WaterJPI project

SMARTControl

Smart framework for real-time monitoring and control of subsurface processes in managed aquifer recharge (MAR) applications

Deliverable D5.3

Real-time observation platform at MAR scheme in Toulon (Gapeau), France

Modeling of groundwater mound and effect of MAR on saline intrusion in a coastal aquifer

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Short summary

The present report describes the works conducted at the Gapeau-Aquarenova case study. It contains a description of the case study and of the monitoring system connected in real time to the INOWAS platform. A simple meshed model has been implemented in order to simulate the impact of the infiltration basin using MODFLOW modeling tool. This model is embedded on the web-based platform INOWAS. This case study has been used to test new analytical solutions in order to simulate the groundwater mound induced by the infiltration basin.

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ABSTRACT

Managed aquifer recharge (MAR) is a widely accepted technique for augmenting groundwater supplies for potable and non-potable uses. Among the objectives of MAR schemes, the mitigation of salt water intrusion is very important in coastal aquifers highly pumped for several usages. This is the case of the Gapeau aquifer located close to Hyères city, South of France, were the Aquarenova project has been launched in the 2010s by SUEZ for mitigating the salt water intrusion using infiltration basins and a pumping strategy controlled by data measurements provided by a monitoring system. In the situation of a wells field highly pumped for drinking water supply, it is very important to control the evolution of water levels and water electrical conductivity in the coastal aquifer near the sea. This is the reason why a highly dense monitoring network has been installed on this site.

The present report constitutes the Deliverable D5.3 of SMART-Control research project, which is related to the Gapeau/Aquarenova case study. It presents the application of the smart-control concept on this case study. The real-time monitoring and modeling INOWAS platform (SMART-Control tool) has been succesfully applied to the Gapeau case study.

For the real time monitoring operation as well as modeling applications, data from the monitoring networks devoted by SUEZ to MAR operations, seawater intrusion prevention and regional monitoring were combined on the INOWAS platform. The time series shows the fluctuating daily groundwater levels which reacts to the annual artificial recharge time periods between November and April and to weather events such as rainfall and droughts. The data can be now vizualised on the platform and sevral tools can be applied to them. A MODFLOW numerical model of the Gapeau aquifer has been implemented on the platform. It is a simple model with one layer, only simulation of the flow, developed under transient conditions. The calibration is quite satisfactory regarding the assumptions. The model includes the MAR scheme. Apart the reference scenario, three scenarios have been simulated on a 2.5 year duration, based on several assumptions on MAR scheme numbers and location.

New analytical solutions have been developed in order to simulate the groundwater mound and flows below an infiltration basin. They have been aplied to the Gapeau case study. More simple than a complex numerical model, they allow computing the impact of the MAR scheme on the aquifer.

The numerical model developed on the web-platform constitutes at this stage a feasibility demonstration: it cannot be used as a management tool without further improvements. The next step are a better evaluation of surface water / groundwater interactions close to the pumping wells field. Considering solute transfer and density processes related to saline intrusion is required in order to properly simulate the impact of MAR schem of salt water intrusion.

CONTENT

FIGURES

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1. INTRODUCTION

Managed aquifer recharge (MAR) is a widely accepted technique for augmenting groundwater supplies for potable and non-potable uses. Among the objectives of MAR schemes, the mitigation of salt water intrusion is very important in coastal aquifers highly pumped for several usages. This is the case of the Gapeau aquifer located close to Hyères city, South of France, were the Aquarenova project has been launched in the 2010s by SUEZ for mitigating the salt water intrusion using infiltration basins and a pumping strategy controlled by data measurements provided by a monitoring system.

In the situation of a wells field highly pumped for drinking water supply, it is very important to control the evolution of water levels and water electrical conductivity in the coastal aquifer near the sea. This is the reason why a highly dense monitoring network has been installed on this site.

The present report constitutes the Deliverable D5.3 of Smart-Control research project, which is related to the Gapeau/Aquarenova case study. It presents the application of the smart-control concept on this case study. This report is constituted by 5 sections. After this introduction, section 2 describes the MAR scheme operated on this case study. Then, water levels and electrical conductivity data are analysed in a way to better understand the salinisation/freshening processes. Section 3 describes how the monitored data have been connected to the web-based INOWAS platform. Sections 4 and 5 describe modeling attemps of the MAR processes of this case study respectively using a meshed model embedded into the INOWAS platform and analytical solutions.

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2. SITE DESCRIPTION

2.1. MAR SCHEME

The study site is situated at the west of Hyères (France). Suez, operating the drinking water service since 2012 in the city of Hyeres-les-Palmiers, has developed Aquarenova program for abstraction, control and restoration of natural resource, leading to a sober economic development (Figure 1). Aquarenova is declined on two axes. The first one aims to reconquer network performance in a context of sharp increases in the summer consumption (x4). The second axis is the restoration of the main water resource of the city, the Bas Gapeau aquifer. It is first of all a real-time abstraction control, based on a continuous monitoring of water level and electrical conductivity (salinity proxy) on several piezometers. The gradients method shall optimize abstraction without risking saline intrusion (detected during early 2000s). The results measured since 2012 are very significant. Suez also conducts aquifer recharge works by abstraction into the coastal river Roubaud during winter, in order to form a piezometric mound to be used in summer. This replenishment is operational from November 2015 to ensure the city water autonomy and to protect the water resource against saline intrusion even under severe drought.

Figure 1: Site overview of the Aquarenova MAR project

Figure 2 and Table 1 diplay the components of the Aquarenova MAR scheme.

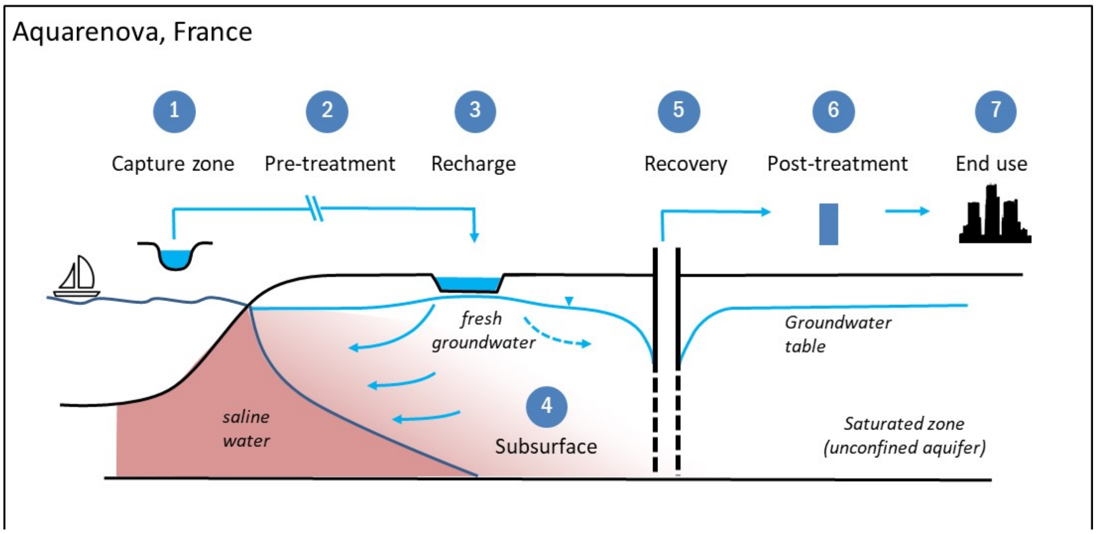


Figure 2: Schematic overview of MAR components at Aquarenova

Table 1: Components of the Aquarenova MAR system

#	MAR component	Aquarenova MAR site
1	Capture zone	River Water
2	Pre-treatment	None, system shut down in case of exceedances of 13 parameters
3	Recharge	Infiltration basins
4	Subsurface	Unconfined aquifer
5	Recovery	Drinking water wells 400 m upstream of the infiltration basins, recovered water <10%
6	Post-treatment	Chlorination at Père éternel water plant
7	End use	Drinking water, groundwater augmentation

The surface water for infiltration is abstracted from the Roubaud River by avoiding pre-treatment process, because the system is designed for shutting down in case of exceedance of one of the 13 monitored parameters. The water is recharged to groundwater through two constructed infiltration basins with a total area of 1480 m^2. Then, most of the water allows the replenishment of the fresh water reserve to maintain a piezometric level above sea level (main objective of the recharge) while a part is recovered by the wells with a recovery rate <10%. The recovery rate was determined by using a numerical groundwater flow model. The aquifer itself is very locally confined in the area of the recharge basins and unconfined in the area of the wells. Afterwards, the recovered water goes to chlorination treatment process at Père éternel water plant before being distributed as drinking water (Figure 2 and Table 1).

