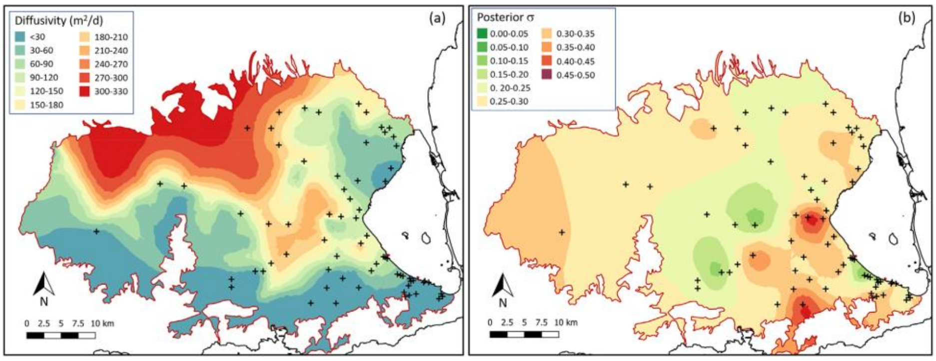


Figure 13: (a) The spatial distribution of hydraulic diffusivity after calibration shows a mean diffusivity of approximately 500 m²/d for existing drains, which is not displayed to maintain the colour scale. (b) composite of posterior standard deviations of the estimated parameters.

Recharge varies significantly daily and seasonally, influenced by semi-arid rainfall patterns and agricultural practices that can lead to peaks due to the region's shallow topography. The mean annual recharge is approximately 73 mm/year, with higher values of around 300 mm/yr in irrigated areas (*Figure 14*).

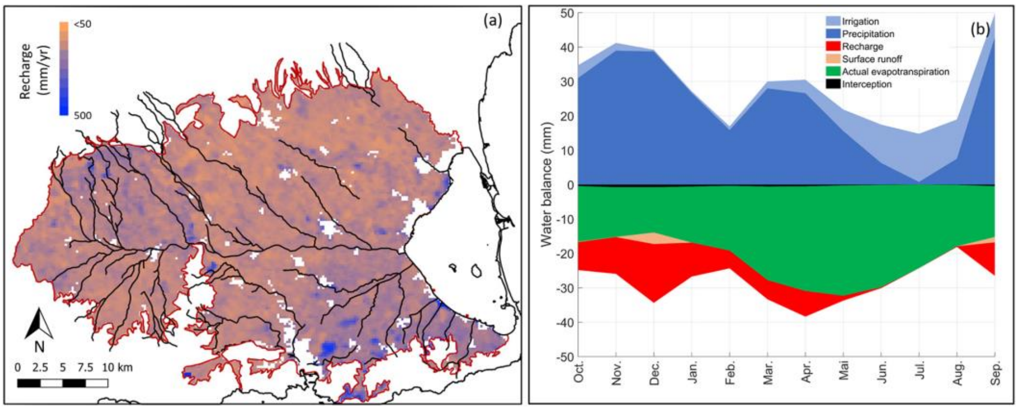


Figure 14: (a) Spatial distribution of estimated mean annual recharge (mm/yr); (b)monthly averaged water mass balance components for the study period (2000–2016).

Hydraulic heads exhibit a non-linear gradient increasing from west to east, with minimal fluctuation during dry and wet periods (*Figure 15-16).* The model reveals that most discharge occurs in the central lagoon sector, with northern segments experiencing slightly higher discharge due to higher concentration of pumping in the south.

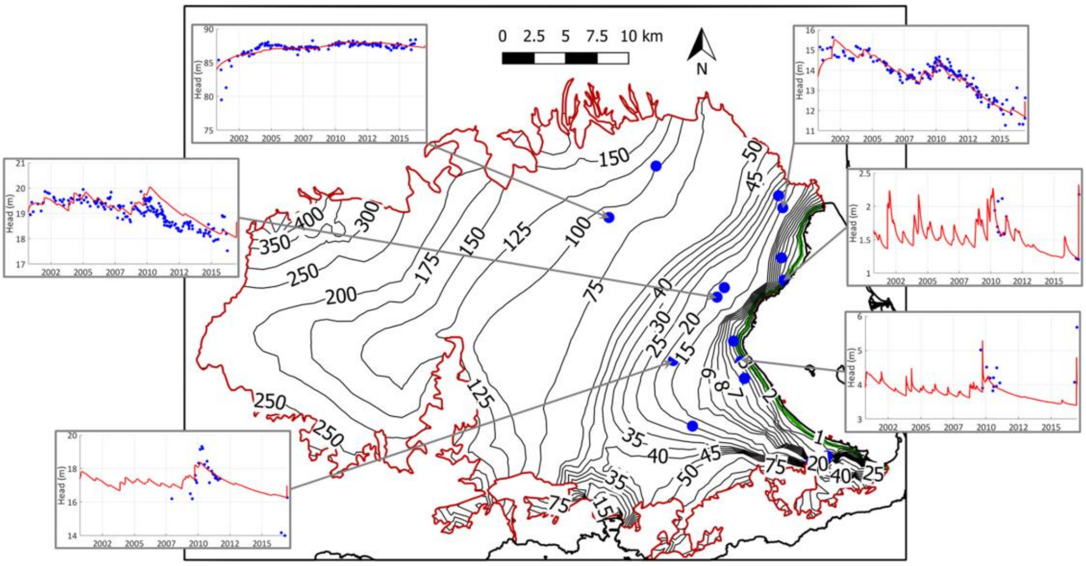
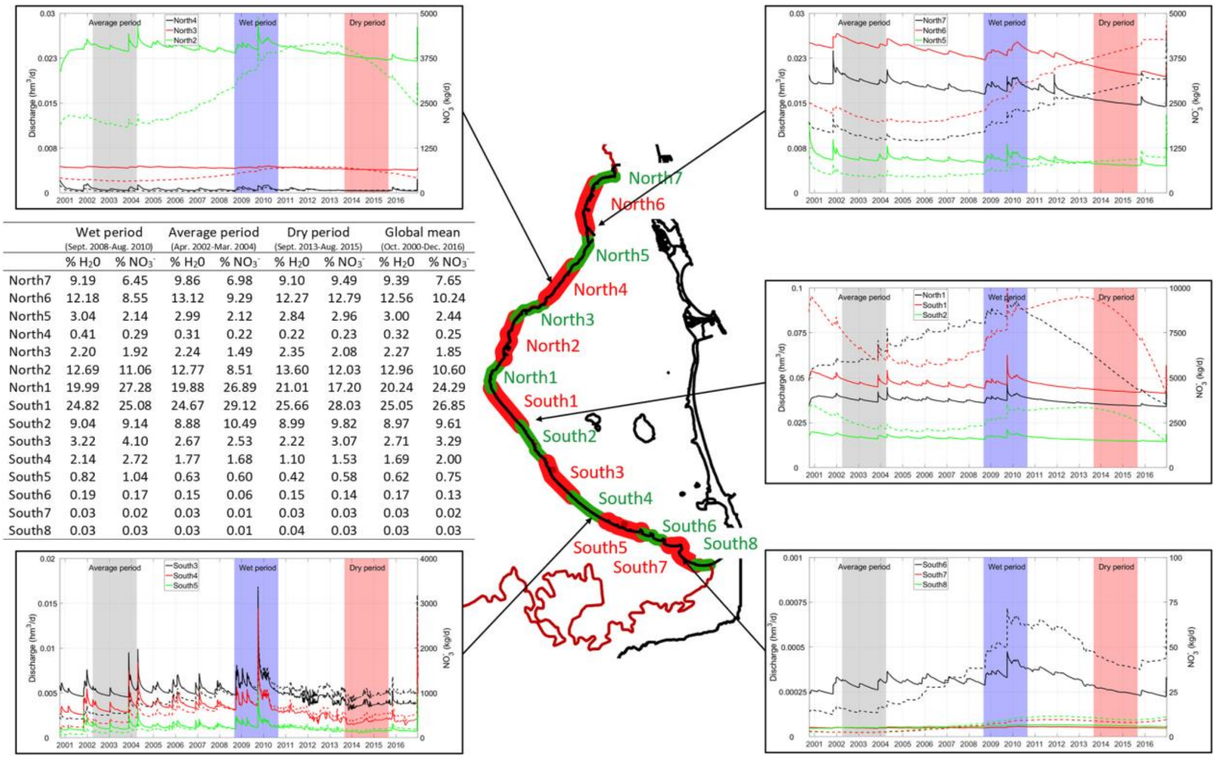


Figure 15: Contours of the hydraulic heads from the calibrated model at date 15/03/2004, after a two-year hydro-meteorological average period



	Wet period (Sept. 2008-Aug. 2010)		Average period (Apr. 2002-Mar. 2004)		Dry period (Sept. 2013-Aug. 2015)		Global mean (Oct. 2000-Dec. 2016)	
	% H_20	% NO_3^-	% H_20	% NO_3^-	% H_20	% NO_3^-	% H_20	% NO_3^-
North7	9.19	6.45	9.86	6.98	9.10	9.49	9.39	7.65
North6	12.18	8.55	13.12	9.29	12.27	12.79	12.56	10.24
North5	3.04	2.14	2.99	2.12	2.84	2.96	3.00	2.44
North4	0.41	0.29	0.31	0.22	0.22	0.23	0.32	0.25
North3	2.20	1.92	2.24	1.49	2.35	2.08	2.27	1.85
North2	12.69	11.06	12.77	8.51	13.60	12.03	12.96	10.60
North1	19.99	27.28	19.88	26.89	21.01	17.20	20.24	24.29
South1	24.82	25.08	24.67	29.12	25.66	28.03	25.05	26.85
South2	9.04	9.14	8.88	10.49	8.99	9.82	8.97	9.61
South3	3.22	4.10	2.67	2.53	2.22	3.07	2.71	3.29
South4	2.14	2.72	1.77	1.68	1.10	1.53	1.69	2.00
South5	0.82	1.04	0.63	0.60	0.42	0.58	0.62	0.75
South6	0.19	0.17	0.15	0.06	0.15	0.14	0.17	0.13
South7	0.03	0.02	0.03	0.01	0.03	0.03	0.03	0.02
South8	0.03	0.03	0.03	0.01	0.04	0.03	0.03	0.03

Figure 16: Spatial-temporal distribution of discharge of groundwater and nitrate into the Mar Menor lagoon. The perimeter of the lagoon is divided into 15 segments with length ~2 km. For each segment, the discharge of groundwater (solid lines) and nitrate (dashed line with same colour) are presented. Periods of average (grey), wet (blue), and dry (red) hydro-meteorological conditions are highlighted. The table contains, for each sector, the percentage of the mean discharge of groundwater (%H_2O) and nitrates (%NO_3) for selected hydro-meteorological periods.

1.3.3.2. CHS (2020)[6]

This model was developed for a coastal strip around the Mar Menor, revised geological model of the superficial aquifer of the Campo de Cartagena based on new geophysical surveys consisting of 71 SEVS, 5 electrical tomography and 22 lithological columns from drillings (plus the review of existing data). The Quaternary aquifer in this region consists of varied sediments including clays, silts, sands, gravels, and conglomerates typical of alluvial and colluvial environments, as well as coastal and lagoon sediments like marls and limestones. The average thickness of the aquifer is 62 m, with variations.

This study identifies four geological layers (*Figure 17*); levels 1, 2, and 3a form the main aquifer section, while levels 3b, 3c, 3d, and 4 act as aquitards. Over 90% of groundwater, flows toward the Mar Menor through the upper layers.

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[6] *CHS (2020).” Cuantificación, control de la calidad y seguimiento piezométrico de la descarga de agua subterránea del acuífero cuaternario del campo de Cartagena al mar Menor.” Modelo de flujo del Acuífero Cuaternario del Campo de Cartagena. https://www.chsegura.es/static/marmenor/DescargasMarMenorCuaternarioCampoCartagena.zip*

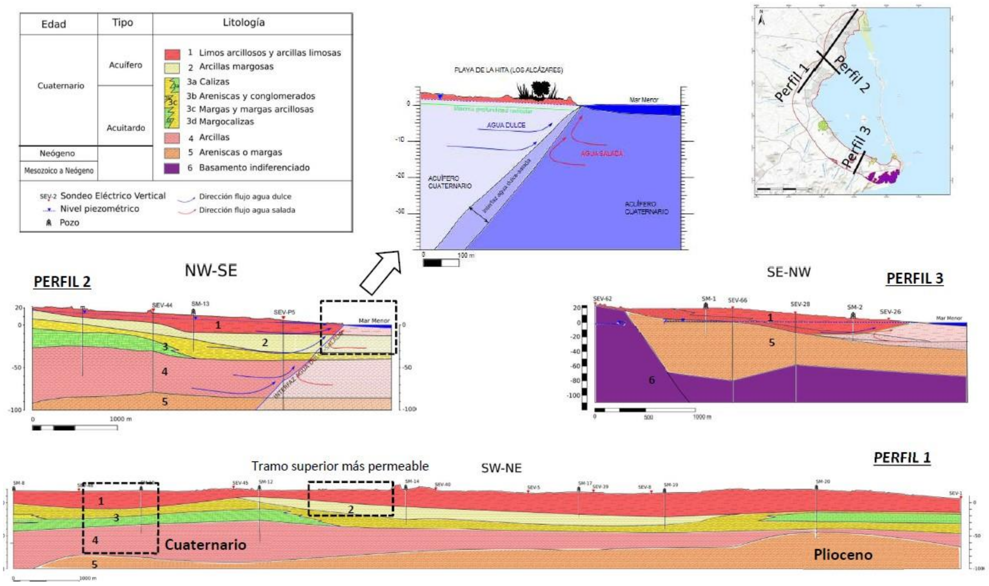

Figure 17: Geological profiles of the study area (CHS, 2020).

A thickness map of the aquifer has been developed using data from 109 geological points. The geometry of the aquifer at the discharge edge to the Mar Menor was then adjusted to reflect the position of the saltwater wedge.

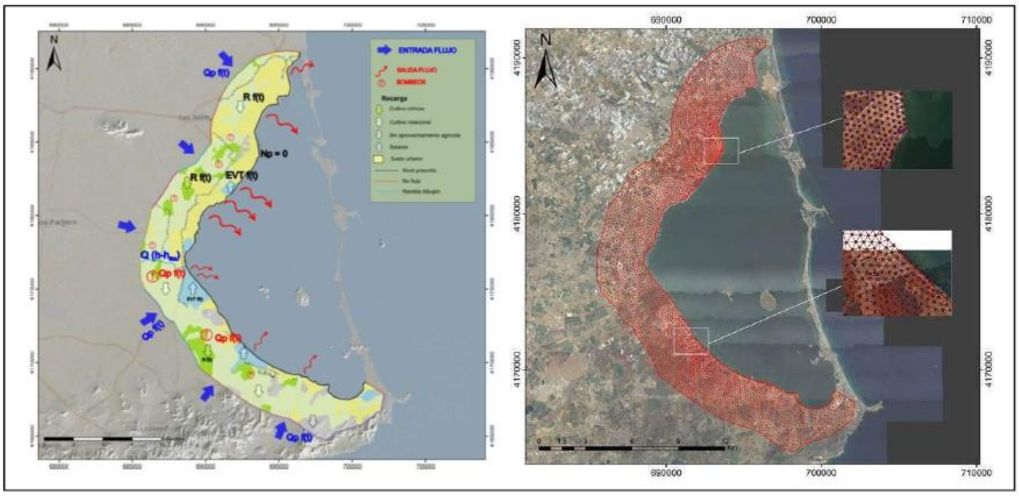

Figure 18: Conceptual model (left) and finite element mesh used in the flow model, with details of refined areas in the mesh (right).

The Ghyben-Herzberg formulation was used to determine the depth of the freshwater-saltwater interface (*Figure 18*), assuming horizontal freshwater flow and no saltwater flow or mixing. Additionally, the Hubbert correction was applied to account for vertical flows in the discharge area due to a gradual reduction in the freshwater outflow section to the sea.

The TRANSIN code then, calculates transmissivity (T) as the product of hydraulic conductivity (K) and aquifer thickness, with map zoning based on data from pumping tests, piezometers and geological information (*Figure 19*). A storage coefficient of S = 0.02 was estimated from data obtained during the pumping tests.

The model considers aquifer recharge from rain infiltration, irrigation returns, and lateral groundwater inflow. The amount of precipitation recharge was estimated using data from meteorological stations CA73 and TP22, with infiltration percentages ranging from 1.7% to 6.9%, based on results from the SIMPA model. Irrigation returns recharge rate was calculated based on Agricultural Demand Units (UDA) in the study area, utilizing CORINE Land Cover maps and field observations to identify crops. A temporal function was developed to implement this parameter in the model, linking UDA, crop type, and nearby meteorological stations. The land was classified into five main groups: rotational crops, woody crops, urban land, salt marshes, and non-cultivated areas.

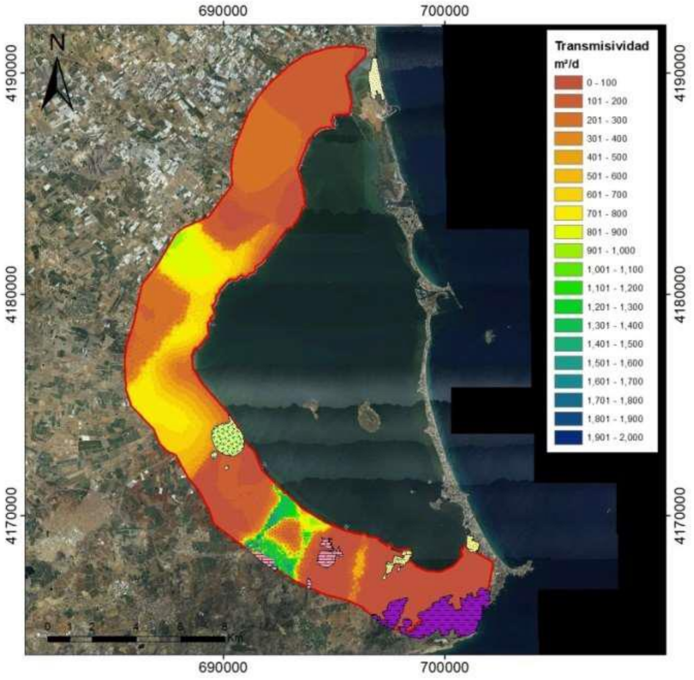

Figure 19: Transmissivity map implemented in the model.

Finally, model calibration adjusted the estimated recharge values, increasing them in certain areas and decreasing them in others, with the highest inflows occurring in rotational crop zones.

The conceptual model identifies several outputs, including pumping from wells, evaporation from salt marshes, discharge from the aquifer to the Rambla del Albujón, and groundwater discharge to the sea, with the latter being the model's main objective (*Figure 20*).

The model incorporates data from the Quaternary aquifer, derived from an initial inventory of control points. The extraction volumes assigned to these points come from the SICA system. It represents the major concessions extracting between 4% and 19% of the allocated volume in 2018-2019, resulting in an estimated extraction volume of 3 hm³/year for the aquifer. Evaporation outputs from salt marshes are calculated based on the estimated groundwater demand in the basin plan, proportionate to the area of each marsh.

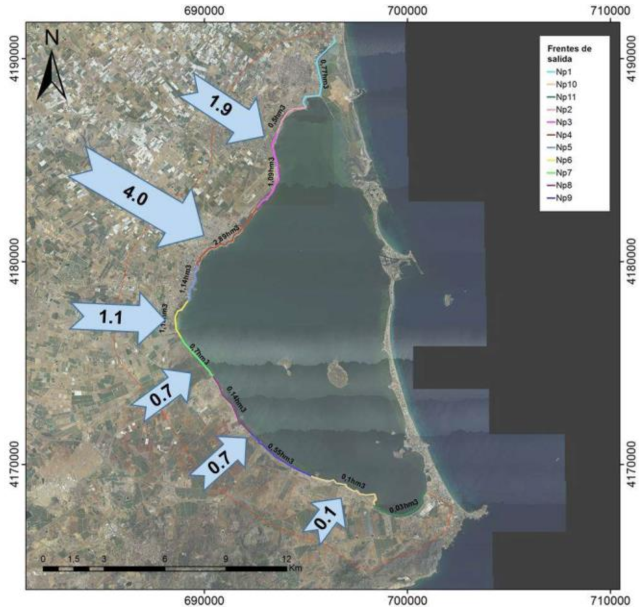

Figure 20: Discharge to Mar Menor from the Quaternary Aquifer of Campo de Cartagena (in hm³) by coastal segments.