2.2. CONCEPTUAL MODEL OF THE GAPEAU AQUIFER CASE STUDY AND PROCESSES AFFECTING SEAWATER INTRUSION

To model the MAR system and its effect at the local and regional scales (see application of Tool 03 Numerical groundwater modeling and optimization described below), we used an extended dataset to improve the conceptual model of hydrogeological funcionning of the Gapeau aquifer in Hyères les Palmiers case study. In this section, we present and interpret this extended dataset, which leads to an improved conceptual model of the hydrogeological functionning of the Bas Gapeau aquifer particular processes with respect to seawater intrusion.

Specifically, the interpretation unravels 1) that flash flood submersion is a short time (day time range) process which contributes to groundwater recharge and refreshening processes and 2) that groundwater pumping rules and MAR operations designed and used by the operator contribute to manage salinity concentrations in the aquifer. While the respective weights associated to each factors remain to be identified, the compiled dataset provides evidence that flood induced recharge, groundwater management rules and MAR operations contribute to lower or maintain salinity concentrations in the Gapeau aquifer.

2.2.1 Available dataset

The extended dataset compiled to improve the conceptual model in the Hyeres study site builds up upon multiple stations spread over the study area (Figure 3). Data sources include : the monitoring network synchronized with the INOWAS platform presented below, vertical profiles (1m depth resolution) of specific electrical conductivity performed on monthly or quatertly basis by the operator, time series of groundwater levels and river discharge from the French national databases devoted to ground (ADES) and surface (Banque Hydro) waters respectively, and daily cumulated amounts of rainfall obtained at the Hyères weather station by the French weather agency (Météo France). Groundwater levels, river discharge and rainfall amounts data spans the last 3 decades. In the following, most of the discussed time series span the 01/2014 and 09/2020 time period.

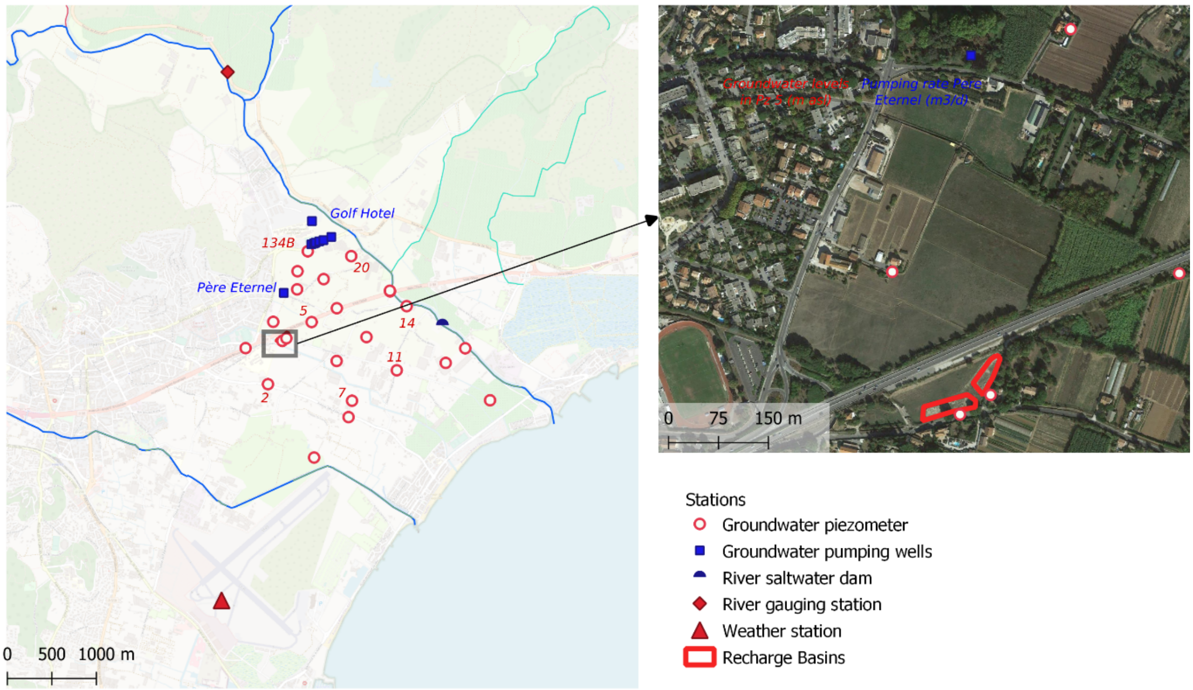


Figure 3: Map of the monitoring piezometers, gauging and weather stations, and infiltration basins used for managed aquifer recharge

2.2.2 Hydrological setting and groundwater pumping management rules

In the Gapeau aquifer, surface water - groundwater interactions play a key role with respect to recharge processes. Figure 4 shows time series of river discharge (red), groundwater table levels (black) in an upstream piezometer close to the pumping wells and daily cumulated rainfall amounts (blue). River discharge as well as groundwater table levels in the area show both synchrone pluriannual and seasonnal fluctuations. On large time scales, for instance during the recent 2015-2017 drought, groundwater levels and river discharge showed low variability. On short time scales (days/week) however, flash floods with extreme discharges (above 350 $m^3.s^{-1}$) occur simultaneously with large groundwater level fluctuations. For example, an increase of about 3m of groundwater levels occurred during floods events in Jan and Dec. 2014. These examples illustrate the strong link between the

Gapeau river status and groundwater levels in the aquifer. In addition to these processes, groundwater withdrawals also impact groundwater levels.

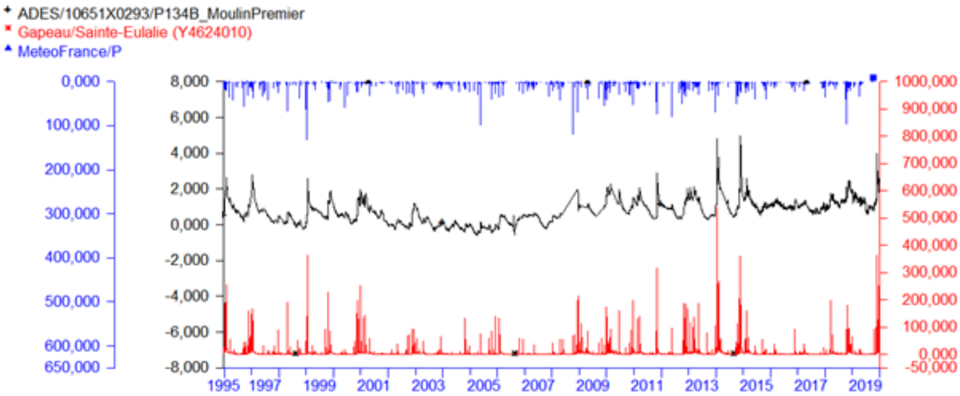


Figure 4: Time series of hydrological variables in the study area of the Gapeau aquifer. Blue : daily cumulated rainfall at Hyères (source : Meteo France). Black : groundwater levels in upstream piezometer P134B (source : ADES). Red : daily discharge rates of the Gapeau river at Sainte Eulalie gaugin station (source : Banque Hydro).