The TRANSIN code facilitates calculating inflow rates at specific nodes along a specific flow boundary. The western edge of the model is segmented into 12 variable-length sections. Those correspond to the watersheds draining into the Mar Menor, allowing for detailed quantification of groundwater inflows to the Quaternary aquifer. For simulating discharge from the latter into the Mar Menor at the eastern boundary, it is used a fixed level condition (Np) set at sea level. By dividing this edge into 11 sectors it was possible to analyse the discharge distribution.

Finally, the numerical model was calibrated by adjusting parameter values to replicate observed water levels using a combination of manual and automatic methods. The mean absolute error was 0.76 m, supporting the hypothesis of preferential groundwater flow zones, both areal and linear, associated with channels or palaeochannels.

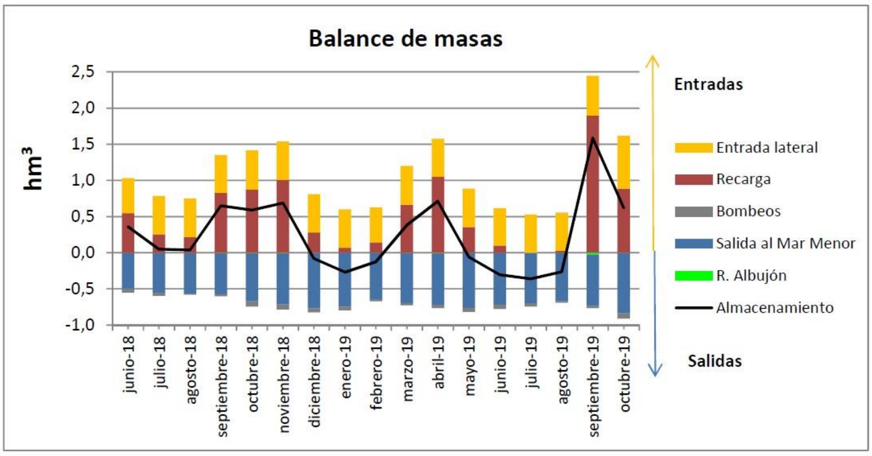

Figure 21: Monthly mass balance with system inputs shown in warm colours (positive values) and outputs in cool colours (negative values).

Figure 21 presents a monthly mass balance for the considered period, showing that system inputs align with three major periods of intense precipitation, which also lead to increase aquifer storage. In contrast, discharge to the sea remains constant and rises months after recharge peaks. This indicates that the fluctuations in recharge, affect the discharge to the Mar Menor despite these effects are moderated by changes in aquifer storage.

1.3.3.3. Project AQUIFER numerical flow model (2023)[7]

The conceptual model is based on the following considerations (more information can be found in Deliverable 2.1.1 "Hydrogeological Report and Model of Campo de Cartagena-Mar Menor"):

- The Quaternary and Plio-Quaternary aquifers in the southern sector are modelled, connected to the Mar Menor lagoon, assuming a disconnection from the lower aquifer units.

- Recharge only comes from rainwater infiltration and irrigation returns.

- Discharges occur towards the Mar Menor lagoon, southward through the Cartagena sector, and through extractions (wells and boreholes).

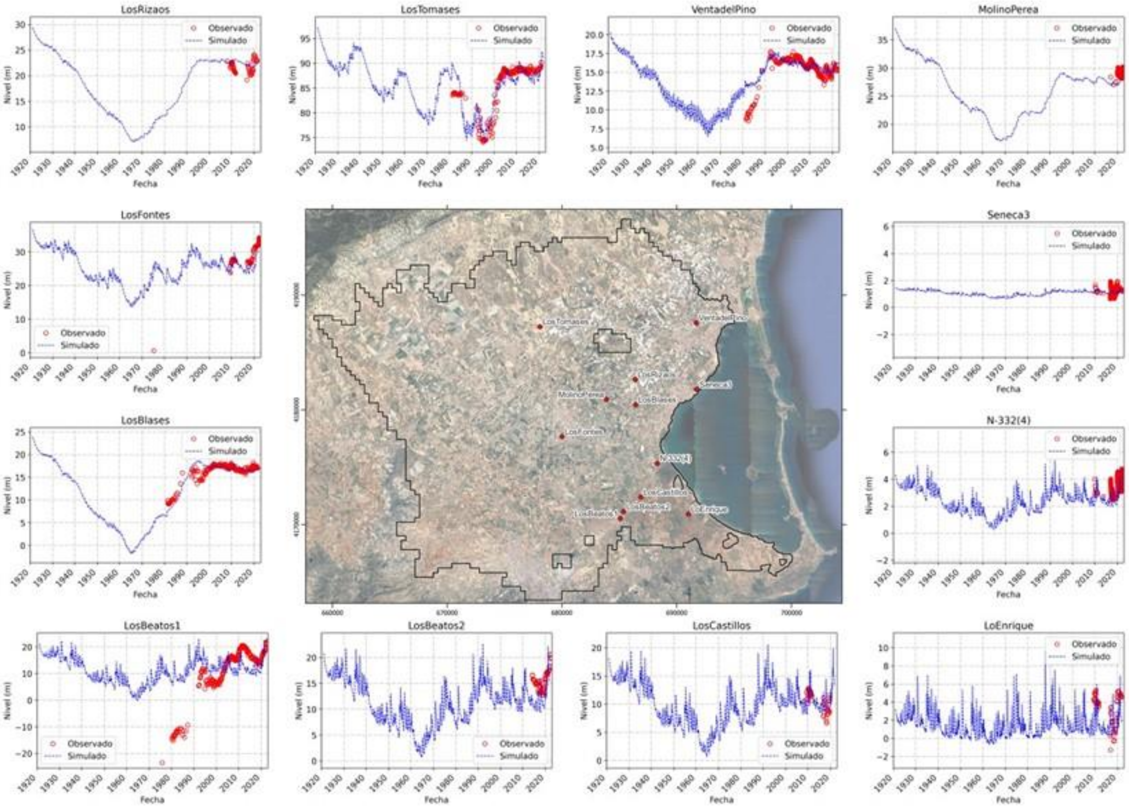

Figure 22: Temporal evolution of measured and calculated levels from 1920 to 2020.

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[7] *García-Aróstegui, J.L., Robles-Arenas, V.M., Pool, M., Mas, R., Sampietro, D., Abarca, E. (2023). Informe y modelo hidrogeológico del Campo de Cartagena-Mar Menor. AQUIFER Project (SOE4/P1/E1045). 119 p.*

The flow model has been developed using MODFLOW software with the graphical interface Groundwater Vistas version 8.23 (GWV8). For the numerical model, the MODFLOW-USG calculation engine has been employed. It allows for mesh refinement in specific areas with an it is unstructured, minimizing balance errors. The model successfully reproduces the level measurements, with all observation points showing perfect alignment between measured and simulated values. This is illustrated in the *Figure 22* shows the temporal evolution of measured and calculated levels from 1920 to 2020 for several observation wells. The piezometric analysis shows a west-east preferred flow discharging into the lagoon, with higher hydraulic potential in elevated areas.

Both the 1920 and December 2020 simulations reveal higher levels in the central sector compared to the 1960s, a period marked by maximum extraction from the Quaternary aquifer that caused widespread level declines and marine intrusion near the coast.

The water balance indicates rain infiltration and irrigation surpluses as system inputs, with average recharge estimated of 72 hm^3/year over the simulation period (1920-2020). Major outputs include discharge to the Mar Menor (averaging 34 hm^3/year) and pumping extractions (31 hm^3/year), along with a minor discharge of about 8 hm^3/year towards Cartagena. Notably, discharge to the lagoon may be underestimated due to un-modelled groundwater transfer to lower aquifers.

Since the simulation began, the storage variation has been negative, with discharges and extractions exceeding recharge. The 1980s saw increased recharge and decreased pumping, resulting in positive storage variation. By the end of the simulation, both recharge and extraction decreased, nearing zero storage variation. Although the aquifer shows signs of recovery, it hasn't reached its pre-1920 natural equilibrium. Calibrated parameters align with previous models, showing consistent patterns in permeability and drainable porosity. Some sectors exhibit high permeability values, possibly indicating geometric errors. Velocity distributions reveal slower speeds (0.3 to 1.5 m/day) in the central and northern areas, while particle transport simulations indicate transit times ranging from 35 years in the north to 225 years in the south, with faster pathways in the central coastal zone averaging around 15 years.

1.4. References

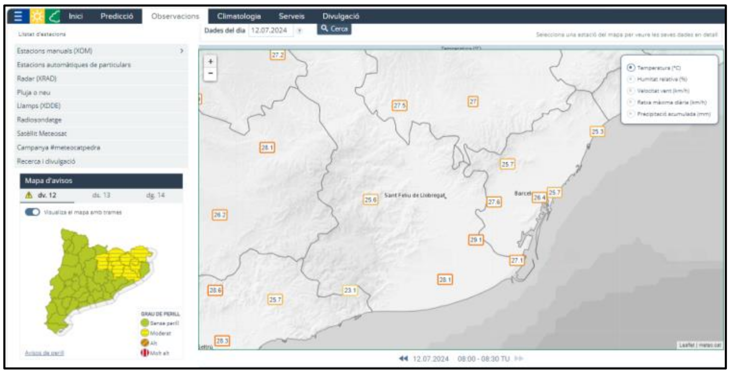
Alcolea A., Contreras S., Hunink J. E., García-Aróstegui J. L., Jiménez-Martínez J. (2019). Hydrogeological modelling for the watershed management of the Mar Menor coastal lagoon (Spain). Science of the Total Environment 663 (2019) 901–914

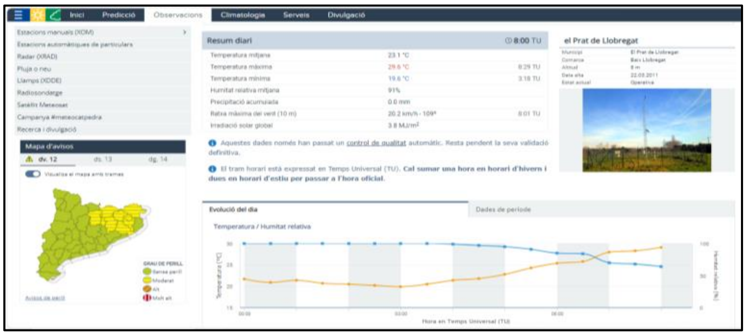
Aragón R., Candela L., García-Aróstegui J. L., Martínez M. (2011). A 3D geological model of Campo de Cartagena, SE Spain: Hydrogeological implications. Geologica Acta, 9(4), 411-425

2. LLOBREGAT DELTA (SPAIN)

The Community of Water Users of the Lower Valley and Delta of the Llobregat (CUADLL) is a corporation that includes all groundwater users located within this specified territorial area. It represents the interests of supply, industrial, and agricultural sectors.

The Lower Llobregat valley is a free alluvial aquifer, formed by several fluvial terraces. At the delta splits into two parts separated by a wedge of silt. The upper aquifer is shallow and covers much of the delta, while the deeper aquifer lies beneath the silt wedge and is confined.





Resum diari		8:00 TU
Temperatura mitjana	23.1 °C	
Temperatura màxima	29.6 °C	8:29 TU
Temperatura mínima	19.6 °C	3:18 TU
Humitat relativa mitjana	91%	
Precipitació acumulada	0.0 mm	
Ratxa màxima del vent (10 m)	20.2 km/h - 109°	8:01 TU
Irradiació solar global	3.8 MJ/m²	

Aquestes dades només han passat un control de qualitat automàtic. Resta pendent la seva validació definitiva.

El tram horari està expressat en Temps Universal (TU). **Cal sumar una hora en horari d'hivern i dues en horari d'estiu per passar a l'hora oficial.**

el Prat de Llobregat	
Municipi	El Prat de Llobregat
Comarca	Baix Llobregat
Altitud	8 m
Data alta	22.03.2011
Estat actual	Operativa

Figure 23: Service viewer meteocat.cat with the location of weather stations.

2.1. Meteorological data collection networks

METEOCAT (Meteorological Catalan Service) has 208 stations, 3 located in the pilot site in the Llobregat plain (*Figure 23*). These stations provide daily data on: precipitation, temperature, hours of sun, relative and absolute humidity, dew point, accumulated and reflected radiation, wind speed and direction, medium vapour pressure deficit and evapotranspiration according to FAO. There's also the AEMET[8] (State Meteorological Agency) rainfall network, although only one station is available for the study area, located in Barcelona's Airport.

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[8] AEMET (State Meteorological Agency) rainfall network website. (https://opendata.aemet.es/centrodedescargas/productosAEMET?).

2.2. Monitoring of the saturated zone

2.2.1. Groundwater level networks

In Llobregat pilot site, there are several piezometric networks coexisting in order to have a greater knowledge of the aquifer (*Figure 24*). Piezometric level databases are being completed with the existence of several monitoring networks with continuous registration. In total, there are 163 piezometric control points.

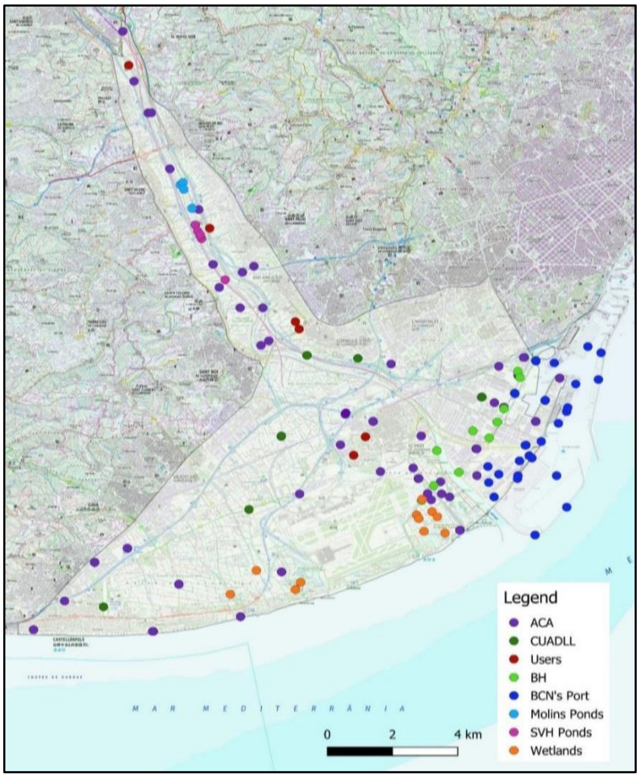

Figure 24:Piezometric networks in Llobregat pilot site.

The Catalan Water Agency[9] (ACA) official piezometric network is made up by 87 control points, which are represented in *Figure 25*. Level measurements are carried out monthly since 1970, and as you can see in the picture below, 6 users control points are measured weekly since 2012 to complement aquifer piezometric control.

CUADLL[10] implemented monitoring network with continuous level registration to expand the groundwater control. These are 7 monitoring points, 6 of those are managed by CUADLL, and only 1 monitoring point is managed by ACA. In all cases, dataloggers recording every 4 hours (*Figure 26*).

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[9] ACA (Catalan Water Agency) official piezometric network website. (https://aplicacions.aca.gencat.cat/sdim21/).

[10] CUADLL (The Water Users Community of the Llobregat Delta) website. (https://www.cuadll.org/).

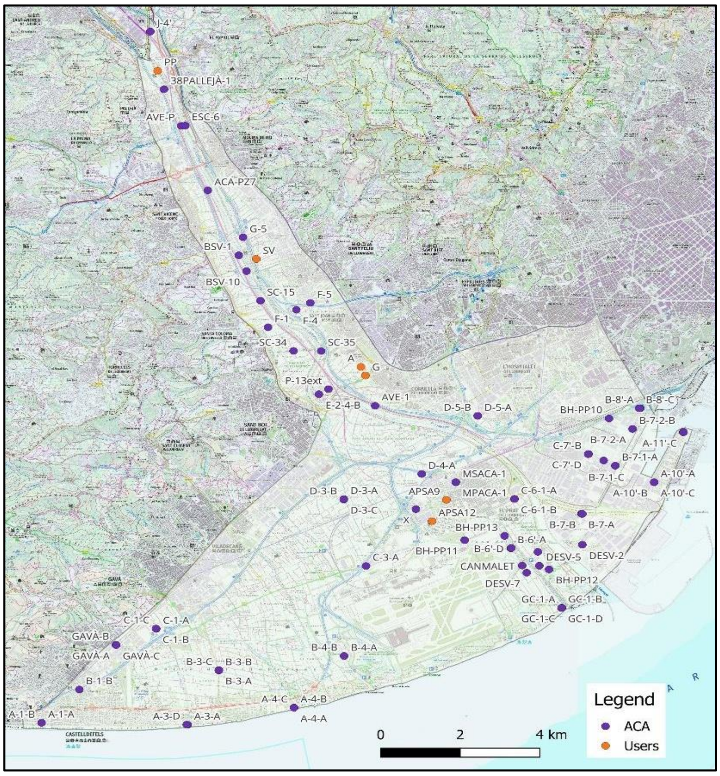

Figure 25: ACA and users' piezometric network exist in Llobregat pilot site.

Moreover, to groundwater level, they record temperature, and some of them electrical conductivity too. The points began to be operational in 2018.

In addition to monitoring the pilot site, there are other several piezometric networks in order to control a specific aquifer zone, such as the possible impact of the expansion works at Barcelona's port or active artificial recharge systems control implemented in this aquifer. In the first case, Barcelona's harbour works (*Figure 27*), piezometric control has been carried out monthly, since 2007.

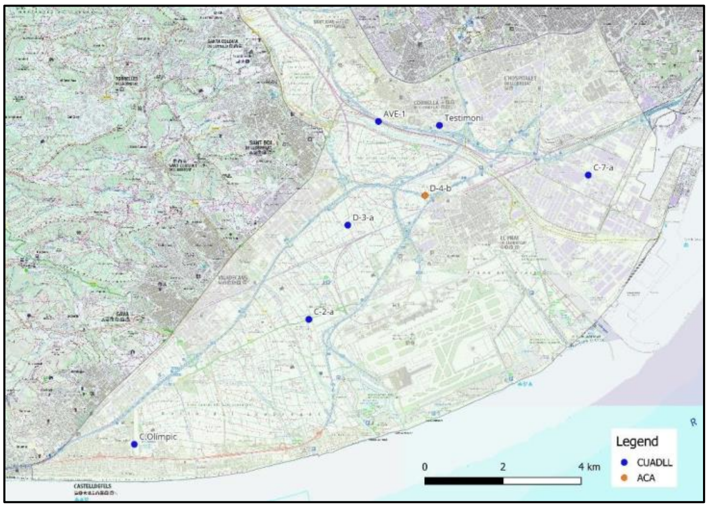

Figure 26: ACA and users' monitoring with continuous registration piezometric network exist in Llobregat pilot site.