Withdrawals rates partly control groundwater levels in the study area. Groundwater is pumped from the aquifer in two well fields located upstream in the area. Since 2012, a specific scheme of pumping rules has been set to restore and preserve the quality and quantity of groundwater in the aquifer. In brief, groundwater withdrawals rates are controlled on the basis of the season and of event-like rules.

During wet conditions (i.e. winter season) groundwater withdrawals can reach maximum authorized values as long as:

1. Groundwater table levels in piezometers are greater than a threshold altitude (0.4m above sea level – asl) and specific electrical conductivity at a depth of 8m is lower than 1400µS.cm^{-1}.

2. Differences of groundwater table levels measured in two sets of upstream-downstream control - piezometers are greater than a threshold value (+0.2m).

During dry conditions (i.e. summer season), groundwater withdrawals can reach the maximum authorized values as long as:

3. The hydraulic barrier overflows on the Gapeau river (saltwater dam is active);

4. Groundwater table levels in control piezometers are greater than a threshold altitude (0.3m asl) and specific electrical conductivity is lower than 1400µS.cm^{-1}.

5. Differences of groundwater table levels measured in two sets of upstream-downstream piezometers are greater than +0.1m.

Note that rules 2 and 4 imply that groundwater altitude at downstream control piezometers should always be greater than 0.3m above sea level. Thus, groundwater flow is ensured towards the sea.

Figure 4 shows groundwater levels, rainfall and discharge time series that illustrate how natural recharge processes and pumping rules contribute to rising the regional groundwater levels in the aquifer. During the relatively wet cycles between 1995 and 2001, groundwater levels are above 0m asl and during dryier hydrologic cycles (2002 - 2007), groundwater levels are close to or even below 0m asl. During these cycles, rules 1 – 5 described above were not active and groundwater was pumped almost constantly, groundwater levels below 0m asl testify from the strong exploitation in the area.

Since 2012, rules 1-5 are applied and the mean groundwater level resumed to an average altitude greater than the mean sea level, even during dry years (e.g. 2015-2017). According to these rules, seasonnal withdrawal rates variations (high rates during summer and low rates during winter) are used for abstraction (Figure 5). In addition to these seasonnal variations, event-like reduction rules impact groundwater abstraction rates. For example when the Gapeau river does not overflow at the saltwater dam downstream, maximum withdrawal rates at both Père Eternel and Golf Hotel well fields are reduced by about 25%. A lack of overflow over the saltwater dam in 2017 required to lower the withdrawal rates (Figure 5). Subsequently, groundwater levels rose and stabilized during the summer time period (shaded area on Figure 5).

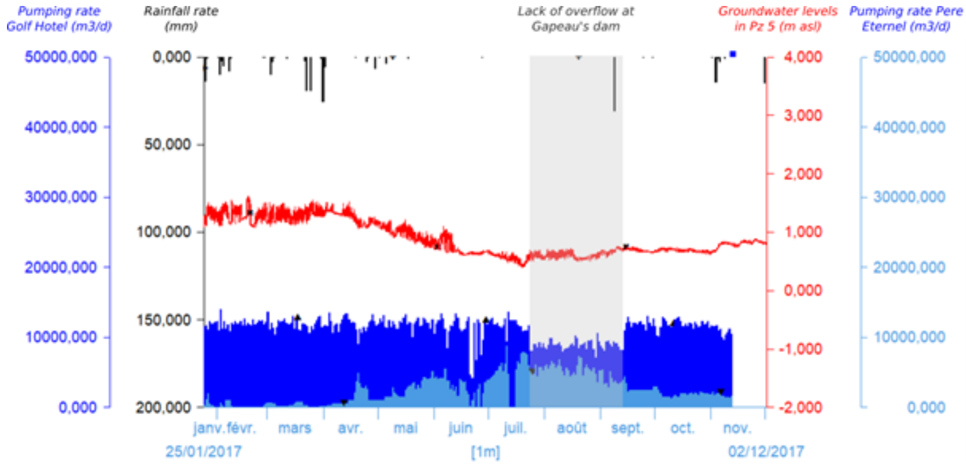


Figure 5: **Evolution of rainfall, groundwater levels in downstream piezometer 5, and groundwater abstraction rates in the two upstream well fields. The shaded area highlights when pumping rates were lowered in the summer (see text and rule 4) due to no overflow at the Gapeau dam constructed to manage seawater intrusion. Groundwater levels rise or stabilize under the effect of lowering or constant pumping rates.**

2.2.3 Management rules and natural processes impact groundwater refreshening

This section discusses the combined effects of pumping management and recharge processes on groundwater salinity in the case study.

The evolution of the saltwater content in the aquifer is assessed using vertical profiles of specific electrical conductivity performed in several piezometers on a monthly or quatertly basis. Figure 6 shows time series examples of groundwater electrical conductivity at multiple depths (1m interval) in three piezometers of the Gapeau aquifer. All three time series and about 88% of the piezometers in which EC profiles were performed show a decreasing trend since 2012. This trend occurred according to a three step sequence:

- A relatively low decline of EC during the 2012-2014 time period
- A strong drop of EC values in 2014 and
- A relatively low decline of EC values since 2014 with an apparent constant EC value for shallow measurements

Since 2012, reduced withdrawal rates during the (wet winter) season, recharging rainfalls and flood events contribute to reduce the salinity content of the Gapeau aquifer. The magnitude of the refreshening process is however dependent on the location of the observation site. The closer to the sea and the Roubaud river, the lower the refreshening. For example, EC in piezometer 4 (close to the sea and the Roubaud river) remains high and declines at a relatively low rate compared to two other piezometers located upstream. SpC time series in piezometers 6 and 10 located in between the two rivers (Gapeau and Roubaud) reveal decreasing trends with different magnitudes (greater refreshening in piezometer 6). In addition, the shapes of the saltwater/freshwater interface are contrasted across sites. A narrow interface is found in piezometer 10 and a broader interface is found in piezometer 4. These differences of decreasing magnitudes and shapes of seawater/freshwater interfaces stems from the heterogeneity of associated to the alluvial aquifer.

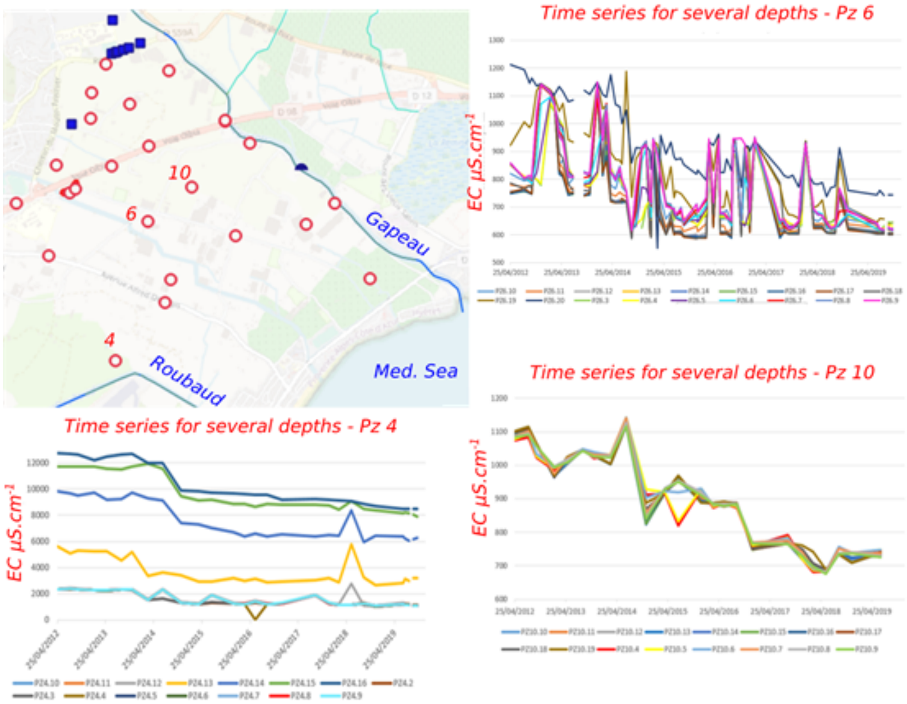


Figure 6: **Time series of specific electrical conductivity at varying depth in three piezometers at the case study aquifer. The series show the heterogeneous decrease of salt content in groundwater with sharp decrease in 2014 and long run decrease of the 2012 – 2019 time period**