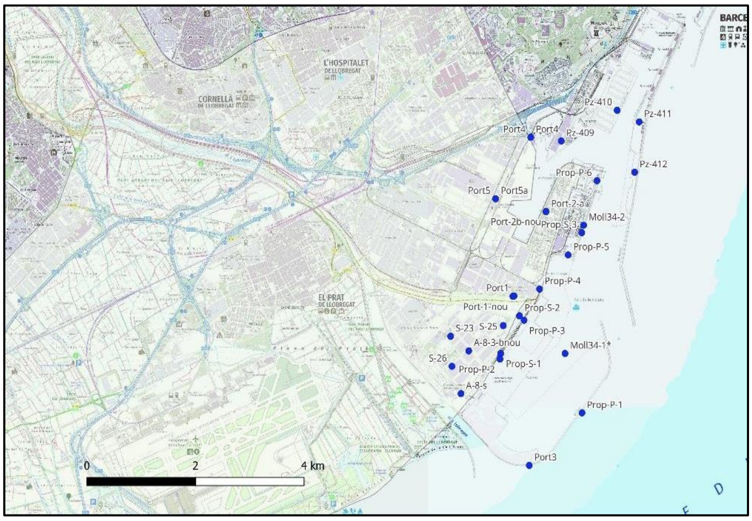

Figure 27: Barcelona's harbour works piezometric network.

In artificial recharge systems, dataloggers are installed to control piezometric level continuously. In the case of hydraulic barrier against sea intrusion *(Figure 28*), data records every day since 2018. Sant Vicenç dels Horts recharge ponds *(Figure 29)* are registered every 10 minutes, since May 2024, and in AQUIFER SUDOE– Molins de Rei ponds, data records every 4 hours, since 2021. In addition to groundwater, temperature and electrical conductivity are measured in the most of control points.

Finally, a piezometric network to control wetlands and their interaction with the aquifer is represented in *Figure 30*. Dataloggers are installed in several piezometers around two of three wetlands to control them, which logger data every hour. The first points began to be operational in January 2020, remaining all installed in the first quarter of 2022. The third wetland, which level control is measured manually, is has been carried out monthly since 2010.

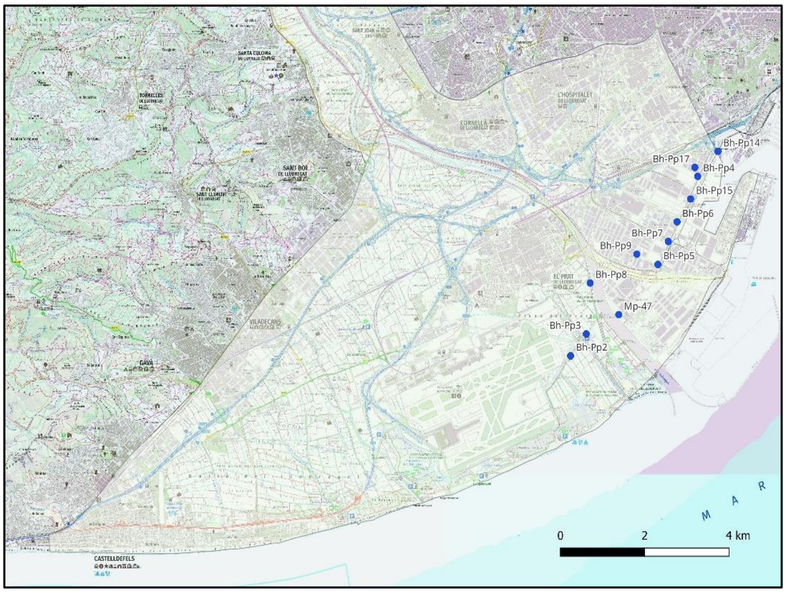

Figure 28: Hydraulic barrier piezometric network.

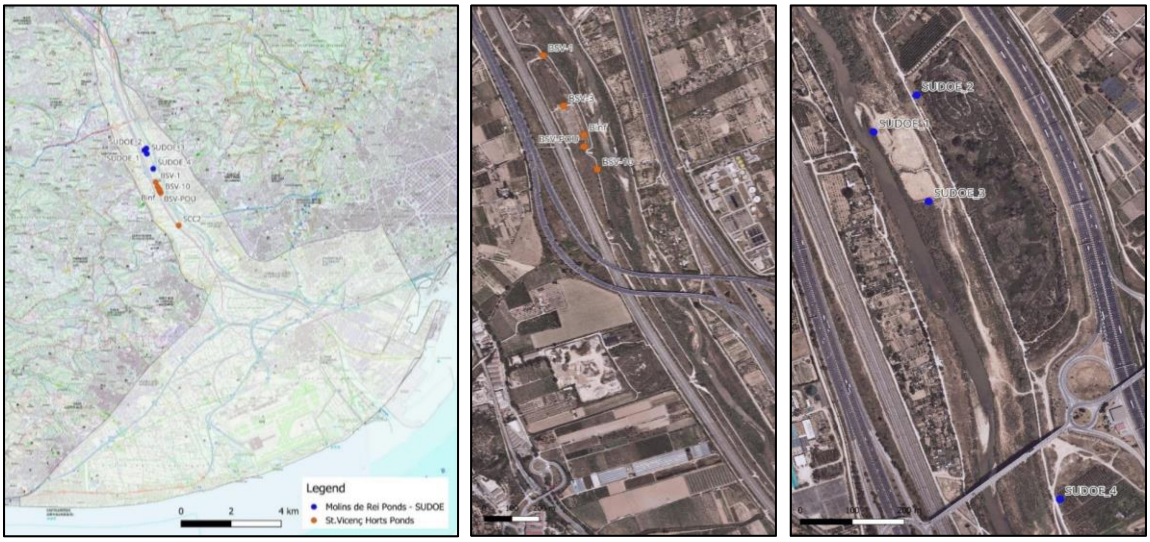

Figure 29: Recharge ponds piezometric network in the Low Valley.

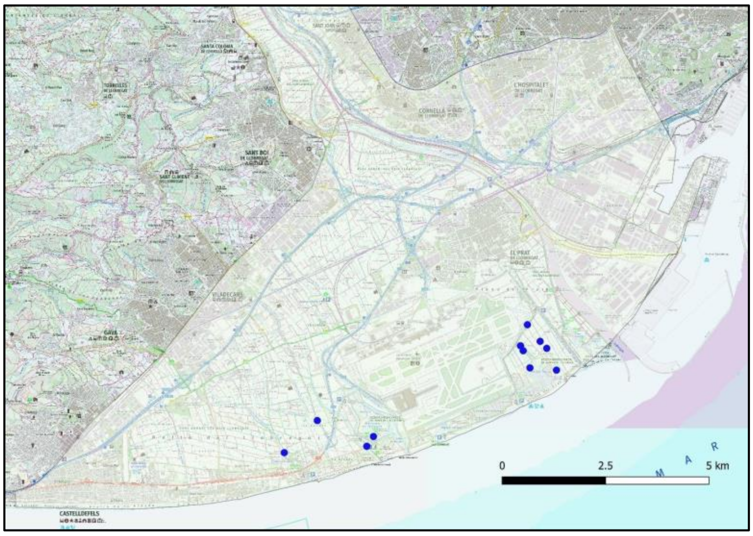

Figure 30: Wetlands piezometric network.

2.2.2. Quality networks

Below several quality networks are full important database available. CUADLL collects all the information from the different quality networks, and this allows to know in detail the quality of groundwater, mainly chlorides and nitrates. Others parameters are analysed, such as majoritarian anions and cations, some metals, microorganisms, organochlorines, other organic compounds, BTEX, pesticides and emergent compounds. *Figure 31* show several quality networks distributed in such a way as to obtain the maximum information about the aquifer. In total, 186 well points and piezometers conformed this global network. Timely data collected from water samples depends on the objective of quality control. It can be quarterly, semi-annually or annually. Below, these networks have been explained in detail.

ACA has a surveillance plan designed in order to determine aquifer status (*Figure 32*). In addition, CUADLL has designed a quality network that complemented the official one. And finally, groundwater users also have their own quality networks, whose data they provide us to add to the global aquifer knowledge. In total, 150 control points are included in this global quality network. Most control points are sampled annually, and users networks the controls are more periodic, such as quarterly.

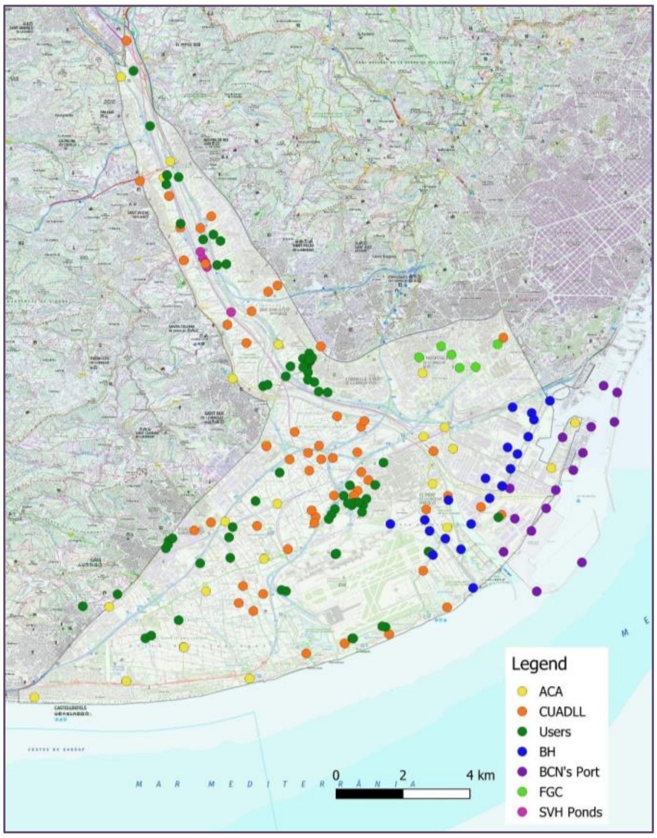

Figure 31: Quality networks exist in Llobregat pilot site.

In addition to monitoring the pilot site quality, there are other several specific quality networks, to control specific aquifer zones, such as the possible impact of the expansion works at Barcelona's port, railway drainage water (FGC) or active artificial recharge systems control implemented in this aquifer. In the first case, Barcelona's harbour works (*Figure 33),* 15 water samples have been carried out quarterly, since 2007. Most of this network's piezometers, 7 ones, have installed sensors CTD which measure continuously, every 4 hours; pressure, temperature and electrical conductivity, with the aim to monitor saltwater intrusion. Data collects is quarterly. In the case of railway drainage water control (FGC), 6 water samples are analysed annually. In this case, the operator has been working hardly on the waterproofing of the railway tunnel, so perhaps the number of control points will end up being reduced.

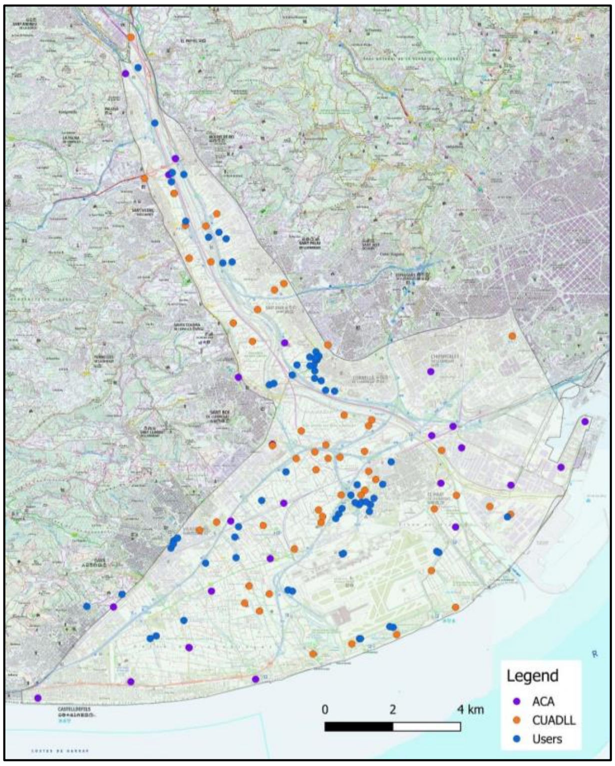

Figure 32: Official quality network (ACA), CUADLL and users' networks in Llobregat pilot site.

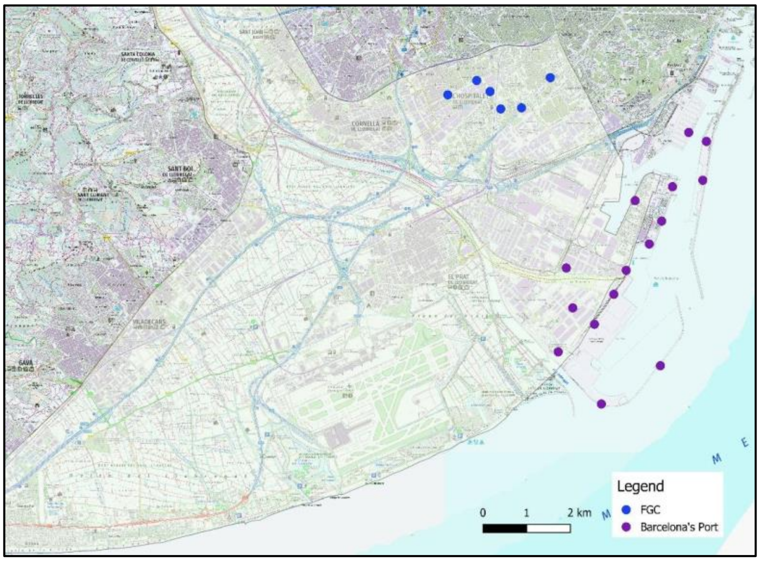

Figure 33: Barcelona harbour works and railway drainage (FGC) quality control networks.

Artificial recharge systems are implemented in pilot zone, hydraulic barrier and recharge ponds. In both cases, in addition to continuous monitoring control, which are controlled pressure, temperature and electrical conductivity, water samples are collected to control other chemical parameters. In hydraulic barrier (*Figure 34*), 7 automatic sensors data are collected pressure, temperature and electrical conductivity every day, since 2018, and 15 water samples are collected semi-annually, since June 2023.

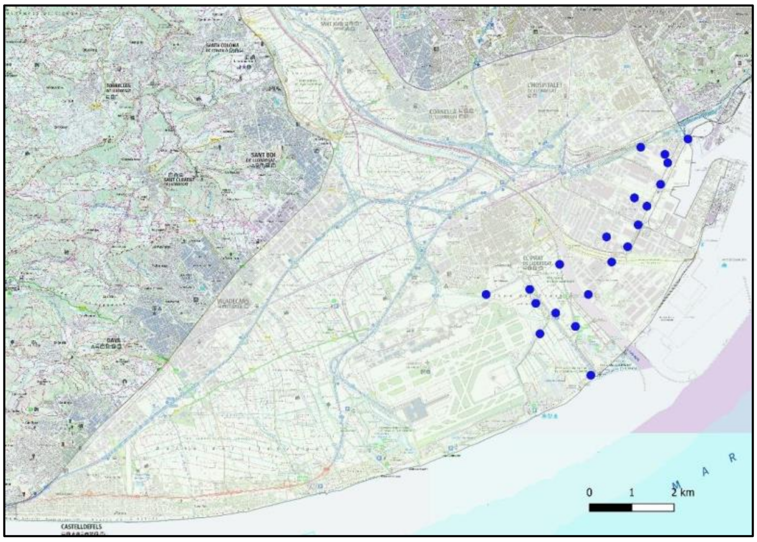

Figure 34: Hydraulic barrier quality control network.

In Sant Vicenç dels Horts artificial recharge ponds (*Figure 35*), 5 automatic sensors data are collected pressure, temperature and electrical conductivity every 10 minutes, and 5 water samples are collected every month and a half. This sampling time depends on the reclaimed water infiltrated volume.

Figure 35: Artificial recharge ponds quality control network.

2.2.3. Hydrogeological models

In 2002, the Groundwater Hydrology Group of the Catalonia Polytechnic University (UPC) drew up, on behalf of the ACA, the "Baix Llobregat Aquifer Management Program” (Vázquez-Suñé et al., 2002). The aim was to restore it to its good status and determine the optimal degree of exploitation for its sustainable use.

The main tool of this program was the development of a numerical model of water flow and chloride transport in order to study marine intrusion in the Llobregat Delta aquifers. Previously to the numerical model, a geological and hydrogeological study and update was carried out which included: the study of geological data and aquifers definition, the revision of piezometric series and hydraulic parameters, the study of historical extractions, hydrochemistry, the mass balance (water inputs and outputs to the aquifers) considering lateral inputs, recharge, and interactions with rivers and sea. The numerical model was based on the conceptual model derived from previous studies, integrated all available data, gave coherence to the conceptual model, and became a tool for aquifer management. This model was built with Visual Transin (*Figure 36*) and with data from 1966 to 2001, with data partly provided by the CUADLL.

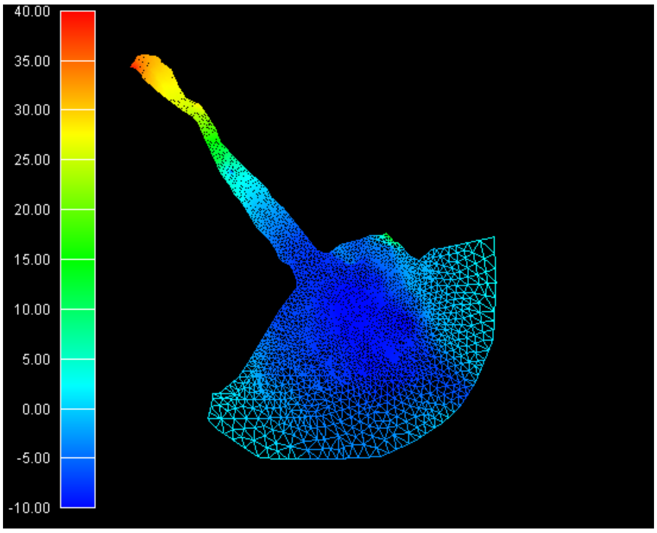

Figure 36: Example of modelling levels in the main aquifer through Visual Transin.

Geometrically, ACA-UPC model is two-layered: the upper layer represents the surface aquifer (only present in deltaic zone), while the lower layer simulates the main aquifer (defined as the Cubeta de Sant Andreu, the Vall Baixa, and the delta deep aquifer). It is a finite element model, where all available properties and data are assigned, such as contours and boundaries, hydraulic parameters, recharge, extractions, piezometric levels and chloride concentrations. It was made with the Visual Transin numerical code, developed by the UPC itself. This code allows solving the linear and non-linear inverse problem, in one, two and three dimensions.

The model covers a region of 120 km^2, has about 50 years of time series, 100 transmissivity and 14 recharge zones, more than 100 extraction wells, some with their time functions, more than 6000 chloride data and many more piezometric levels. Once the geometry and geology of the model is built, the time functions derived from the conceptual model are implemented. Then the model calculates and gives as a result of piezometric level values and concentration of chlorides at each point and each unit of time, as well as the mass balance in each cell or region of the model.

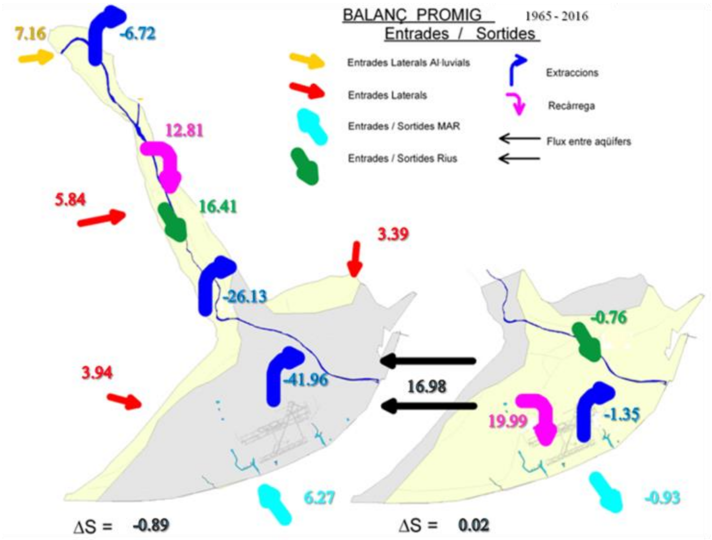

Figure 37: Water balance of Transit model.