A strong drop of EC values at shallow and deeper depth occurred in about 66% of the piezometers during the wet year of 2014 (Figure 7). Over the course of 2014, about 1240mm of rainfall cumulated (average of 685 mm between 1995 and 2019) and two strong flood events at the beginning and end of the year. This large amount of rainfall favored diffuse infiltration and dilution of the saltwater content, even at depth. In addition, flood and associated runoff effects may have contributed to enhanced the dilution process as revealed by a significant decrease of shallow EC time series (see Figure 7 EC time serie for “pz 11”) during the flood events ; however flood and seasonnal recharge processes may induce the rise of the saltwater/freshwater interface linked to the rise of the groundwater table level (see Figure 7 EC time series for “pz 14” and “pz 2”). These specific refreshening events associated to large rainfall amounts are singular compared to the reccurent dry state during summers and to the pumping management which appear to affect saltwater content in the aquifer over the long term.

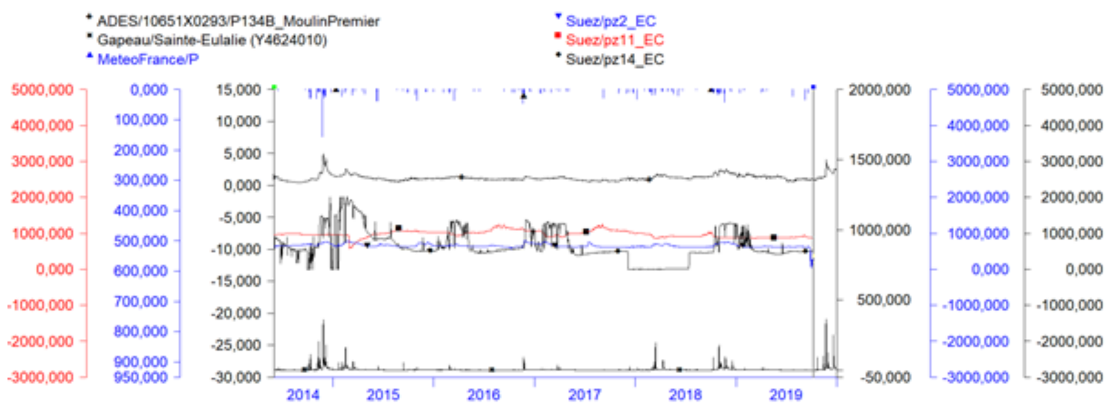


Figure 7: **Groundwater levels, specific electrical conductivity and rainfall discharge (Gapeau) time series at the study site**

2.2.4 Conclusion

In this section, we analyzed and interpreted an extended dataset including EC depth profiles, EC time series and other hydrogeological (groundwater table levels, pumping rates) and hydrological (rainfall amounts, river discharge) variables to improve the conceptual model of hydrogeological functionning of the Gapeau aquifer in Hyères les Palmiers.

The analysis revealed that groundwater pumping rules designed and used by the operator since 2011 appear as a significant factor which help lower and maintain groundwater salinity at both shallow and deep depths in more than 50% of the piezometers over the long run. Furthermore, the analysis revealaed that flash flood submersion is a short time (day time range) process which contributes localy to groundwater recharge and refreshening processes.

3. APPLICATION OF SMART-CONTROL WEB-BASED TOOLS AT THE HYÈRES CASE STUDY

This section describes the application of the Smart-Control web-based tool for the case study of Hyères les Palmiers city.

3.1. DATA ACQUISITION

A multiscale data acquisition scheme is set up for the Hyères les Palmiers site (Gapeau aquifer). This scheme is motivated by the different actions and management rules set by the local operator Suez to prevent seawater intrusion to occur in the aquifer.

Figure 8 shows a map of the spatial distribution of observation sites where groundwater levels, electrical conductivity and pumping rates are monitored in the area. Specifically, the map shows all sites which are set to collect and send data at high frequency for synchronization with the INOWAS platform. As we discuss below, these data aim to feed the following INOWAS Tasks applied to the Hyères case study: T10 – Real Time Monitoring ; T03 – Numerical Groundwater Modelling and Optimization and T20 – Real Time Modelling (the latest has not been applied on this case study).

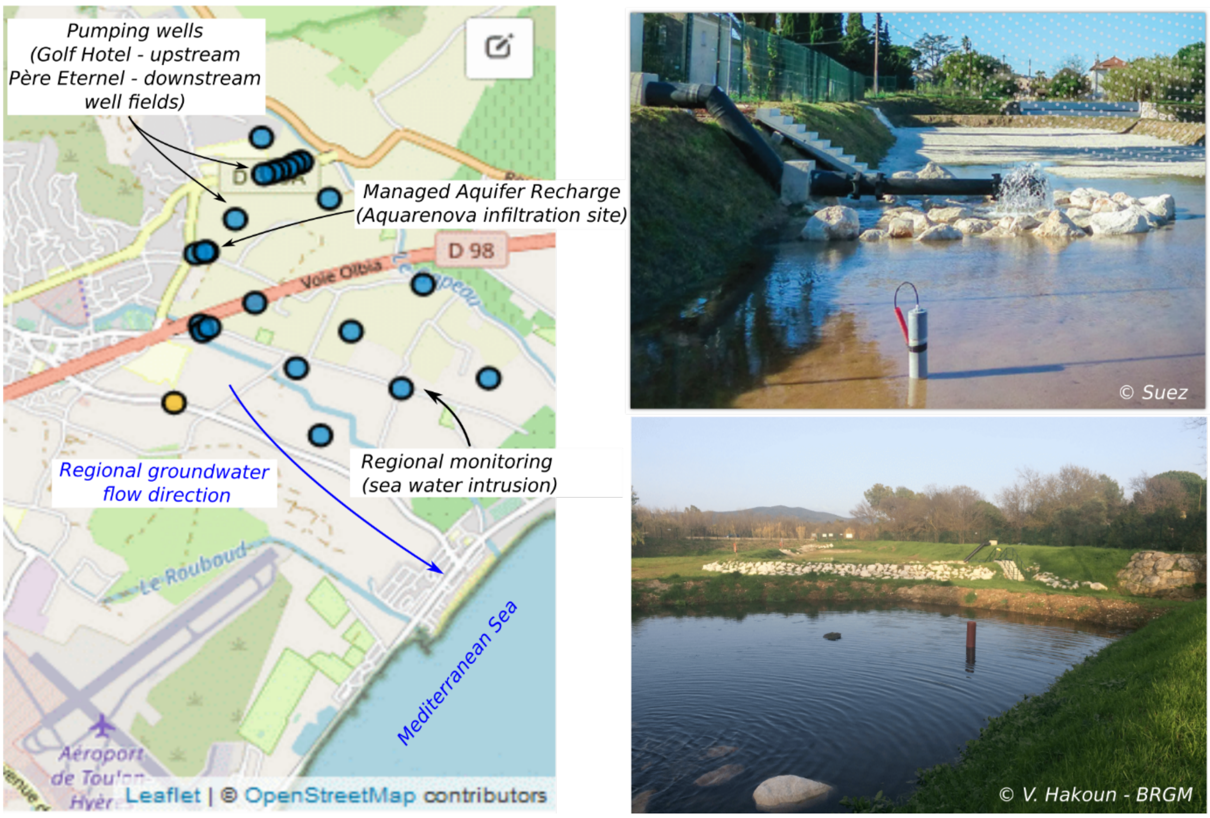


Figure 8: **Map of monitoring sites and Managed Aquifer Recharge system in the Hyères les Palmiers site (France). Left : Notes the map give details about the multiscale monitoring network set up in the area. Right : Overview of the MAR system with recharge water filling the basin in the background and water level sensor casing on the foreground (top) and partially filled basin with water level sensor casing (bottom)**

The monitoring network is multiscale : groundwater related variables are monitored spread over the aquifer and cover a broad range of distances (meters to hectometers). The precise location of the monitoring sites was determined by the different actions set to preserve the groundwater system of Hyères les Palmiers from seawater intrusion (described above). For example, Figure 8 provides an overview of a meter scale monitoring network in the MAR area. These two pictures show the infiltration basins with recharge water flowing out in basin 1 and casings implemented *in situ* in the basins where water levels are monitored using pressure sensors. Two piezometers (not shown) located on the other side of the basins' banks are equipped with pressure sensors and monitor groundwater level fluctuations in the Gapeau aquifer, in the vicinity of the infiltration basins. Overall, the monitoring network allows a detailled monitoring of groundwater levels and salinity in the Gapeau aquifer.