If the results are not consistent enough with the observables (measured piezometric levels and chlorides, and mass balance of the conceptual model), then the calibration phase is started, which consists of modifying the input data to the model until the results are sufficiently consistent with the observables ones.

The model has been updated, accompanied by improvements and recalibrations, validated by ACA. During this period, ACA-CUADLL meetings were held in which the numerical model was used for the "Technical bases for the drafting of Baix Llobregat aquifers exploitation rules". The mass balance, coinciding with the conceptual model, is summarized in *figure 37*. This balance gives an idea of the dimensions of the flows involved with respect to the aquifer.

Due to the growing interest in having an updated and functional model, it was decided to migrate the model to commercial software, in this case FEFLOW, which contains a powerful visualization.

This migration has been carried out by the Institute of Environmental Assessment and Water Research CSIC-IDAEA[11], whose staff created the first model in Visual Transin when they were at the UPC. The new migrated model corresponds to the period 1966 – 2020, and was delivered to Catalan Water Agency in June 2021. The model, in this new code, has made it possible to manage future changes in the study area more quickly, such as the implementation or modification of infrastructures, pumping updates, time series updates, etc. without limitations of the code used in terms of spatial and temporal discretization.

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[11] *CSIC-IDAEA website (Institute of Environmental Diagnosis and Water Studies). (https://www.csic.es/es/el-csic/organizacion/institutos-centros-y-unidades/instituto-de-diagnostico-ambiental-y-estudios-del-agua).*

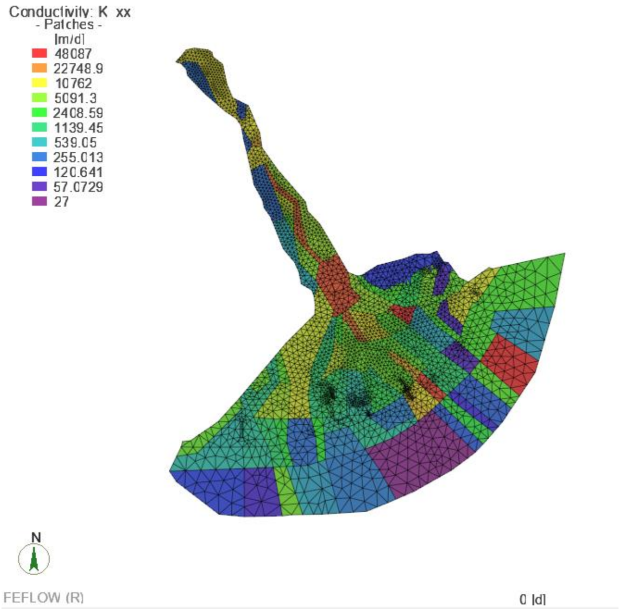

Figure 38: FEFLOW 2d model. Map of main aquifer hydraulic conductivities.

Subsequently, FEFLOW 2D model (*Figure 38*) has been transformed into a 3D model *(Figure 39*) by the CSIC-IDAEA group who are the same authors of the migration of the regional model in Transin to the FEFLOW code, implementing the digital terrain model and the geological model. The resulting model is made up of 42,413 elements, 22,267 nodes, 7 layers, incorporating information from more than 360 geological surveys, more than 40,000 observed piezometric level data and around 9,000 chloride concentration data (*Figure 40*). This model was shared and accepted by Catalan Water Agency in July 2024.

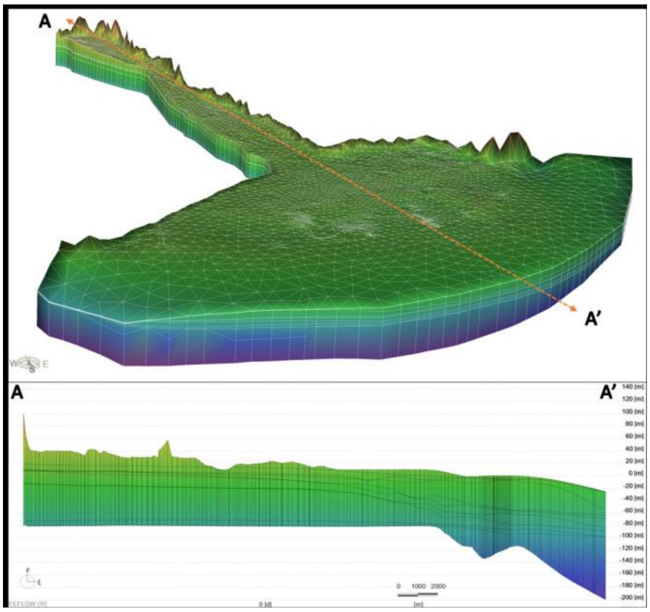

Figure 39: Update of 3D numerical model of La Cubeta de Sant Andreu and Llobregat Lower Valley, made by CSIC-IDAEA.

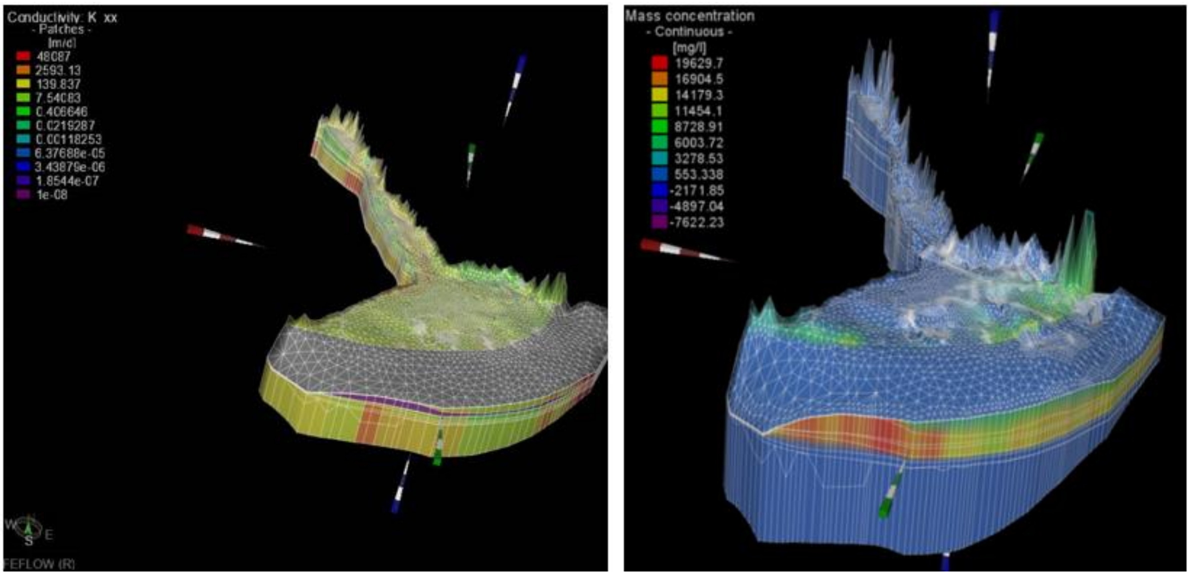

Figure 40: Conductivity model and example of chloride concentration in the FEFLOW 3D Model.

2.3. References

Vázquez-Suñé E., Abarca E., Carrera J., Capino B., Gámez D., Pool M., Simó T., Batlle F., Niñerola J. M., Ibáñez X. (2002). Groundwater modelling as a tool for integrated management. the Llobregat case (Spain), Baix Llobregat Aquifer Management Program. *Jornadas Internacionales: De la toma de datos y la realización de modelos de agua subterránea a la gestión integrada International Workshop: From data gathering and groundwater modelling to integrated management Alicante, Spain 2005 · AIH-GE*

3. ALUVIÕES DO TEJO (PORTUGAL)

The Tagus Nitrate Vulnerable Zone (TVZ) is located in the catchment of the river Tagus in Portugal (*Figure 41a*). The initial designated TVZ area (Ordinance 1100/2004) comprised 19 000 ha but was subsequently extended (Ordinance 1433/2006) to 100 000 ha. Another extension (Ordinance 1366/2010) increased the TVZ to 241 686 ha. Currently the TVZ contains 60% of total NVZ area in Portugal. It comprises 72 parishes organized into 20 municipalities. Agriculture accounts for the majority of land use and is of great economic importance in the area. The Utilized Agricultural Area (UAA) is on average 52%, slightly above the national and EU-28 averages.

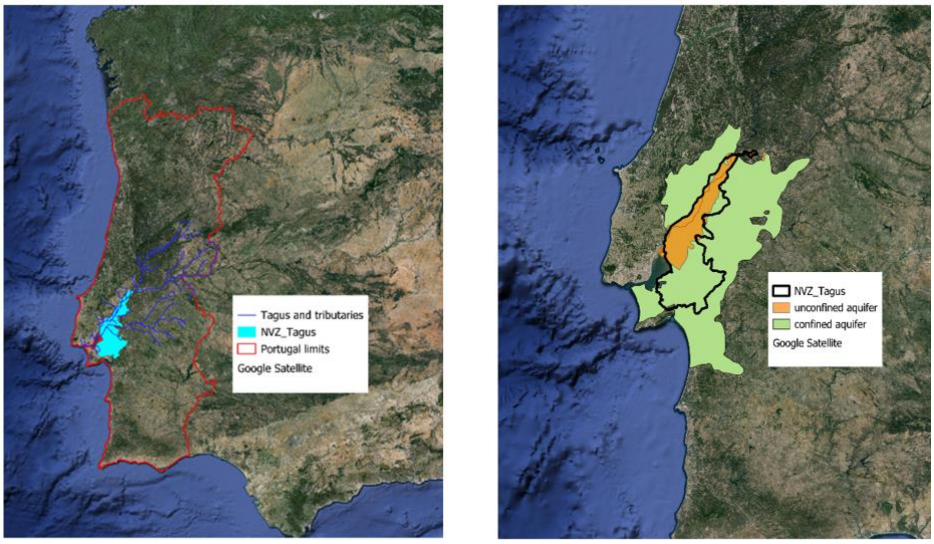

Figure 41: a) Tagus Vulnerable Zone location in Portugal; b) aquifers in Tagus Vulnerable Zone.

Nevertheless, it varies between 6% and 83% among the municipalities in the TVZ. Irrigated land in the municipalities varies between 30 and 90% of the UAA, well above the national and the EU-28 average. These figures highlight the importance of irrigated intensive agriculture in the study region. About 14% of the UAA is occupied by small farms with areas between 5 and 20 ha, 12% by farms with areas between 20 and 50 ha and 62% by farms larger than 50 ha.

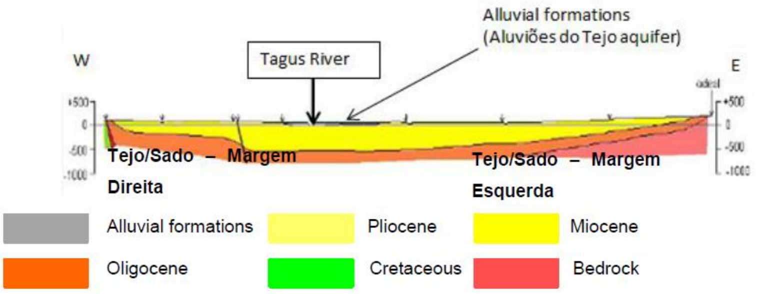

Figure 42: Cross section of Tagus sedimentary basin showing the location of the Aluviões do Tejo aquifer and the formations of Tejo/Sado underlying aquifers.

Long term daily minimum and maximum air temperatures are 13 and 29 °C, respectively. About 90% of the landscape is flat and only in 6% of the territory there is a mild slope. The TVZ extends over a hydrogeological complex area (*Figure 41b*), comprising two layered aquifers separated by an aquitard, i.e., a geological layer with reduced permeability. Above the aquitard, in the upper aquifer (2 to 14 m below soil surface), 55% of the monitoring wells record nitrate concentrations higher than 50 mg/L. This is considered a greater threat than the lower aquifer due to its proximity to the soil surface which makes it react rapidly to agricultural management.

The Portuguese pilot site corresponds to the area associated with the unconfined upper aquifer: Aluviões do Tejo (*Figure 41b*) in orange and its geological section is represented in *Figure 42* (Cameira et al., 2019).

3.1. Meteorological data collection networks

The Portuguese Environment Agency[12] (APA) has a nationwide meteorological network that was launched in 1980, although some stations have since been deactivated. *Figure 43* shows the stations covering the pilot site. There are two types of stations: climatological (4) and udometric (2). This first type provides measurements of daily precipitation, temperature, hours of sunshine, relative and absolute humidity, wind speed and direction. Udometric stations only provide only daily precipitation records.

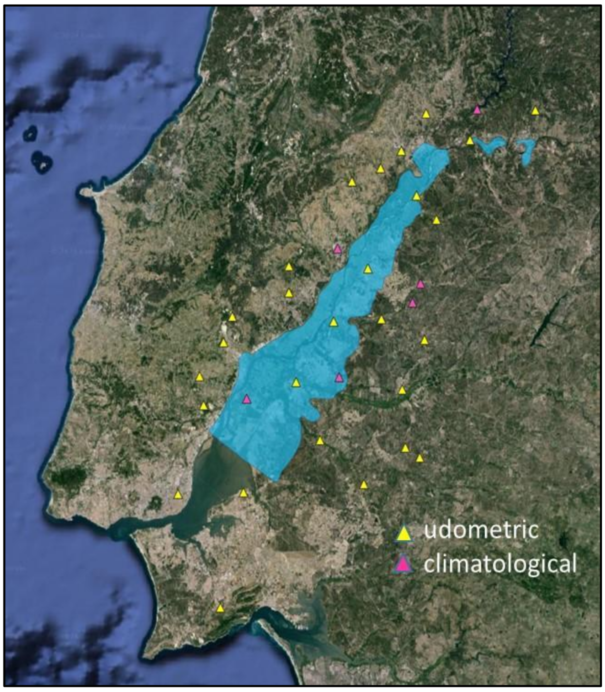

Figure 43: Meteorological (climatological and udometric) stations in the Portuguese pilot site: Aluviões do Tejo (blue area).

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[12] *APA (Portuguese Environment Agency) website. (https://apambiente.pt/)*

3.2. Monitoring of the unsaturated zone

To this day, there is no official monitoring of the unsaturated zone. Within the scope of the Clepsydra project, equipment to monitor water and nitrates in being installed in the root zone and bellow in the pilot site.

3.3. Monitoring of the saturated zone

APA is the institution responsible for the groundwater-monitoring network and monitoring protocols nationwide. It is also responsible for the publishing the monitoring results. Monitoring takes place in wells owned by farmers. There are two different monitoring networks, the piezometric network and the quality network. Groundwater monitoring information databases are available in the national system for water resources information (SNIRH in Portuguese) (https://snirh.apambiente.pt/). The locations of the monitoring wells in the Portuguese pilot site are presented in *Figure 44*.

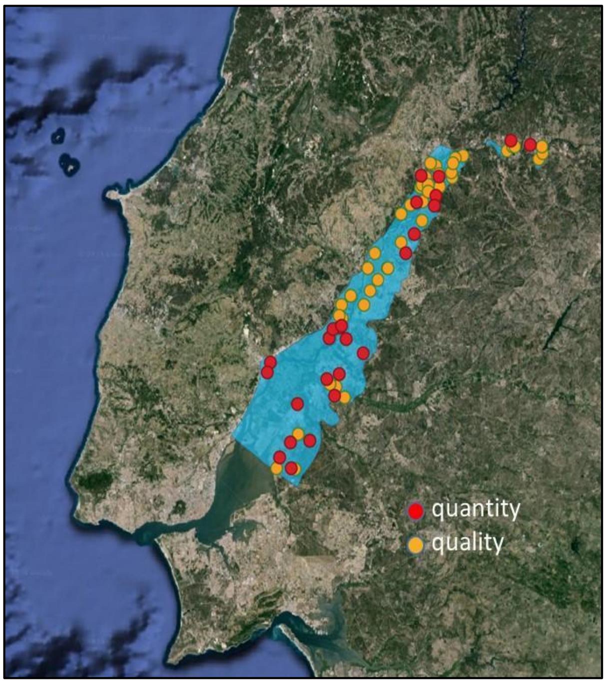

Figure 44: Location of the monitoring network managed by the Portuguese Environmental Agency.

3.3.1. Groundwater level networks

The wells belonging to the piezometric monitoring network are shown in *Figure 44*. There are 23 monitoring points in the aquifer Aluviões do Tejo, the first ones installed in 1981. However, in 2024 only 11 are active. The water level measurements are carried out once a month. *Figure 45* shows a print screen from the SNIRH platform.

As part of the Clepsydra project, divers have been installed in four wells and measurements are being taken continuously with hourly registration, the data of which is downloaded regularly.

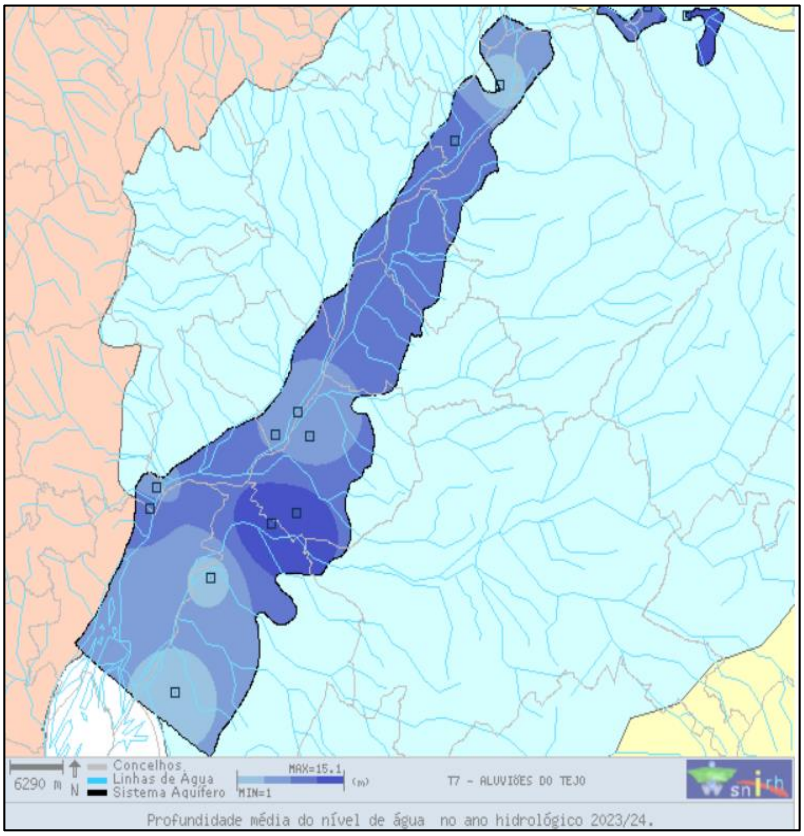

Figure 45: Print screen of the SNIRH platform showing the average groundwater depth in the Aluviões do Tejo aquifer relative to March 2024 (https://snirh.apambiente.pt/).

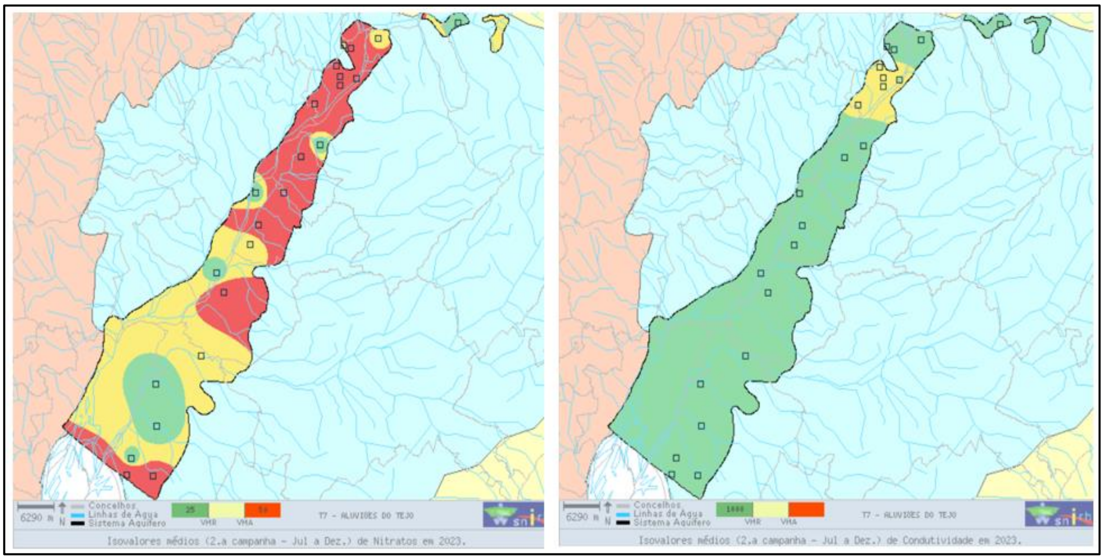

Figure 46: : Print screen of the SNIRH platform with the results of nitrate and electrical conductivity monitoring in the Aluviões do Tejo aquifer (December 2023 https://snirh.apambiente.pt/).

3.3.2. Quality networks

The wells belonging to the quality monitoring network of the unconfined quaternary aquifer Aluviões do Tejo are shown in *Figure 44*. The number of monitoring wells reached 54, but currently (2024) only 25 wells are active.

The collection of groundwater samples started in 1989. Two water samples per year are taken from the wells and analysed for nitrates and electrical conductivity. *Figure 46* shows a print screen from the SNIRH[13] platform.

3.3.3. Hydrogeological models

The Tagus alluvial aquifer, "Aluviões do Tejo," is described as a multilayer, primarily unconfined aquifer formed by Pleistocene and Holocene deposits, including alluvial and terrace formations. It covers approximately 1,113 km² along the Lower Tagus Basin, directly connecting with the Tagus River. Its sedimentary layers include sands, gravels, silts, clays, and basal conglomerates, with considerable horizontal and vertical hydraulic variability due to the complex internal structure. The primary source of recharge is direct precipitation, estimated to contribute between 210 and 220 hm³ per year, which is about 30% of total precipitation.

Additionally, recharge can occur from underlying aquifers (Tejo/Sado right and left margins), suggested by hydrogeochemical data. In the over-exploited areas, there is also upward leakage from the deeper Miocene formations. The alluvial aquifer interacts hydraulically with the Tagus River and receives discharges from the Pliocene and Miocene aquifers. Under natural conditions, the Tagus River and tributaries serve as discharge zones for the aquifer.

However, due to current levels of groundwater exploitation, this natural flow can be reversed, with the Tagus River now recharging the aquifer in certain areas. Over-extraction also alters the natural flow between aquifers, leading to flow inversions between the alluvial and Pliocene layers and between Pliocene and Miocene layers. The aquifer is also influenced by tidal effects near the estuarine border, where over-extraction has facilitated saltwater intrusion. This is a significant concern for the southern estuarine boundary, especially near coastal areas and urban regions. In the Tejo alluvium region, various studies have utilized both hydrological and hydrogeological models to understand and manage water resources effectively. These models are crucial for addressing both surface and groundwater components, which is essential for the comprehensive study being undertaken.

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[13] *SNIRH (National Water Resources Information System) platform. (https://snirh.apambiente.pt/)*

3.3.3.1. BINGO Project Flow Model [14]

The hydrogeological model used for the Tagus alluvial aquifer in the context of the BINGO H2020 Project is a numerical groundwater flow model based on FEFLOW software, which was selected for its ability to simulate complex groundwater systems. FEFLOW is a finite-element computer program from DHI-WASY GmbH, able to simulate regional problems with a high number of elements. It can simulate interactions between rivers and aquifers, saltwater intrusion, saturated and unsaturated flow, multi-species mass transport (pollution problems) and transport controlled by fluids' density effects and chemical kinetics, amongst other groundwater issues.

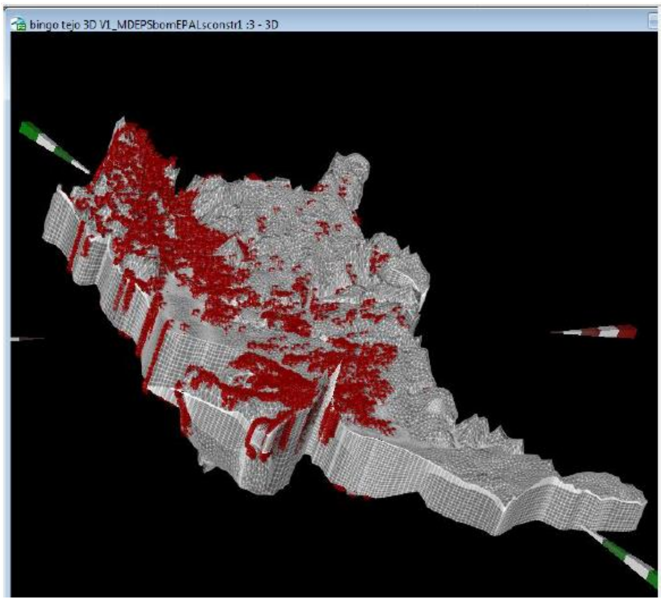

Figure 47: Multilayer wells boundary conditions in the model.

Key features of this model include:

- Conceptual Model Development: the aquifer system was defined as a multilayer, mostly unconfined aquifer comprising alluvial, Pleistocene, and Holocene formations. These are interconnected with nearby aquifers in the Lower Tagus Basin. This conceptual model incorporates the hydraulic connection between the Tagus River and the aquifer, considering both recharge from rainfall and possible hydraulic interactions with surrounding aquifers.
- Data Integration: the model incorporates climate simulation outputs from the MiKlip model for climate projections and uses BALSEQ_MOD for recharge estimation. This enables the analysis of recharge variability under different climate scenarios. Hydraulic properties, such as transmissivity, porosity, and specific storage, were obtained from previous studies and Tagus Watershed Plans, allowing for accurate calibration and input parameter definition.

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[14] Novo et al. (2020) https://repositorio.lnec.pt/jspui/handle/123456789/1012984

- FEFLOW Numerical Model Structure: a three-dimensional mesh was created to represent the aquifer geometry, divided into multiple layers and slices to capture variations in hydraulic properties and thickness across the aquifer.
- Boundary conditions, such as flux boundaries and river interactions, were defined to simulate the Tagus River’s influence on groundwater levels.
- Scenarios and Simulations: the model runs simulations across various recharge and drought scenarios, from extreme high and low recharge conditions to permanent and transient droughts (1, 3, and 5 year durations).

Results showed anticipated responses, with water levels rising under high recharge scenarios and decreasing during droughts, particularly in areas with high hydraulic gradients. This model serves as a tool to evaluate the impacts of climate change on groundwater availability and to inform water management strategies in the Lower Tagus Basin (*Figure 47*).

3.3.3.2. SWAT Flow Model (2021) (Costeira et al., 2021)

Costeira (2021), study involved a hydrological study of the Alenquer basin using the Soil and Water Assessment Tool (SWAT) to improve the delineation of Nitrate Vulnerable Zones (ZVN) in the Tejo region. This study aimed to enhance the hydrological balance analysis of the Alenquer basin and identify major runoff flows potentially transporting nitrate (*Figure 48*).

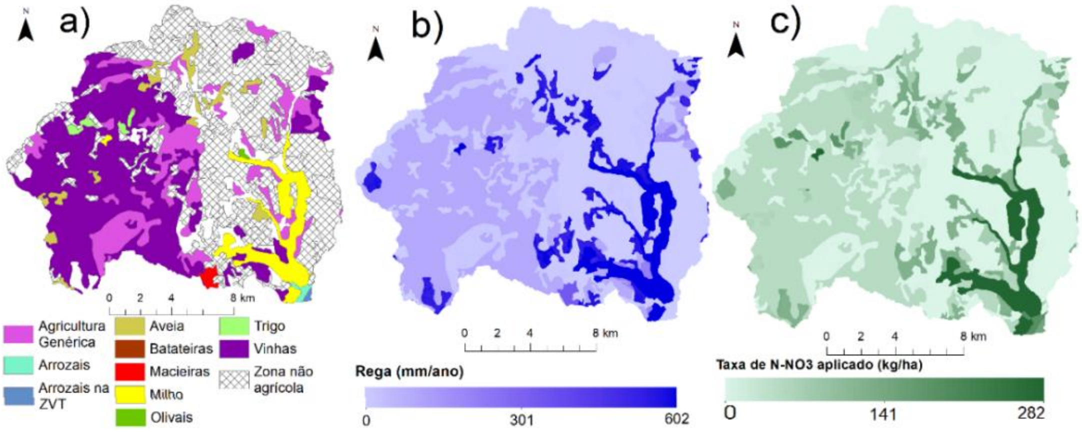


Figure 48: Spatial distribution of: a) crops, b) annual irrigation allocation, and c) nitrogen application rate in the Alenquer River Basin in 2012.

The SWAT model was calibrated for the Barnabé and Ota sub-basins using meteorological, hydrological, land use, and agricultural practice data. The model achieved high efficiency (Nash-Sutcliffe coefficients of 0.83 and 0.93) for downstream flow simulations and responded well to different boundary conditions and agronomic practices.

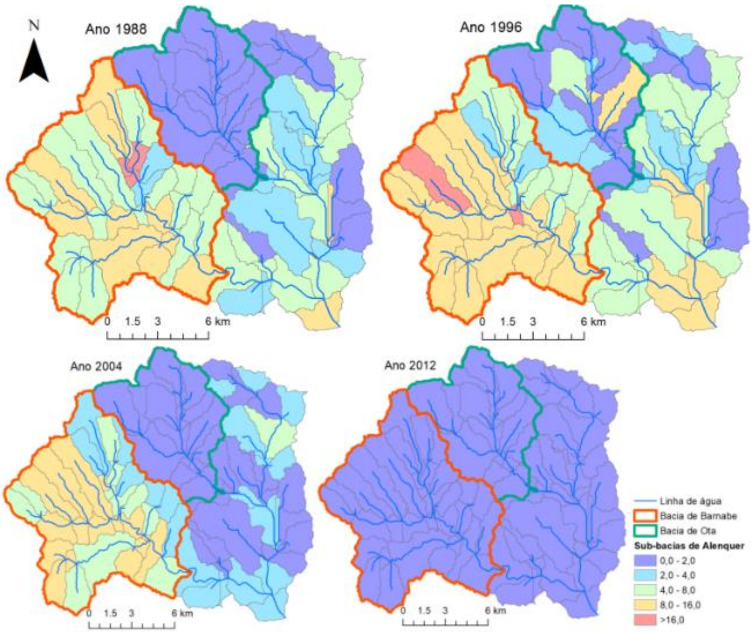


Figure 49: Temporal evolution of nitrate leaching (kg N ha⁻¹) for the years 1990, 1997, 2006, and 2012 in the Alenquer Basin.

The results indicated that approximately 5% of percolated water from the root zone reached the confined aquifer, with the majority contributing to the recharge of the phreatic aquifer. This recharge averaged 220 mm in wet seasons and 93 mm in dry seasons over 30 years. The study concluded that the Alenquer basin significantly impacts the surface waters of the ZVN, suggesting future work should focus on aquifer recharge and runoff estimates rather than administrative boundaries modelling with the Root Zone Water Quality Model *(Figure 49)*.

3.3.3.3. RZWQM (2007)

Studies regarding the water and nitrate balances in the unsaturated zone have been performed using the Root Zone Water Quality Model (RZWQM) developed by the USDA. The model requires as input irrigation, fertilisation and other crop management practices and produces as a result water and nitrate fluxes out of the root zone (Cameira et al., 2007).

3.4. References

Cameira M. R., Fernando R. M., Ahuja L., Ma L. (2007) Using RZWQM to simulate the fate of nitrogen in field soil crop environment in the Mediterranean region. *Agricultural Water Management*. Volume 90(1): Pages 121-136. DOI:10.1016/j.agwat.2007.03.002

Cameira M. R., Rolim J., Valente F., Faro A., Dragosits U., Cordovil C. (2019) Spatial distribution and uncertainties of nitrogen budgets for agriculture in the Tagus river basin in Portugal – Implications for effectiveness of mitigation measures. *Land Use Policy*. Volume 84, May 2019: 278-293.

Costeira A., 2021. Estudo Hidrológico da Bacia de Alenquer com recurso ao modelo SWAT. Lisbon University, Dissertation for the attainment of a Master's Degree in Environmental Engineering.

4. MALTA MEAN SEA LEVEL (MALTA)

The Energy and Water Agency (EWA), the Clepsydra project partner from Malta, it is a Policy Agency entrusted with the development of national policies for the energy and water sectors. In this role, EWA is also the National Competent Authority for the implementation of the EU Water Framework Directive (WFD) for inland waters in Malta.

Malta's groundwater is stored in three main aquifers: Mean Sea Level (MSL), perched, and coastal. The MSL aquifer is the project pilot site. It is the largest and most sustainable, covering a significant portion of southern and central Malta.

4.1. Meteorological data collection networks

5 weather stations are operational close to ZNS monitoring network. More details are provided in the following section.

4.2. Monitoring of the unsaturated zone

The Unsaturated zone monitoring network was set up with Sensoil Innovations Ltd and is composed of a total of 16 stations; 12 of which are within the recharge area of the Malta Mean Sea Level Aquifer (MSLA). These stations are all located in an agricultural setting around Malta, with 5 of these stations having an accompanying weather station. The monitoring of the unsaturated zone enables the assessment of the qualitative characteristics of recent recharge to groundwater. Moreover, this network aims to understand the volumes of water which will end up percolating through the unsaturated zone as a result of the seasonal variations in rainfall events, irrigation practices, and the impact of different soil types. Moreover, the different geological formations will also provide information on the recharge velocity occurring at that particular location. Malta's geology is primarily composed of five distinct layers: Upper Coralline Limestone, Globigerina Limestone, Blue Clay, Greensand, and Lower Coralline Limestone. The surface layer is generally covered by soil or Quaternary deposits. These geological formations are not uniformly distributed across the island, and their presence varies in depth and thickness; in some areas, certain layers may even be absent altogether. The unsaturated zone network is predominantly situated in regions where the geological sequence begins with Globigerina Limestone and extends downwards to the older formations, reaching a maximum of the younger member (Mara member) of the Lower Coralline Limestone formation.

Each station in the unsaturated zone monitoring network consists of a slanted borehole, approximately 20 m deep, angled between 35^{o}- 45^{o}. This design is intended to effectively capture water percolating through the area of the field being monitored. Each borehole is equipped with a sleeve containing multiple Vadose Zone Pore Water Sampling Ports (VSP) and Flexible Time Domain Reflectometry (FTDR) sensors at various depths, distributed throughout the unsaturated zone. The sensors are positioned along the sleeve, with two in the soil (around 0.5 m deep) and nine along the various geological formations. The sensors are connected to a control panel which allows for interaction with the VSP sensors and facilitates water sampling from the unsaturated zone.

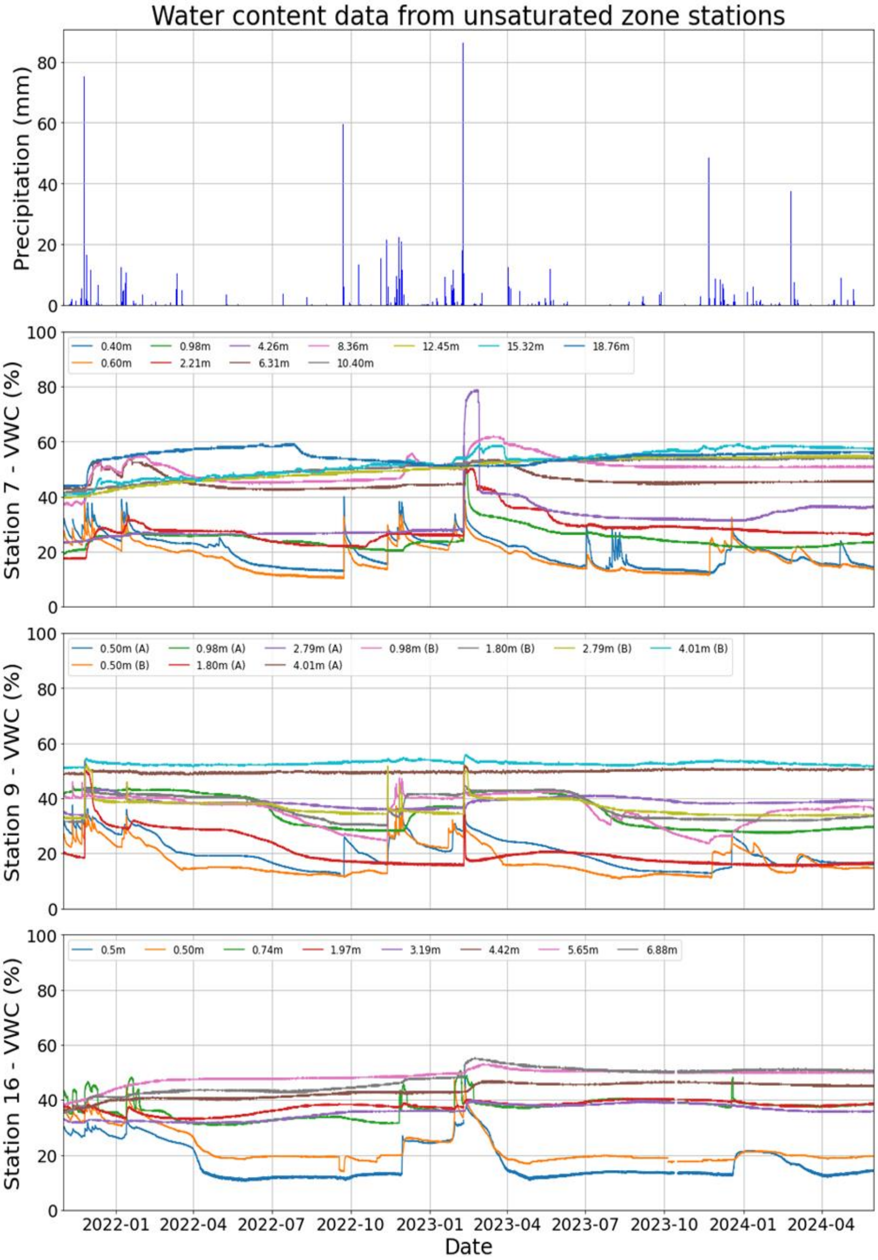


Figure 50: Water saturation being detected in the rock during increased rainfall, and during irrigation periods.

The VSP sensor creates hydraulic continuity between sediment pore water and a sampling cell that allows for water sampling. This is done by having a porous interface between the unsaturated zone and a sampling cell. There are up to 11 different sampling ports which enable sampling from different depths. At each depth, the system allows the sampling of a volume of water which can then be analysed for selected parameters at the lab. In the case of Malta, given the focus on nitrate the following parameters have been analysed: nitrates, ammonia and nitrite. Whilst electrical conductivity, pH and dissolved oxygen are analysed on site.

Whilst the FTDR sensor enables continuous measurement of water content and temperature. Data from all the monitoring stations is remotely sent to an online portal, called Grafana, which displays the water saturation of the rock at that specific depth. Variations in the values of this water content can provide information on the hydrogeological impact of periods of rainfall and/or irrigation on the water content and recharge processes in the unsaturated zone (*Figure 50*).

The Clepsydra project shall focus on monitoring within the Malta MSLA. The unsaturated zone monitoring network has 12 stations located throughout the Malta MSLA (*Figure 51*). The agricultural setting varies, covering a range of situations including perennial plants, permanent plants (orchard/grapes), rain fed, irrigated, greenhouse, and open field setups.