Table 4 (Annex) provides a summary of the stations and the main variables monitored and used in the framework of the Smart-Control project for the Hyères les Palmier case study. More precisely, the table contains station names, types, variables, data acquisistion and transmission frequencies, and the specific network associated to the stations.

The area of the bas Gapeau alluvial aquifer, about 14km^2, is relatively small and no less than 14 monitoring stations (incl. piezometers and wells) are devoted to groundwater levels monitoring. Thus, the monitoring network is relatively dense. The sampling time interval of 15 min is relatively short. Such a dense network generates quite an amount of data, which was successfully integrated to the INOWAS platform.

All variables (e.g. groundwater specific electrical conductivity, levels and flow rates) are transferred via the General Packet Radio Service (GPRS) technology to Suez's datacentre. From there, the data is transferred to a Secure File Transfer Protocol (SFTP) server. This SFTP server with secured access can be interrogated and data can be pulled from there to the INOWAS platform. Deliverable D3.1 details data transfers solutions (Junghanns and Glass, 2020).

3.2 DATA INTEGRATION AND VIZUALIZATION

The INOWAS platform provides the software infrastructure developed in the SMART-Control project to enable the import of third-party data and to perform evaluation processes. Details on the developed software infrastructure (tool T2) is given in the SMART-Control Deliverable 4.2 (Junghanns and Glass, 2020).

For the real time monitoring operation as well as modeling applications for the Hyères les Palmiers-Gapeau case study, data from the monitoring networks devoted to MAR operations, seawater intrusion prevention and regional monitoring were combined on the INOWAS platform.

Figure 9 shows a screenshot of groundwater level fluctuations in an observation piezometer that belongs to the monitoring network in the vicinity of the MAR system. The time series shows the fluctuating daily groundwater levels which reacts to the annual artificial recharge time periods between November and April (see injection flow rates time series) and to weather events such as rainfall and droughts.

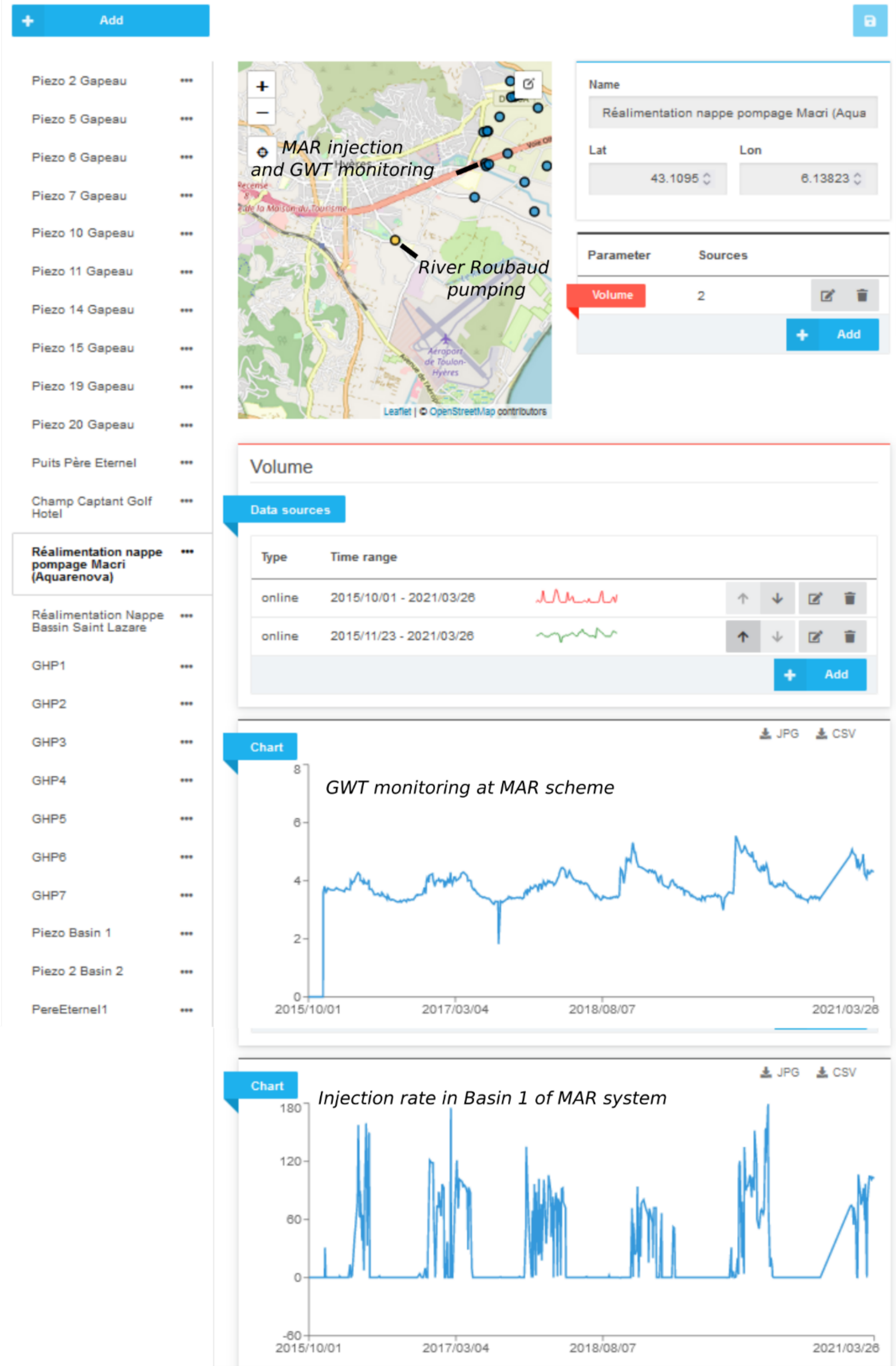


Figure 9: Screenshot of real-time sensor as data source of the MAR system of Hyères Les Palmiers (France) on the web-based SMART-Control platform.

4. MODELING THE MAR SCHEME ON THE WEB-BASED PLATFORM

This section describes the application of the Smart-Control web-based tool T03 – Numerical Groundwater Modelling and Optimization[1] applied on the case study of Hyères les Palmiers city for modelling Bas Gapeau alluvial aquifer and its groundwater management (the gradients method and the Managed Aquifer Recharge system) as described above. This groundwater flow model, based on the Darcy equation (Darcy, 1856), is built directly on the web-based tool using the interface developped during this SMART-CONTROL project which led to the design of a quite simple model for this application phase. The model provided with the tool T03, which is based on the MODFLOW calculation code 2005 and FloPy (numerical groundwater flow model developed by the USGS (Harbaugh, 2005; Bakker et al., 2016; Ringleb et al., 2016)), was however built on the basis of the conceptual model described above, but also on the more complex existing model "3D Gapeau model" (Casanova et al., 2010; 2008a; 20008b) created using the MARTHE calculation code (numerical groundwater flow model developed by the BRGM (Thiéry, 1990; 2010a-b-c; Thiéry and Picot-Colbeaux; 2020) not implemented at this stage on the Smart-Control web-based tool. Beyond the description of the hydrogeological model applied to this case study, it is particularly interesting to show the relevance of modeling tools in the studies related to the recharge systems initiated by Kloppmann et al. (2012).