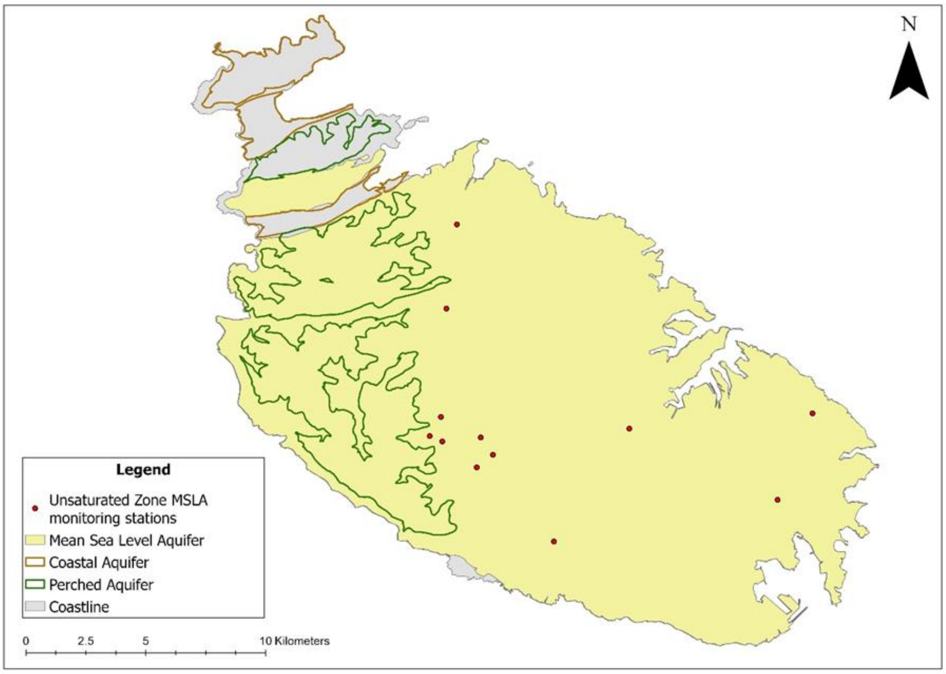


Figure 51: Unsaturated Zone Monitoring stations within the Malta Mean Sea Level Aquifer.

The analysis will also aid in understanding the rate of recharge waters through the various rock formations and the eventual impact and degradation process of nitrate as it percolates through the upper horizons of the unsaturated zone.

Nitrates in Malta's groundwater bodies are found at high concentrations and arise from anthropogenic activities. The results of a 2012 study (Heaton et al., 2012) using isotopic source tracing indicated that over application of fertilisers in agriculture are the main source of nitrate contamination. This also explains why this innovative approach to the monitoring of the quality and quantity aspects of recharge waters has been adopted for the unsaturated zone. The results generated from this monitoring network will provide the opportunity to collaborate with other governmental entities and the agricultural community to educate and optimise their agricultural inputs.

4.3. Monitoring of the saturated zone

4.2.1. Groundwater level networks

The first groundwater level data available for the Malta Mean Sea Level Aquifer is from 1944. This data set was collected every couple of months throughout that same year from a number of groundwater sources. At the time, only manual water level measuring instruments were available, and this method was utilised to measure groundwater level in 40 groundwater sources spread across Malta only, given a spatial resolution of 5 stations per square kilometre. This data set for groundwater level is mainly used to calibrate a steady state groundwater model, meaning when the aquifer was in a more natural state, with limited groundwater abstraction occurring.

Monitoring between the 1960s and early 1990s was done in the same manner. However, during this period, groundwater level monitoring was more sporadic and not the same groundwater sources were utilised routinely for monitoring. As a result, the time series of some of these groundwater level monitoring stations presents multiple gaps, and at times, changes in their use from a gauging to an abstraction station, led to the loss of such monitoring stations.

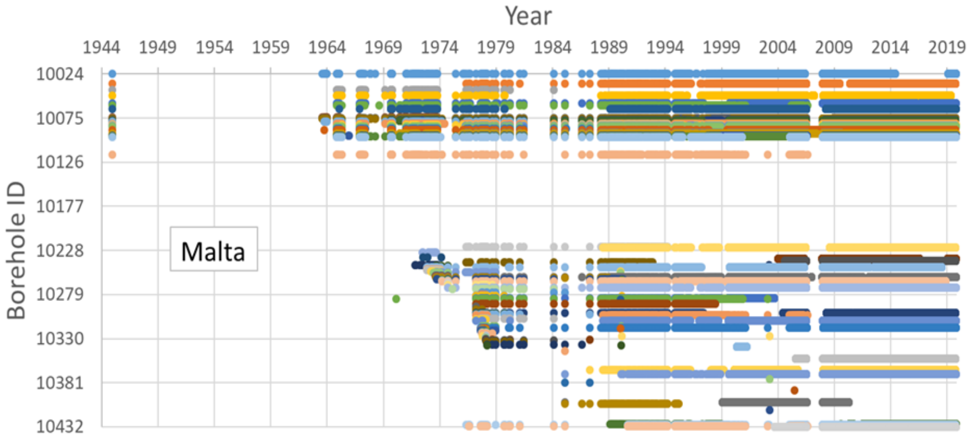
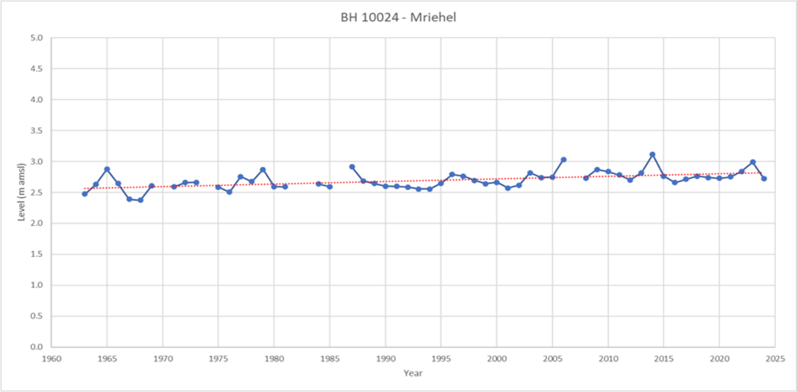
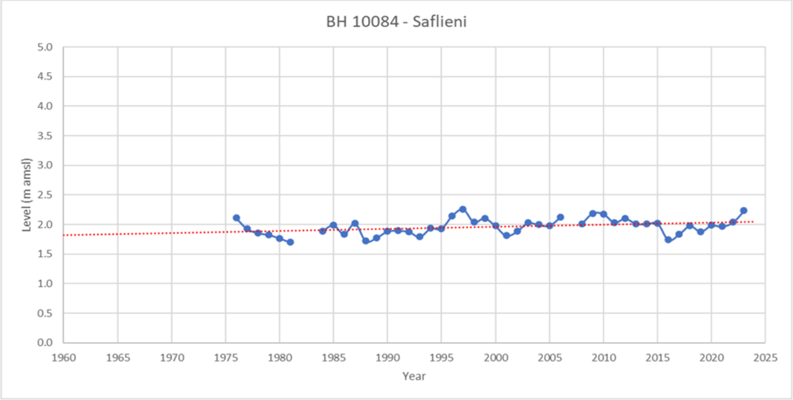
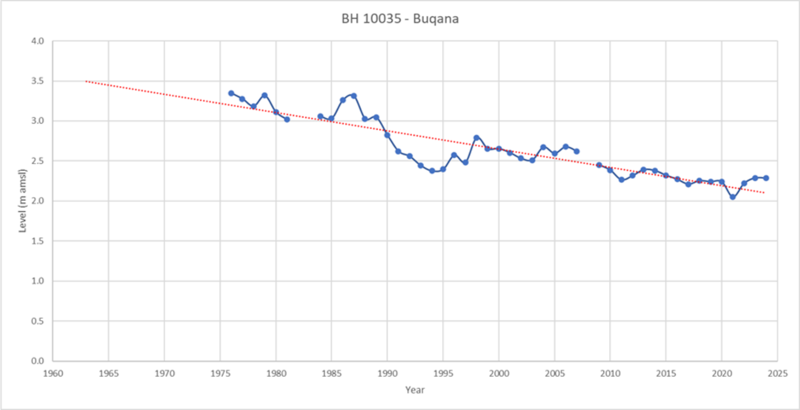


Figure 52: Quantitative data availability for the Malta Mean Sea Level aquifer.







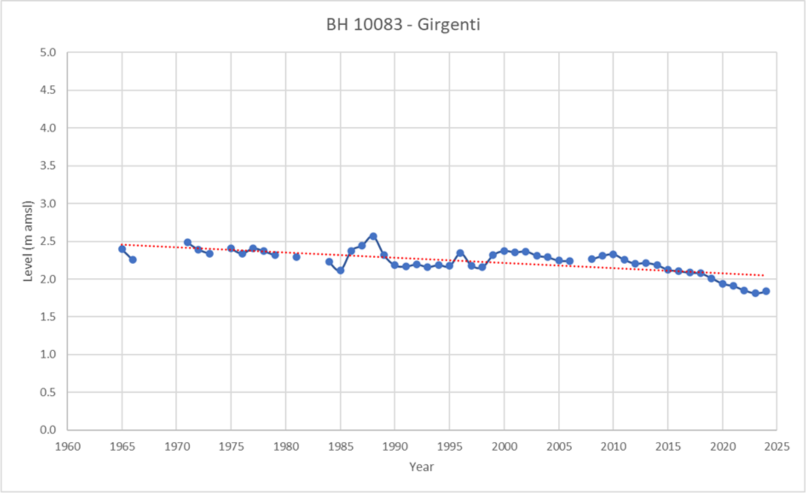


Figure 53: Yearly Average groundwater level data from 1944 to 2023 for four monitoring stations.

By 1999, groundwater level monitoring began shifting to a more automated process using a float type water level sensor, with an integrated data logger which allowed for more frequent and automated monitoring. At the time, at least 38 boreholes in Malta were monitored at 30- minute frequency. These instruments remained operative until 2020, when they started being replaced by the Energy and Agency in favour of pressure sensors given their increased reliability. Given that groundwater level measurements which are available as from 1944 (*Figure 52*), it is possible to plot a prolonged time series and calculate statistical trends of groundwater level in support of the quantitative status assessment of the Malta MSLA (*Figure 53*).

In 2020, the monitoring network shifted from float-type sensors to pressure sensors. In some sites, these pressure sensors are measuring depth, conductivity, and temperature and in other sites, these are measuring just depth and temperature. In 2023, groundwater level was monitored in 39 wells spread throughout the Malta MSLA have been utilised for groundwater level monitoring (*Figure 54*).

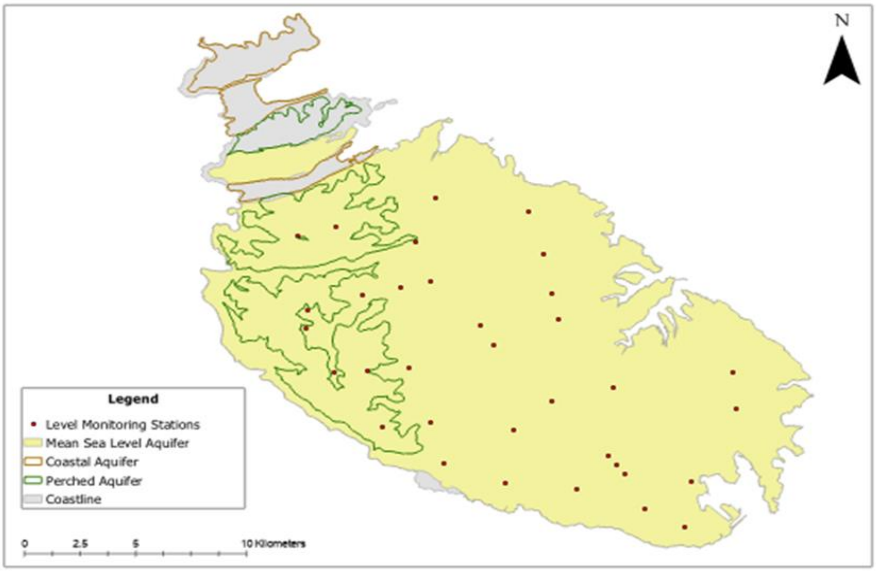


Figure 54: Quantitative Network monitoring stations.

For monitoring to be done correctly, a solid reference point of the meters above mean sea level of the borehole, known as the benchmark, is recorded. This reference point is crucial to calculate the level of water above the mean sea level, given that the resultant groundwater level is measured with respect to this benchmark. These benchmarks were set when these boreholes were primarily drilled in the 1940s and 1970s. In recent years all the newly drilled groundwater monitoring stations were surveyed to establish benchmarks, and where necessary, previously drilled boreholes were resurveyed to confirm their existing benchmarks.

Monitoring is currently being done with the use of water pressure sensors that are lowered in the gauging boreholes at a fixed depth, which is approximately 5 meters from the top of the water column. Water pressure is then compensated for by the atmospheric pressure. Barometers (Baro-Diver gauge) have also been set up at several sites in Malta, Gozo, and Comino. When setting up and placing these barometers, it was ensured that all the different elevations where groundwater level monitoring is occurring are covered as these would then affect the calculations for groundwater level. At each of these monitoring stations, the groundwater level data is recorded at 30-minute intervals. The current setup for the monitoring of groundwater level allows for a good spatial coverage of the regional variations in groundwater level trends and the overall assessment of the groundwater quantitative status.

4.2.2. Quality networks

Groundwater in Malta has been monitored for qualitative parameters since the 1960's by the Water Services Corporation (WSC[15]) including the monthly monitoring conducted by the same entity on several boreholes in the Malta Mean Sea Level aquifer for nitrates and chlorides. The latter stations are in operation for water supply purposes.

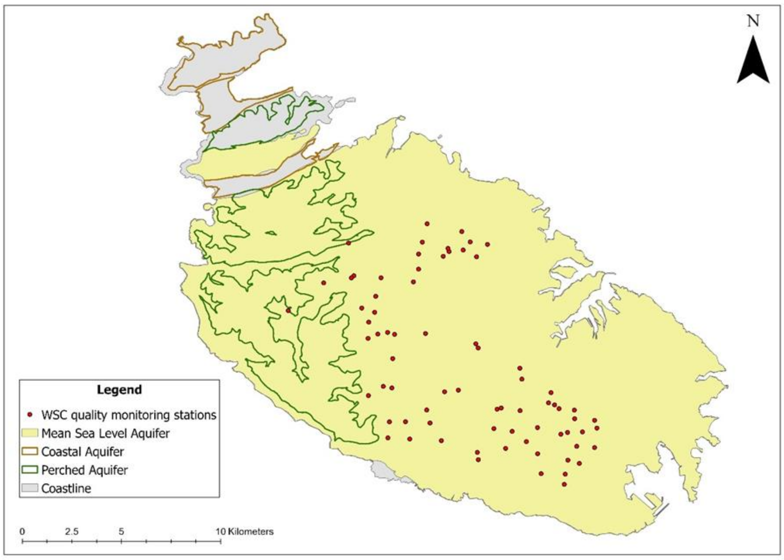


Figure 55: WSC's monitoring stations located in the Malta MSLA.

A map illustrating the location of WSC's water supply stations within the Malta MSL aquifer, which are also used to monitor quality parameters are displayed in figure 55. Since 2009, the Water Framework Directive network was set up which covers all fifteen groundwater bodies in Malta. A total of 42 stations are monitored including 15 stations in the Malta MSLA (Figure 56) which results in an overall average monitoring density of one station, roughly every 7 square kilometres for the Malta MSLA. As required

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[15] *WSC (Water Services Corporation) website. (https://www.wsc.com.mt/).*

by the WFD there are various types of stations to ensure that the network reflects the spatial variability of land use in Malta including privately owned hand-dug wells and boreholes and boreholes that are managed by the Water Services Corporation (WSC) and form part of the water distribution network.

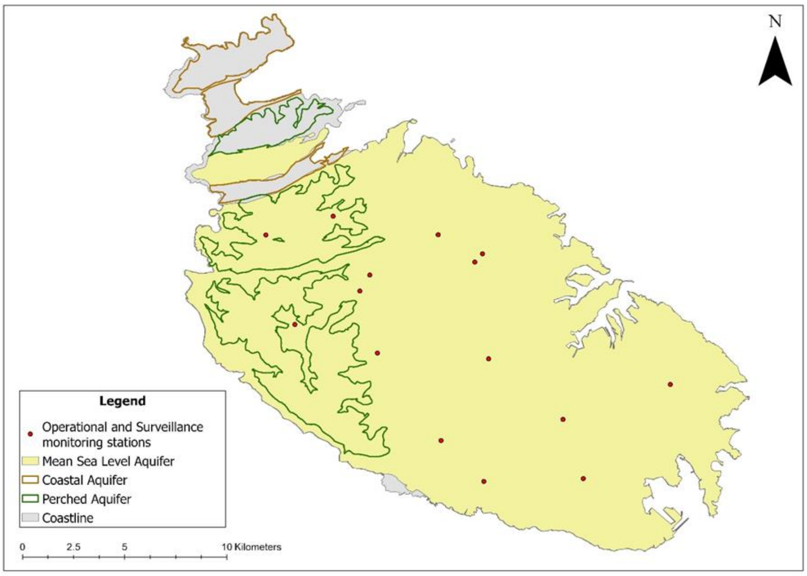

Figure 56: Operational and Surveillance monitoring stations located in the Malta MSLA.

Qualitative monitoring is carried out bi-annually and follows the Water Framework Directive (WFD) reporting cycle. Hence, the qualitative groundwater monitoring strategy adopted in Malta envisages a six-year cycle starting with a 'Surveillance' monitoring exercise which is then complemented by five years of 'Operational' monitoring (*Figure 57*).

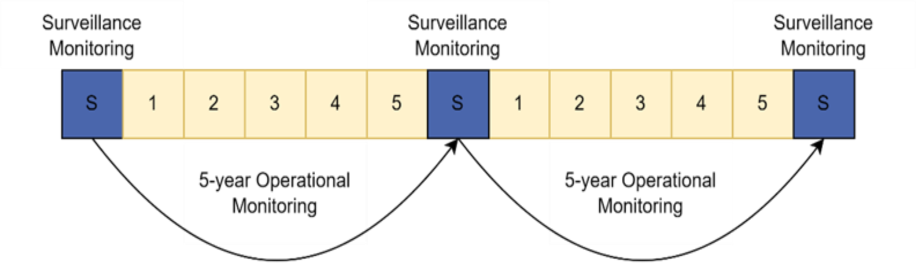

Figure 57: Surveillance and Operational Monitoring Cycle.

Surveillance monitoring entails a full qualitative analysis of the status of each groundwater body. Moreover, this monitoring programme also serves the purpose of identifying those parameters for which more frequent (operational) monitoring is required to enable the assessment for long term trends in natural conditions and in pollutant concentrations resulting from human activity. Surveillance monitoring also informs and validates risk assessments in the context of the WFD.

Operational monitoring is carried out bi-annually during the five-year periods between Surveillance Monitoring and can be considered as a specific monitoring exercise focused on assessing the specific identified risks to the achievement of the Directive's objectives. This monitoring exercise is carried out generally in spring and autumn.

The operational monitoring programme is designed based on the analysis of the results of the Surveillance Monitoring programme and the assessment of pressures and impacts on the groundwater resources.

The list of parameters assessed during the operational monitoring sessions aligns with the requirements of the EU Groundwater Directive, as well as the parameters indicated in the WFD voluntary watch list. Nitrates (NO_3) is a key indicator being monitored due to its impact on water pollution. A list of parameters being analysed is listed in *Table 1* with the corresponding quality standard or threshold value set for Malta Mean Sea Level.