4.1 MODFLOW MODEL DESCRIPTION

The model of the Bas-Gapeau aquifer was constructed on the basis of a 3D geological model which takes into account the lateral and vertical variability of the alluvial formations making up the Bas-Gapeau aquifer. The Figure 10 illustrates the domain extension of around 14.00km^2 (entire grid). Spatial discretization is done with a grid of 79x89 cells of 50 m in x and y (Figure 11). Only one layer represent the alluvial aquifer in which the cells are activated for the flow calculation on a surface around 8.95km^2.

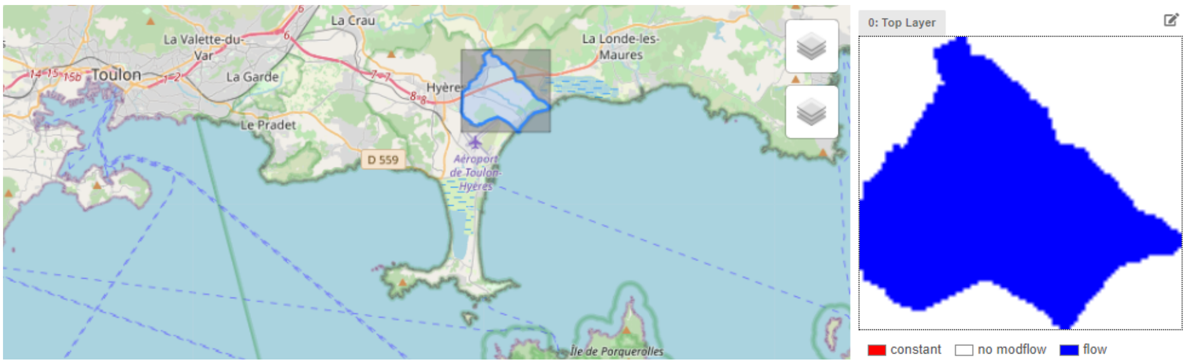


Figure 10: Screenshot of the extension of the Bas-Gapeau aquifer model of Hyères Les Palmiers (France) on the web-based SMART-Control platform.

The geometry of the alluvial aquifer is also defined by the top and bottom elevation (Figure 12). The top elevation of the aquifer is the topography which ranges from 0 to +20mASL (above sea level). The surface is more or less plane and close to 2.5mASL over most of the modelled area. The bottom of the alluvial aquifère ranges from -23.2 to +8.8 mASL and close to a mean of -14mASL over most of the modelled area. The thickness of the alluvial aquifer is around 16.5m over most of the modelled area and it represents the sum of all heterogeneous layers considered in the existing "3D Gapeau model".

There are no data available from pumping tests. Hydraulic conductivities (Hk) and Storage coefficient are considered homogenous and values are adjusted to simulate hydraulic heads and water budget the much as better.The hydrodynamic properties of the alluval aquifer are specified for:

[1] https://dss.smart-control.inowas.com/tools/T03/ ; « aquarenova_small_v5-cal3 »

- Hydraulic Conductivity : Horizontal (Hk) of 200m.d^{-1} and Vertical (vka) of 200m.d^{-1},
- Storage coefficient : Specific storage of 0.00002 m^{-1} and Specific yield = 0 to 0.13.

Constant heads are applied as boundary conditions on particular cells (Figure 12) to simulate 1) sea position in the south, 2) lateral groundwater flow from the north (Gapeau alluvial groundwater flow) and 3) lateral groundwater flow from the west (Roubau alluvial groundwater flow). The values of constant head are comprised between top elevation and bottom elevation.

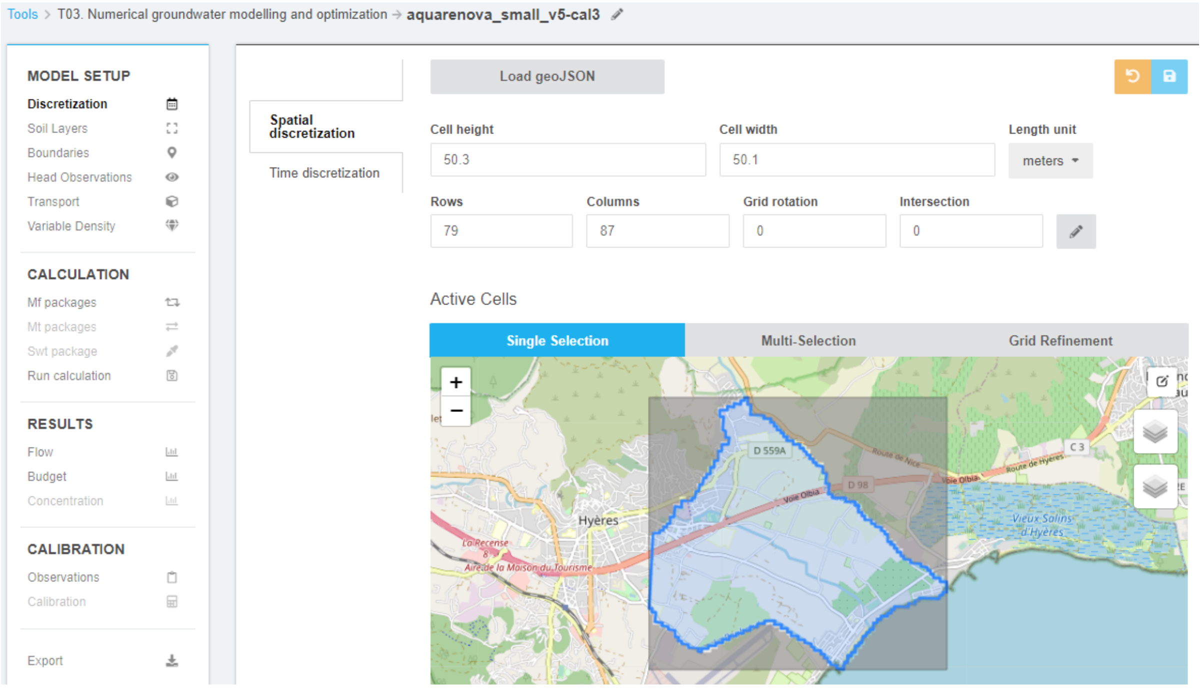


Figure 11: **Screenshot of the spatial discretization edition of the alluvial aquifer layer on the web-based SMART-Control platform (in grey cells with no flow calculation, in blue the limit of the domain).**

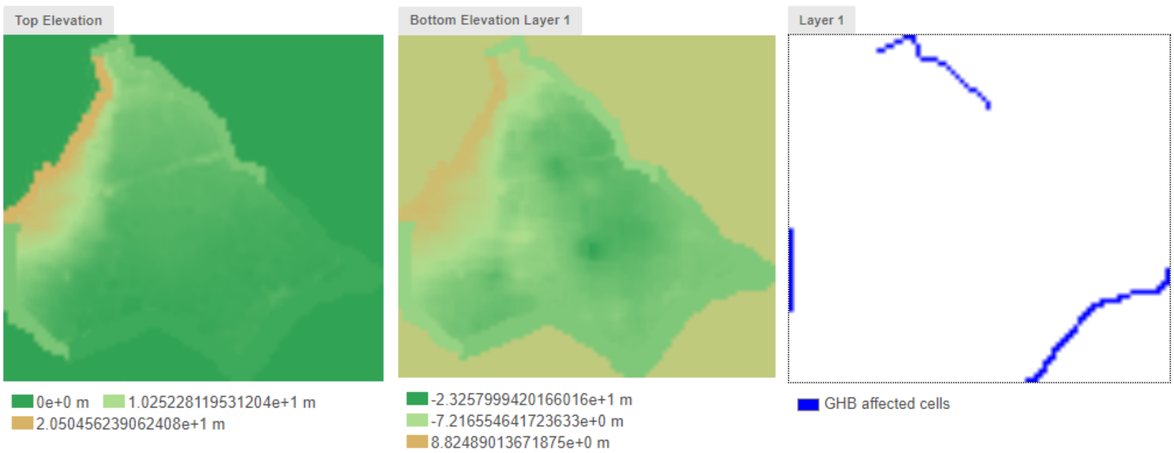


Figure 12: **Screenshot of the top (left) and bottom (center) elevation of the alluvial aquifer layer and of the applied boundary conditions "constant head" (right) on the web-based SMART-Control platform.**

The simulation is carried out in transient state for an observation period of 2.5 years with a daily time step considering 910 "stress periods" from the 1st November 2016 to the 30th April 2019. The simulation period is determined according to the objective of the implementation of this model, i.e. 3 MAR cycles integrated in their exploited hydrosystem (upstream groundwater flows, groundwater abstraction and atmospheric recharge). The boundaries are:

- Constant heads (Figure 12) :
    - at the south fixed at +0.20 mASL for simulating sea,
    - at the north fixed at +2.50 mASL for simulating Gapeau alluvial groundwater flow,
    - at the west fixed at +2.00 mASL for simulating Roubau alluvial groundwater flow,
- Pumping wells – time dependent (Figure 13 and Figure 14) :
    - 7 « Golf Hotel » (GH) continuous pumping wells with a median of -11200 m^3/day,
    - 1 « Père Eternel » (PE1PE2) discontinuous pumping well with a median of -2000 m^3/day,
- MAR infiltration basins – time dependent (Figure 13 and Figure 14) during winter with a median of +1500 m^3/day simulated as an injection pumping well,
- Atmospherical recharge – time dependent (Figure 15) considered as homogeneous values on the whole domain and calculated using GARDENIA calculation based on precipitation and potential evapotranspiration, is estimated with a mean of 1000 m^3/day.

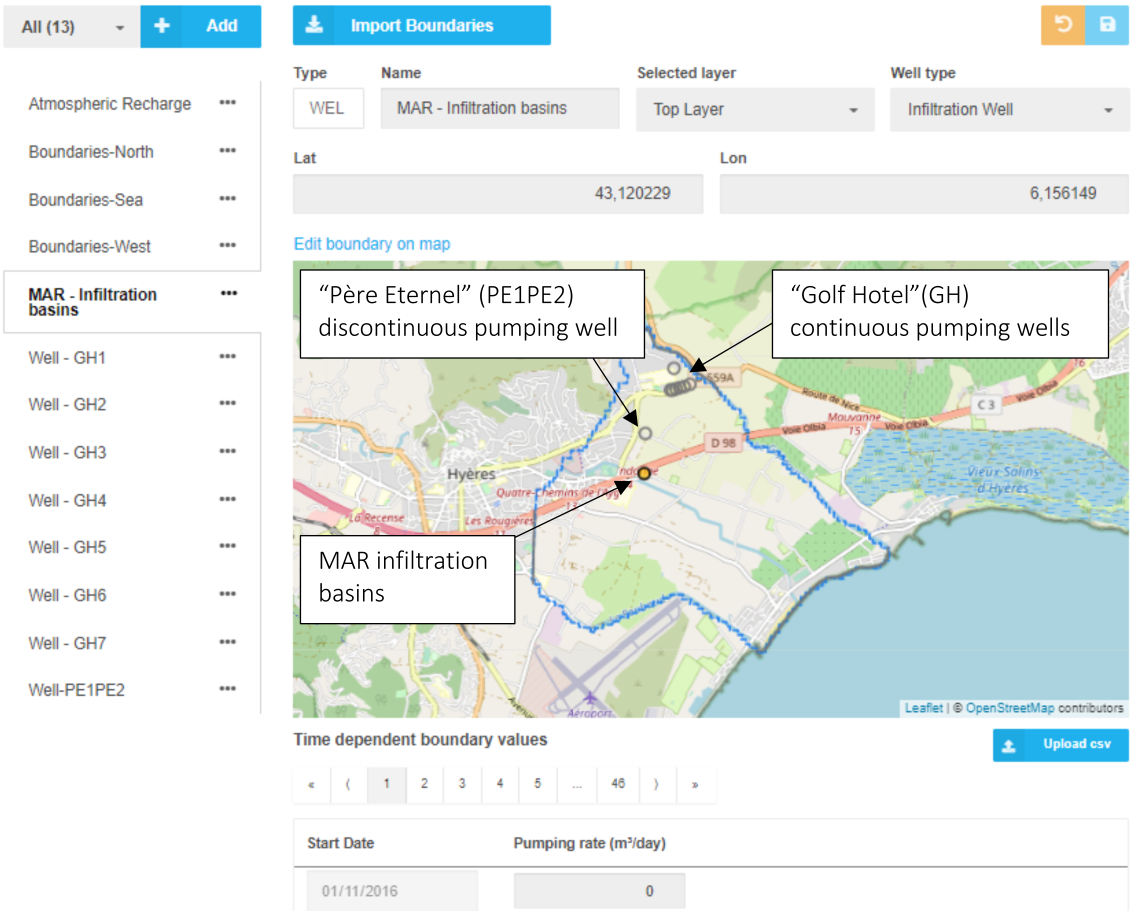


Figure 13: Screenshot of the applied boundaries carried out (pumping wells and infiltration MAR system) on the web-based SMART-Control platform.

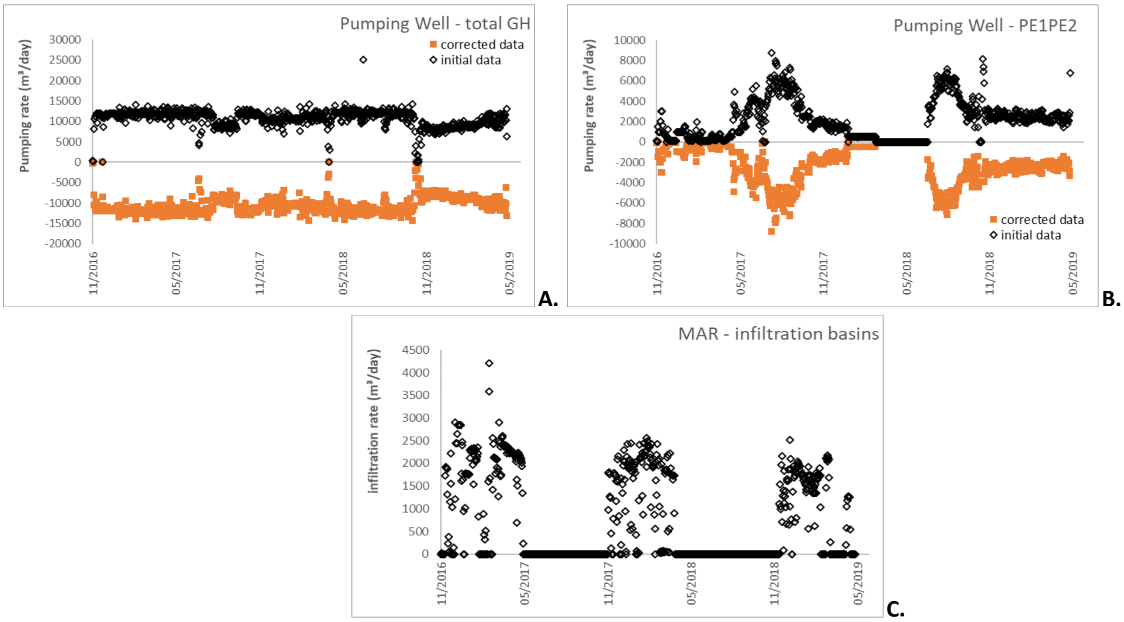


Figure 14: **Time dependent boundary values for the 910 stress periods for the “Golf Hotel” (GH) continuous pumping wells (A), the “Père Eternel” (PE1PE2) discontinuous pumping wells (B) and the MAR infiltration basins (C) considered in the model on the web-based SMART-Control platform (corrected data).**