Table 1: List of Parameters Monitored in Operational Monitoring

Parameters monitored and corresponding quality standards/ threshold values (where applicable)	
PARAMETER	**MALTA MEAN-SEA LEVEL**
Nitrate (NO_3)	50 mg/l
Pesticides	0.1 µg/l per pesticide and 0.5 µg/l for total pesticides
Chloride (Cl)	1000 mg/l
Sulphate (SO_4)	475 mg/l
Electrical Conductivity	4500 µS/cm
Lead (Pb)	10 µg/l
Ammonium (NH_4^+)	0.25 mg/l
Ammonia (NH_3)	
Trichloroethylene	5 µg/l
Tetrachloroethylene	5 µg/l
Nitrite (NO_2)	0.25 mg/l
Phosphate (PO_4^{3-})	0.03 mg/l
Boron (B)	0.6 mg/l
Copper (Cu)	2 mg/l
Zinc (Zn)	3 mg/l
Sodium (Na)	450 mg/l
Arsenic (As)	5 µg/l
Fluoride (F)	1.5 mg/l

The results from operational and surveillance monitoring are then utilised to assess the qualitative status per groundwater body which is reported in the River Basin Management Plan. Status is determined by comparing the results to present threshold values that take into consideration the background values of the parameter being assessed.

4.2.3. Others

In addition to the main groundwater level and flow monitoring networks and qualitative monitoring network, two additional networks have been developed; the groundwater "deep" well network and the groundwater freshwater-saltwater interface network. Both networks focus on the Malta MSLA given their importance from a water resources perspective. The groundwater deep well network enables the profiling of salinity across the freshwater lens, whilst the freshwater-saltwater interface network was set up to further understand the changes occurring at this complex interface.

Groundwater deep well network

A "deep" groundwater monitoring network was setup in 2023 in collaboration with the British Geological Survey (BGS) whereby the deeper parts of the groundwater column can be analysed. This network started with the drilling of 17 new wells, within the Malta MSLA, and these boreholes were drilled in strategic locations, mainly in areas that do not overlap with the current groundwater level monitoring network (*Figure 58*). The depths of these boreholes range between 49 meters below ground level, in locations which are close to the coastline, to 322 meters below ground level, at sites with the highest elevation in the islands. The lengths of the water column in these sites ranges from 30 meters to 120 meters. Each borehole has a pump and sensor configuration bundled together around a central hauling wire rope core. The bundle is anchored at the headwork using a separate steel rope. Through this network, EWA will be able to monitor both the quantitative and qualitative elements of the mean sea level aquifers at specified strata and assess the stratification of groundwater quality in the Malta MSLA. The first pump and sensor were placed at 5 metres below water level, the second at 20 metres below water level, the third at 40 metres below water level, and the fourth at 60 metres below water level. Given the variable range of lengths of water columns in these sites, not all of them have the same amounts of pumps and sensors. The setup at each of these deep groundwater monitoring stations consists of the following: a) A sensor at the surface measuring conductivity, temperature, and depth, b) Between 1 and 3 sensors at different depths within the water column measuring conductivity and temperature, c) Between 2 to 4 bladder pumps at different depths which facilitate the collection of water samples at different depth.

Each borehole is equipped with a well enclosure within which telemetry equipment is also kept. Through this setup, EWA[16] will be able to monitor the groundwater level above the mean sea level, the variations in conductivity and temperature at different depths within the water column and

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[16] The Energy and Water Agency of Malta. Link to the website (*https://energywateragency.gov.mt/*).

simultaneously collect water samples from the different depths within the water column. Such a setup will allow for the assessment of the stratification of groundwater quality with depth in the MSLA and therefore greatly enhance the qualitative monitoring of our groundwater.

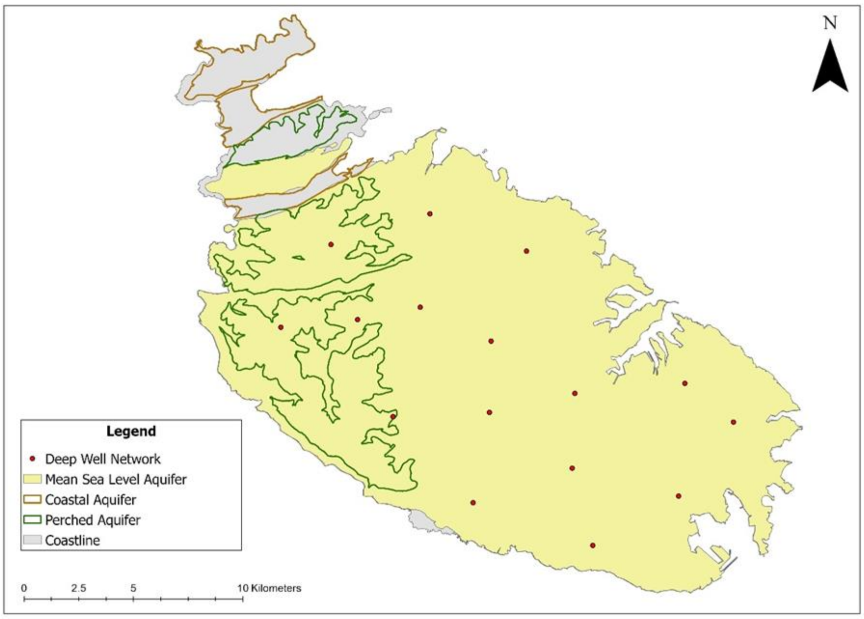

Figure 58: Deep well monitoring network sites.

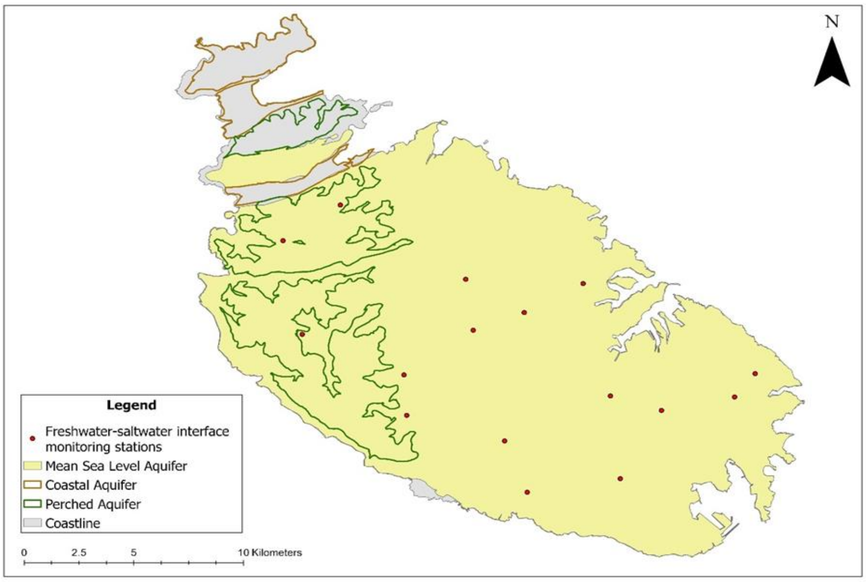

Figure 59: Freshwater-saltwater interface monitoring network sites with the Malta MSLA.

Groundwater freshwater-saltwater interface network

In 2023, a monitoring network consisting of 20 stations (15 in Malta, all within the Malta MSLA, and 5 in Gozo) was established in collaboration with KIGAM, with a focus on the freshwater-saltwater interface. *Figure 59* displays those stations that form part of the Malta MSLA.

The Korea Institute of Geoscience and Mineral Resources (KIGAM) is a government-funded research organisation focused on advancing geological science through research and development.

The established monitoring network shall provide near real-time information on groundwater level above sea level, the thickness of the freshwater lens above the groundwater-salt interface, and the depth to the upper boundary of the freshwater-saltwater interface. This innovative method uses a probe which is housed within a capsule which floats at the density which is specifically pre-set for that probe. The depth of the sensor with respect to the groundwater level is measured via the pressure sensor which allows for the determination of the exact location of the probe with respect to the interface. This is better illustrated in *Figure 60* below.

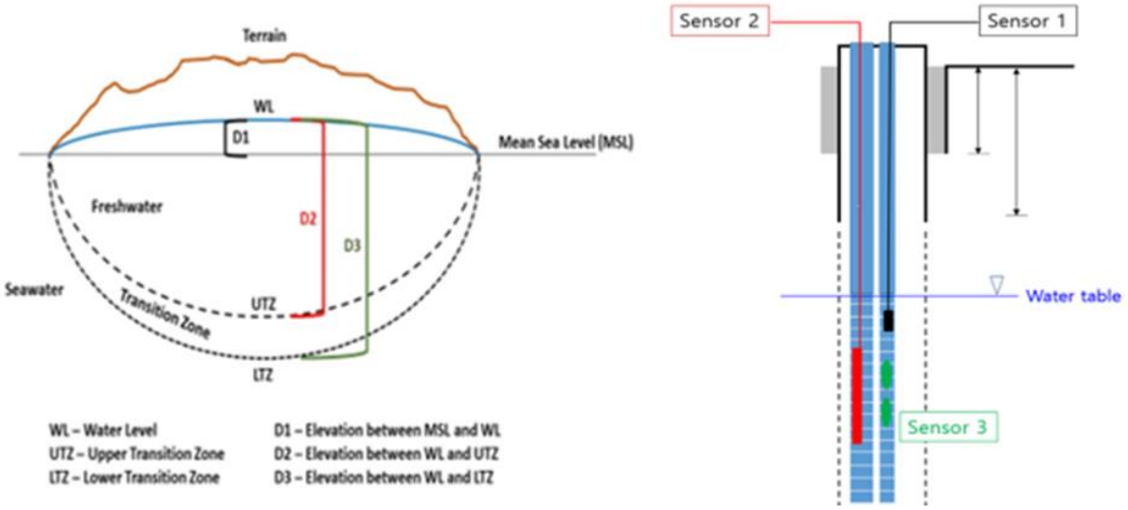

Figure 60: An explanation of the freshwater-saltwater interface network.

The data acquired from the monitoring network shall be analysed to better characterise the spatial and temporal distribution of fresh groundwater within the main aquifer of the Maltese Islands and to understand its complex interactions with saline waters.

Monitoring of the freshwater and saltwater interface and its characteristics is an important aspect for a proper assessment of the groundwater quantitative status in coastal and island aquifer systems.

Since changes in the piezometric (water table) levels are expected to give rise to more pronounced changes in the interface. This network will therefore complement the existing and newly commissioned water level monitoring networks and enable a more comprehensive and reliable assessment of the groundwater quantitative status in the Malta and Gozo Mean Sea Level groundwater bodies.

4.2.4. Hydrogeological models

The hydrogeological model of the Malta mean sea level aquifer was done in 2020 (Barbagli et al., 2020). This was part of a larger project co-financed by the LIFE Programme [LIFE16 IPE/MT/00008]. This model included both steady state and transient state periods.

The main aim was to understand the issues that this groundwater body faces, and to assess the impact of its status in the future. Groundwater flow was simulated using MODFLOW2005 through the FREEWAT, where SWI2 and PEST packages were also applied to the model given the local context.

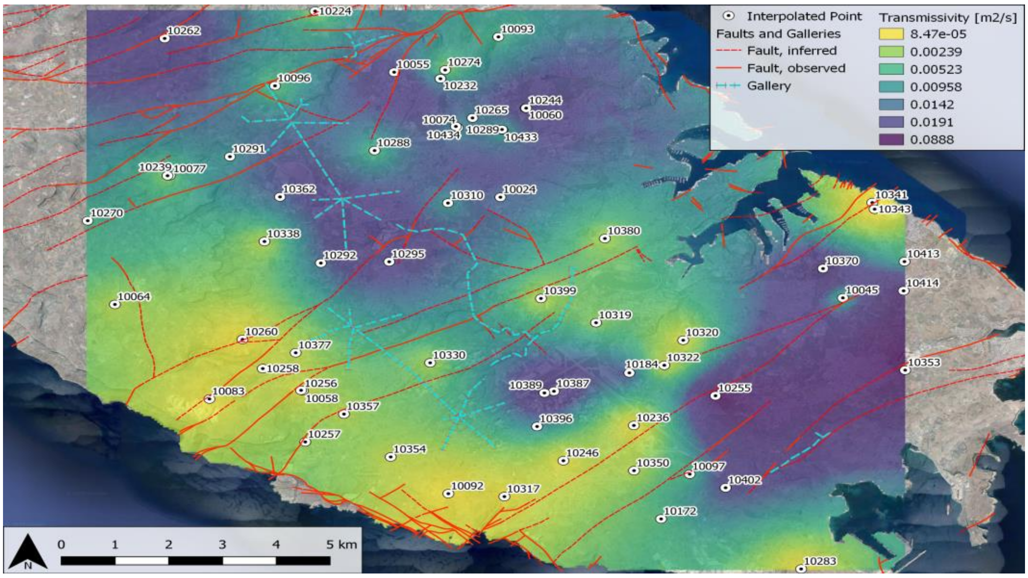

Figure 61: Ordinary Kriging representing the distribution of T in m²/s.

The Malta mean sea level aquifer is hosted within the Maghlaq member of the lower coralline limestone. This sea level groundwater body forms as freshwater lens floating over seawater, therefore, an unconfined aquifer for the most part. Confined or leaky conditions could only be found in the eastern sector of the island where the globigerina limestone dips below sea level. The thickness of this freshwater lens is equal to 36 times the piezometric head when applying the Ghyben-Herzberg formula. The aquifer recharges through fractures overlying the globigerina limestone, leakage from the overlying perched aquifers, and artificial recharge from leakages from the potable supply network and sewage network.

The calibrated steady state model aimed to assess and represent the water balance at the early stage of exploitation (1941 – 1944), and to represent the freshwater-saltwater interface at the time. The model consisted of 43318 cells of 50 by 100 meters that would cover the 216.6 km^2 area of the groundwater body. Vertical discretization was done, and the thickness of the aquifer was assumed to be about 180 meters represented as a 1 model layer. After initial analysis of the hydrodynamic parameters, a distribution map of transmissivity of the domain could be developed as shown in *Figure 61*.

The potentiometric surface was built from the available heads from 1944. This data was also integrated with fictitious points to introduce the seawater elevation at 0 m asl. The boundary conditions for the groundwater body were as follows:

- General head boundary [GHB] was used to represent the sea with elevation that is equal to 0.15 m. this was set due to the tidal analysis that was done as part of this work.
- The conductivity, after calibration, had a starting value of 50 m^2/day.
- WELL package was used to represent the pumping wells and galleries.
- Hydraulic Flow Barrier [HFB] was used to represent the main discontinuities created by the faults with a K = 8.64 m/day. This value was given equally to all faults.

Table 2: Time discretization for the model.

Stress Periods	Start	End	Meaning	Frequency	Type
1 – 2	01/01/1600	31/12/1943	Natural (no exploitation and initial exploitation)	Multi-year	Steady State
3	01/01/1944	31/12/1955	1st exploitation age	Multi-year	Steady State
4	01/01/1956	31/12/1998	2nd exploitation age	Multi-year	Steady State
5 – 18	01/01/1999	31/12/2012	3rd exploitation age	Yearly	Transient
19 – 42	01/01/2013	31/12/2014	Recent years	Monthly	Transient

A highly parameterized approach was applied to the transient model versions. The available datasets were used for the calibration of the models. The properties and boundary conditions which were included in the calibration parameters were:

- Aquifer hydraulic conductivity
- Hydraulic conductivity of faults, uniform along each fault
- General head boundary conductance
- Recharge multipliers

At this stage pilot points were also introduced that included other parameters, rather than just head observations. The newly introduced parameters included pumping tests, tide tests and the relationship between chlorides concentration and transmissivity. The calibrated parameters presented some bias due to the attempt to calibrate observed data affected by local conditions, by the roughness of some of the assumptions or by errors in the assigned boundary conditions.

Finally, the groundwater-seawater interface was simulated using SWI2. This package was coupled to the flow model and run modifying the numerical solver parameters to reach a smooth convergence. The results showed gave a sharp interface contour map as shown in *Figure 62* below.

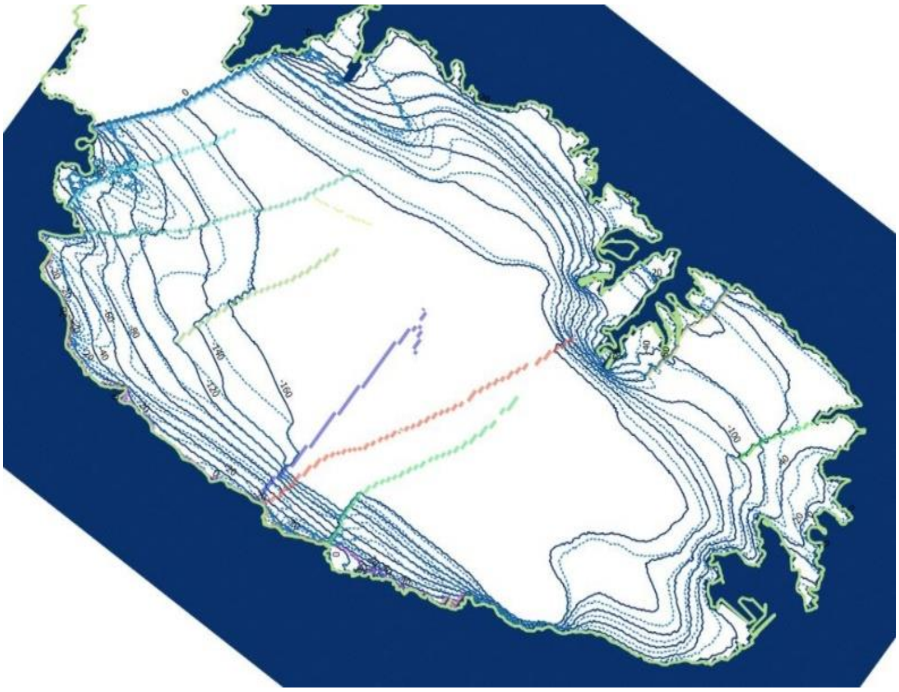

Figure 62: Comparison of SP1 [dashed lines] and SP3 of the interface simulated with SWI2.

When these simulations were compared to the observed data, the difference was extremely high, and the simulated interface was much deeper. This difference was attributed to a number of things, namely the bottom of the aquifer that was set at 180 m, the calibrated value of K and transmissivity values. Therefore, further calibration of this with more data about EC would be needed.

4.4. References

Barbagli A., Basile P., Borsi J., Guastaldi E., Lotti F. (2020). Numerically enhanced conceptual modelling (NECoM) applied to the Malta Mean Sea Level Aquifer. *Journal of Hydrology*. DOI:10.1007/s10040-021-02330-2

Heaton T. H., Sapiano M., Stuart M. E. & Sultana M. M. (2012). An isotope study of the sources of nitrate in Malta’s groundwater. *Journal of Hydrology*, Volume 414, Pages 244-254.

5. SWOT ANALYSIS OF NUMERICAL MODELS

A detailed SWOT analysis has been conducted for each of the numerical models summited by project partners. The objective of this evaluation is to identify the strengths and weaknesses of the models, assess their potential, and guide targeted improvements to address existing limitations.

5.1 Campo de Cartagena

Three numerical models have been analysed for the Campo de Cartagena site. The following paragraphs summarize the strengths and weaknesses of each model. Regarding external variables, the models share common opportunities and threats. The predictive capabilities of the calibrated models provide a valuable framework for evaluating the impact of integrated management scenarios on surface–groundwater interactions within the catchment. These models enable spatio-temporal quantification of groundwater and nitrate discharges into the Mar Menor lagoon. However, model forecasts should be interpreted qualitatively, as socioeconomic variables are not incorporated. Moreover, predictions are strongly influenced by data lack, inherent uncertainties in observational data, and significant changes that could be produced in the agroecosystem over time.

5.1.1 SUTRA-SPHY model (Alcolea et al., 2019)

- Strengths:

A three-dimensional (3D) hydrogeological model integrating a surface water balance model with a groundwater flow model, enabling the simulation of density-driven processes, particularly at the interface between the unconfined aquifer and the lagoon.

It utilizes open-source codes: SPHY (Spatial Processes in Hydrology) for daily computation of water balance components and soil moisture dynamics across discrete soil layers, and SUTRA (Saturated-Unsaturated TRAnsport) for groundwater flow using finite element methods.

Finally, it is successfully calibrated using available data from 2000 to 2016, effectively reproducing the recent hydrogeological history of the aquifer.

- Weaknesses:

It represents the first numerical modelling effort for the area, thus subject to opening limitations.

Limited data availability resulted in simplified geometry and lithological distribution, as well as low-quality and sparse parameter data (e.g., permeability, specific yield).

Deeper aquifers are excluded from the model, based on the assumption of negligible natural fluxes from the Quaternary to the underlying Pliocene and Messinian aquifers at the regional scale.

Calibration is affected by the scarcity of observational data.

Losses in water distribution and sewage systems, discharges into channels and ephemeral streams, and potentially significant lateral fluxes are not accounted for.

5.1.2 Visual Transin model (CHS, 2020)

- Strengths:

It is developed using the finite element software Visual Transin, which incorporates an inverse problem algorithm for automatic calibration. This allows for parameter optimization (e.g., permeability, storage coefficient) within defined variability ranges based on pumping test results.

By incorporating new, high-resolution data from geophysical surveys, newly drilled wells, and pumping tests, the delineation of 15 permeability zones was enabled.

- Weaknesses:

The model domain is limited to a 3 km-wide strip extending inland from the Mar Menor coastline; deeper aquifers are not modelled.

Submarine groundwater discharge to the lagoon is quantified using only 106 km² of the Campo de Cartagena Quaternary aquifer (~10% of the total area).

The simulation period is relatively short, spanning from June 1, 2018, to October 31, 2019.

Losses in water distribution and sewage systems, discharges into channels and ephemeral streams, and lateral fluxes are not considered.

5.1.3 MODFLOW model (Aquifer project, 2023)

- Strengths:

It employs MODFLOW, a widely recognized modular finite-difference flow model developed by the U.S. Geological Survey. Moreover, a newly developed SPHY model simulates water balance in the soil root zone from the 1950s to 2020, incorporating a novel module that estimates irrigation inputs at the pixel level using satellite data.

Long-term simulation from 1920 to 2020, calibrated for both steady-state and transient (monthly) conditions.

- Weaknesses:

Limited data availability affects the accuracy of the model’s geometry, lithological distribution, and hydraulic connectivity between aquifers.

Calibration requires unrealistically high permeability values in certain zones, suggesting potential inaccuracies in the geometric configuration.

Sparse groundwater head measurements, particularly for the early decades of the simulation period, introduce uncertainty. Additionally, the absence of pumping data compromises the reliability of piezometric dynamics and water balance estimations.

Losses in water distribution and sewage systems, discharges into channels and ephemeral streams, and lateral fluxes are not considered.

5.2 Llobregat delta

Three regional models built with different codes have been analysed: Visual Transin (the original) and FEFLOW in 2D projection, and FEFLOW in 3D projection. The FEFLOW 3D model, although already available for use, is still under construction. This model lacks the inclusion of three-dimensionality in the free aquifer section in the Vall Baixa region. All changes must also be implemented to eliminate, as far as possible, the weaknesses detected in the previous models. Currently, the three models are practically identical, since it was decided to migrate the code rather than create a new model. Priority was given to ensuring that the three models provided the most similar adjustment levels and concentrations, and this was achieved. Thus, in the SWOP analysis, the strengths and weaknesses of the three models as a whole will be mentioned, and then those of each model with a different code in particular.

5.2.1. Evaluation of the three models

- Strengths

The model has a good geological description, a very long calibration period (from 1966 to 2001 originally), and contains lots of data, the quality of which has improved in recent periods. It has a good fit of piezometric levels and a well-described mass balance. The model has been updated and validated until 2020.

- Weaknesses

The transport adjustment is not adequate enough, especially in areas where the concentration is very high. On the one hand, improving the transmissivity zoning with new geological information can fix this problem. On the other hand, the inclusion of variable density can also do so.

The river boundary condition in the free aquifer part in the Vall Baixa is implemented as a prescribed flow rate linked to flood events. Although the approximation to this term of the mass balance is quite good, it is believed that there are some areas where a certain infiltration flow is underestimated. In addition, if at some point the aquifer and the river were to connect, a mixed boundary condition would be necessary.

The same strength of a very long calibration period is also a weakness in these models, given that during this period the changes that have occurred in the aquifer (changes in land use, river regulation regime, infrastructures,) are not sufficiently well described.

5.2.2. Visual Transin model

- Strengths

It is developed using the Visual Transin finite element software, which incorporates an inverse problem algorithm for automatic calibration. This allows the optimization of parameters (for example, permeability, storage coefficient) within defined ranges of variability based on the results of the pumping tests. The numerical calculation is robust and the boundary conditions for the transport are well programmed.

- Weaknesses

The mesh is very rigid and does not allow to refine the mesh areas to improve the detail in some areas. It also does not allow the change of zoning over time, it is in these approximations to the modelling where the changes in the aquifer in such a long period are poorly described, for example the change in land use.

In addition, the infrastructures built after the first delivery of the model in 2001 cannot be implemented. And the non-linear mixed condition for infrastructures is not implemented and therefore cannot be used for the case of underground infrastructures prior to 2001.
The database in use is overflowing. It usually happens that when implementing new elements, zoning, points or boundary conditions are disconnected.

5.2.3. FEFLOW 2D model

- Strengths

FEFLOW is a robust and well-maintained modern visual code. It allows to refine the mesh, the inclusion of new elements of the territory, and the changes of the zoning over time, in particular it is important for the implementation of surface recharge, the inclusion of infrastructures and the inclusion of new hydrogeological information.

- Weaknesses

This model is halfway between the original and the 3D. Its particular weaknesses lie in the fact that, despite having been able to be realized, the implementation of infrastructures has not been resolved correctly, nor the zonal changes over time, nor the variable density, waiting to be realized in the new 3D model. It also does not include the new geological information obtained in recent years.

5.2.4. FEFLOW 3D model

- Strengths

Good implementation of the underground linear infrastructure (the tunnels of the metro, railway lines and the high-speed train).

It is hoped that in this approach the weaknesses detected in the previous models can be fixed.

- Weaknesses

Still incomplete.

5.3 Aluviões do Tejo

5.3.1. FEFLOW model (BINGO H2020 Project)

- Strengths

High capacity to simulate complex 3D hydrogeological systems and can model multiple processes: saturated/unsaturated flow, pollutant transport, river-aquifer interaction, etc. It allows the integration of climate data (MiKlip) and recharge estimation (BALSEQ_MOD) for future scenarios.

- Weaknesses

Requires large amounts of input data and time for calibration. Its high technical complexity, which may limit its use by non-specialist water managers.

It is sensitive to the quality of input data (hydraulic properties, boundary conditions).

- Opportunities

Assessment of climate change impacts on groundwater availability.

Support for decision-making in integrated water resource management.

Potential to extend the model to other areas of the Tagus Basin or connected aquifers.

- Threats

Uncertainty in climate projections may affect the reliability of results and changes in water management policies may require frequent model updates

5.3.2. SWAT model (Costeira et al., 2021)

- Strengths

High efficiency in flow simulation (Nash-Sutcliffe coefficients above 0.8).

Strong capability to assess nitrate transport and water balance. It allows incorporates agricultural practices and land use in the analysis being useful for delineating Nitrate Vulnerable Zones (NVZs).

- Weaknesses

Lower resolution for deep subsurface processes (focused on surface and root zone) and strongly dependent on accurate agronomic and meteorological data. Does not directly simulate deep aquifer flow or river-aquifer interactions.

- Opportunities

Improvement of agricultural management and reduction of diffuse pollution.
Support for surface and groundwater protection policies.
Potential to be combined with more detailed aquifer models (e.g., FEFLOW).

- Threats

Changes in land use or farming practices may affect model validity.
Limited availability of historical and high-quality data and risk of misinterpretation if used outside its calibrated context.

5.3.3. RZWQM model (Cameira et al., 2007)

- Strengths

Specialized in analysing water and nitrate flow in the unsaturated zone. Evaluates the impact of agricultural practices (irrigation, fertilization) on water quality, in consequence is useful for studying point and diffuse pollution.

- Weaknesses

Does not simulate deep flow or interactions with surface water bodies and requires detailed agricultural management data, which may be hard to obtain at large scales.
Less applicable for regional or integrated water management studies.

- Opportunities

Ideal complement to deep flow models (like FEFLOW) in pollution studies.
Supports sustainable agriculture strategies and aquifer protection and can be adapted to new farming practices and climate scenarios.

- Threats

Limited scalability to larger regions and changes in agricultural practices may require frequent recalibration.

5.4 Malta Mean Sea Level

SWOT analysis on the hydrogeological model of the Malta Mean Sea Level Aquifer is provided below.

- Strengths

Availability of long-term datasets for major groundwater abstraction sources, providing a solid information-based foundation for model calibration and validation under transient conditions.

Capability to simulate a wide range of water management strategies and variations in natural conditions.

Ability to generate visual representations of groundwater bodies, facilitating communication and engagement with stakeholders.

- Weaknesses

Strong dependence of model results on geological fracture and fault systems, highlighting a significant level of uncertainty in model results. Challenges in accurately defining lower boundary conditions due to the interface. Model assumes a sharp interface, whereas field data indicate a more diffuse transition zone. Lack of integration with water quality parameters, particularly electrical conductivity (EC).

- Opportunities

Supports the identification of data gaps in hydrogeological data required for model development, thereby guiding and prioritising future hydrogeological research initiatives.

Provides scenario-based insights that can inform the design and implementation of future sustainable water management measures.

- Threats

If not regularly updated with hydrological data, the model may underpin unsustainable management practices. This in particular given the increased variability in hydrological conditions arising due to climate change impacts.

Limited or incomplete datasets can compromise model reliability and potentially lead to misguided management decisions.

6. MONITORING NETWORKS COMPARISON

To make a comparative analysis of the monitoring networks described, in table 3 and 4 are summarised some data and in figure 43 is shown a comparative matrix.

Table 3: Pilot sites' general monitoring network.

Meteorological data			
Site	**Area (km²)**	**Total points**	**Frequency**
Llobregat Delta	120	4	Daily
Aluviões do Tejo	1113	6	Daily
Malta Mean Sea Level	160	5	Continuously
NSZ			
Site	**Area (km²)**	**Total points**	**Frequency**
Campo de Cartagena	1238	~500[17]	Daily
Llobregat Delta	120		
Aluviões do Tejo	1113		
Malta Mean Sea Level	160	12	Continuously
Groundwater level			
Site	**Area (km²)**	**Total points**	**Frequency**
Campo de Cartagena	1238	61	Continuously
Llobregat Delta	120	123 6 34	Monthly Weekly Continuously
Aluviões do Tejo	1113	11 4	Monthly Hourly
Malta Mean Sea Level	160	**39** (17)	Every 30 minutes GDWN
Groundwater quality			
Site	**Area (km²)**	**Total points**	**Frequency**
Campo de Cartagena	1238	163	Monthly
Llobregat Delta	120	186	Annually/ Semi-annually/ Quarterly
Aluviões do Tejo	1113	25	Twice a year sampled
Malta Mean Sea Level	160	15 (17)	Bi-annually GDWN

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[17] Soil moisture probes

Table 4: Pilot sites' specific monitoring network

Site	Area (km²)	Other monitoring networks	Total points	Frequency
Malta Mean Sea Level	160	Groundwater "deep" well network	17	
Malta Mean Sea Level	160	Freshwater-saltwater Interface Monitoring	15	Continuously
Llobregat Delta	120	Railway drainage water	15 6 7	Quarterly sampled Annually sampled Continuously (4h)
Llobregat Delta	120	Active artificial recharge systems	5 5	Every 10 minutes Semi-annually sampled
Llobregat Delta	120	Hydraulic barrier	7 15	Every day Every 45 days sampled

The assessment of these networks revealed significant variability in data availability and development. While some sites benefit from well-established systems, others show notable deficiencies. Given the complexity of implementing specific and feasible improvements, especially when such actions fall outside the direct control of stakeholders and require coordination among multiple authorities, this document outlines a set of best practices to enhance monitoring efforts.

METEOROLOGICAL DATA: The national meteorological networks of Portugal and Spain provide the most complete and reliable datasets. Expanding the number of stations could further improve spatial coverage and data representativeness in all the study cases.

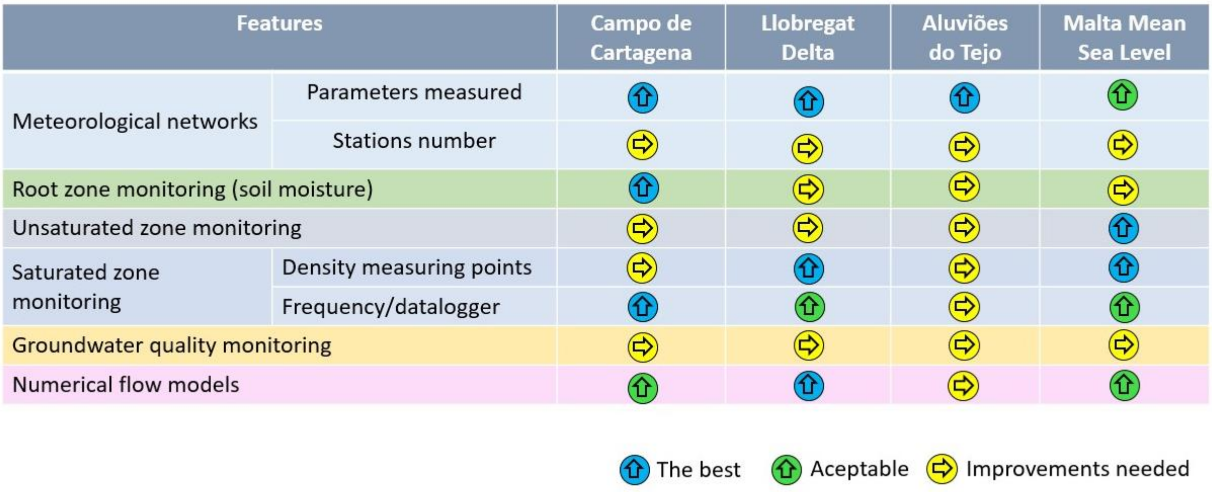
ROOT ZONE MONITORING: In Campo de Cartagena, pairs of soil moisture probes have been installed to control every irrigation events. Although these do not support hydrochemical analysis, they offer valuable quantitative insights of infiltration rates. Moreover, by monitoring water crops consumption, these tools allow to optimise the available resources, and minimise the risk of leachate percolation into the groundwater.

UNSATURATED ZONE MONITORING: At the Malta Mean Sea Level site, 16 stations have been deployed to enable both real-time monitoring of vertical water flow, and punctual sampling for assessing contaminant transport through the unsaturated zone at several depths. Malta is the only pilot site with an unsaturated zone monitoring network well developed, highlighting to the other partners the necessity to implement a tool/probe/station with similar purposes to have a comprehensive understanding of the groundwater bodies.

SATURATED ZONE MONITORING: Llobregat Delta and Malta Mean Sea Level sites feature a higher density of piezometers, while Campo de Cartagena offers more remote data access points. In all cases, careful consideration must be given to the characteristics of each monitoring water point due to several reasons. The main issue is related with the origin of the observation wells because not all of them were drilled expressly for monitoring purposes. Consequently, very often, building characteristic such as depth of the borehole, screen pipe locations and so on, are unknown influencing the reliability of the measure, as well as the lack of information about pumping periods (transient or steady state condition).

GROUNDWATER QUALITY MONITORING: Sampling frequencies and procedures vary across pilot sites according to regional and local protocols. However, the limited representativeness of the data reduces its reliability, making it difficult to identify consistent best practices. Aimed by this concern, the activity 2.1 will design a protocol for the data collection and the deliverable "D.2.1.1 Groundwater monitoring protocol for the pilot sites" will be redacted.

NUMERICAL MODELING: The software programs used are widely adopted and scientifically validated. Nevertheless, the limited availability and representativeness of observational data constrain model performance. Despite satisfactory calibration and low uncertainty, further improvements are needed. These findings underscore the importance of enhancing data acquisition strategies to strengthen model robustness. The aquifers of the Llobregat Delta are the best modelled of all the pilot sites.



Features		Campo de Cartagena	Llobregat Delta	Aluviões do Tejo	Malta Mean Sea Level
Meteorological networks	Parameters measured	🔵	🔵	🔵	🟢
	Stations number	🟡	🟡	🟡	🟡
Root zone monitoring (soil moisture)		🔵	🟡	🟡	🟡
Unsaturated zone monitoring		🟡	🟡	🟡	🔵
Saturated zone monitoring	Density measuring points	🟡	🔵	🟡	🔵
	Frequency/datalogger	🔵	🟢	🟡	🟢
Groundwater quality monitoring		🟡	🟡	🟡	🟡
Numerical flow models		🟢	🔵	🟡	🟢

🔵 The best 🟢 Aceptable 🟡 Improvements needed

Figure 63. Comparison chart.

7. CONCLUSIONS

The evaluation of monitoring networks across the four Clepsydra pilot sites, Campo de Cartagena (SE Spain), Llobregat Delta (NE Spain), Aluviões do Tejo (Central West Portugal), and Malta Mean Sea Level (Malta), revealed varying levels of development in the data collection assessed. These included meteorological networks, root zone, saturated and unsaturated zone monitoring, groundwater quality monitoring and hydrogeological models available. While some sites have comprehensive networks, others are deficient, particularly in the monitoring of the unsaturated zones and groundwater quality assessment.

Malta has the higher overall level of knowledge regarding its aquifer with special targeted monitoring networks. On the other hand, Aluviões do Tejo and Llobregat Delta lack any control point for monitoring the unsaturated zone while the stations located in Campo de Cartagena, only allow for measure root zone moisture without further water quality analysis. The Clepsydra project will make an effort to integrate a monitoring system targeted for these zones with the main purpose of allocate all the deficiencies.

Although Campo de Cartagena already installed over 500 pairs of probes in the root zone, these do not allow quality assessment of the infiltration water so the unsaturated zone flows need to be fully characterize. On the other hand, Malta installed across the whole territory, 16 advanced probes, 12 of them in the pilot site with this finality. Furthermore, it owes two innovative monitoring systems: the groundwater freshwater-saltwater interface and groundwater deep well networks. This makes Malta the pilot with the most comprehensive networks.

Groundwater sampling campaigns are carried out with different annual frequencies across the pilot areas depending on each regional/local protocol. The Campo de Cartagena aquifer has the highest sampling frequency so here, the largest number of groundwater samples is collected and analysed. However, the analysis of available hydrochemical data does not allow to a proper assessment of the whole groundwater bodies highlighting the lack of reliability of the collected data.

Among the pilot sites, Llobregat Delta aquifer has the highest density of piezometers, followed by Malta, Campo de Cartagena, and lastly, the Aluviões do Tejo. The latter's monitoring network is the least settled among pilots. However, Portugal uniquely features two type of weather stations, the udometric and the climate one, recording precipitation, sunlight hours, temperature, and absolute and relative humidity.

Concluding, the Clepsydra project provides an opportunity to improve the monitoring networks across all pilot sites. This document offers a complete inventory of pilot areas' control points and aims to identify gaps to address them and improve the representativeness of the data collected. Only through more careful and precise monitoring of the aquifers and its surrounding areas it will be possible to fully understand the processes affecting groundwater bodies.

Being fully aware that a large number of points does not necessarily means good representativeness, the installation of new probes and tools must be strategic. The areal distribution has to fit each pilot site, especially for the improvement of the data. Monitoring stations should be arranged to allow for the comprehension of groundwater dynamic and quality as much as possible. The precision in choosing new points will be given great importance, supporting the strategy for their allocation to the quantity.