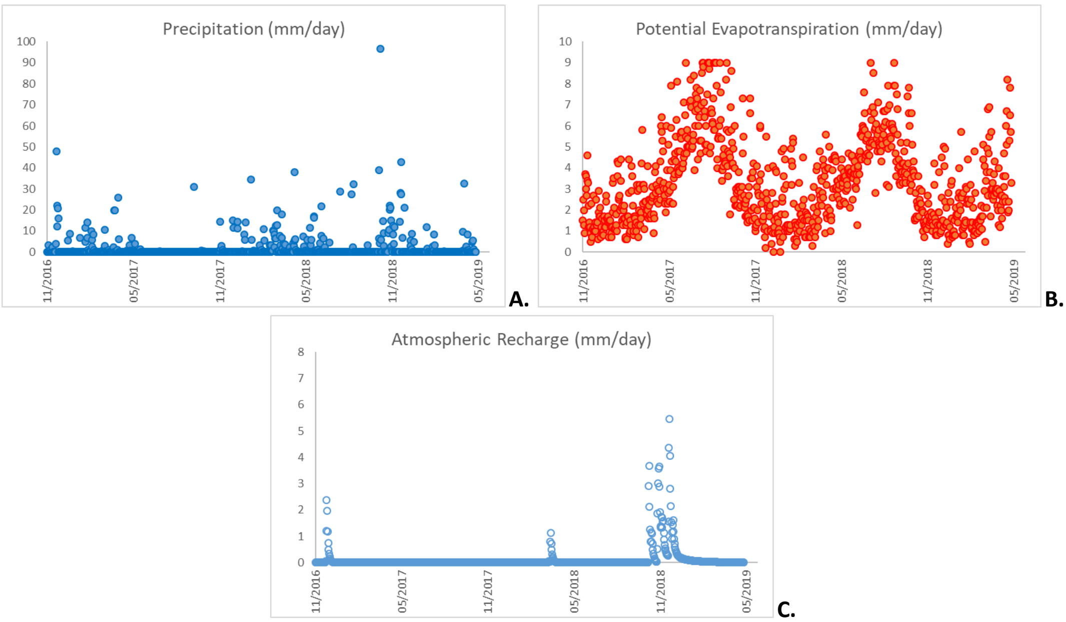


Figure 15: **Time dependent boundary values for the 910 stress periods for the atmospheric recharge (C.) considered in the model on the web-based SMART-Control platform based on precipitation (A.) and potential evapotranspiration variations (B.).**

Nine observation wells and their groundwater level evolutions are taken for conducting the calibration stage of the simulation : Pz2, Pz4, Pz5, Pz6, Pz7, Pz11, Pz14, Pz19 and PzWell-PE2 (Figure 16, Figure 18 and Figure 17). Hydraulic heads measured in these observation wells have a median of +1.04mASL between a maximum of +2.62mASL and a minim of -3.00mASL. Without including PzWell-PE2 measurements, the minimum of groundwater level is +0.44mASL that is due to a pumping effect concerning this observation well PzWell-PE2.

The simulation is initialized with a calculated steady state considering an initial hydraulic head equal to the top elevation of the alluvial aquifer and the different boundary conditions described above. The transient calculation is then carried out for each 910 stress period using preconditioned conjugate-gradient for matrix conditioning (modified incomplete cholesky method) with a maximum number of outer iteration of 200 and a maximum number of inner iteration of 50. Output at each time step is calculated for the water budget and for the groundwater elevation on the 9 observation wells.

The simulation associated with this model description is available on the web-based SMART-Control platform in a « public » version and is entitled : « aquarenova_small_v5-cal3 ». Based on this model, several simulations are carried out for testing 1) sensibility of hydrodynamic parameters and boundary conditions using the « CALIBRATION/OBSERVATIONS » functionalities available on the Tool T03 and 2) two senarios of infiltrationMAR system using the tool T07 – MODFLOW model scenario manager[2] available on the web-based SMART-Control platform.

On this case study and at this stage, no automatic links are established between this model provided on the tool T03 and the real time monitoring available on the Tool T10[3] for the differents sensors installed for measuring groundwater levels (Pz2, Pz5, Pz6, Pz7, Pz10, Pz11, Pz14, Pz15, Pz19, Pz20, PzWell-PE2, PzBassin1, PzBassin2) and rates of the pumping wells (Golf Hotel and Père Eternel) and infiltration MAR system.

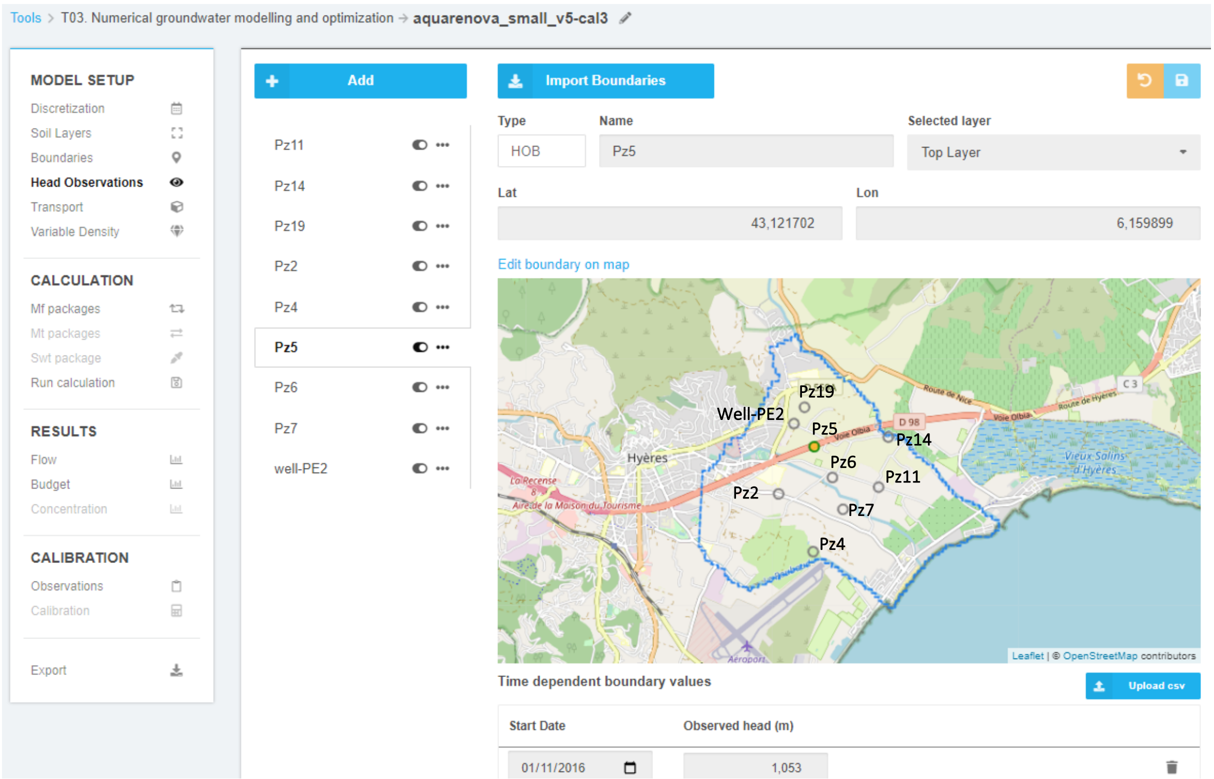


Figure 16: **Screenshot of the location of the 9 observation wells (Pz2, Pz4, Pz5, Pz6, Pz7, Pz11, Pz14, Pz19 and PzWellPE2) considered in the model on the web-based SMART-Control platform.**

[2] https://dss.smart-control.inowas.com/tools/T07/
[3] https://dss.smart-control.inowas.com/tools/T10/

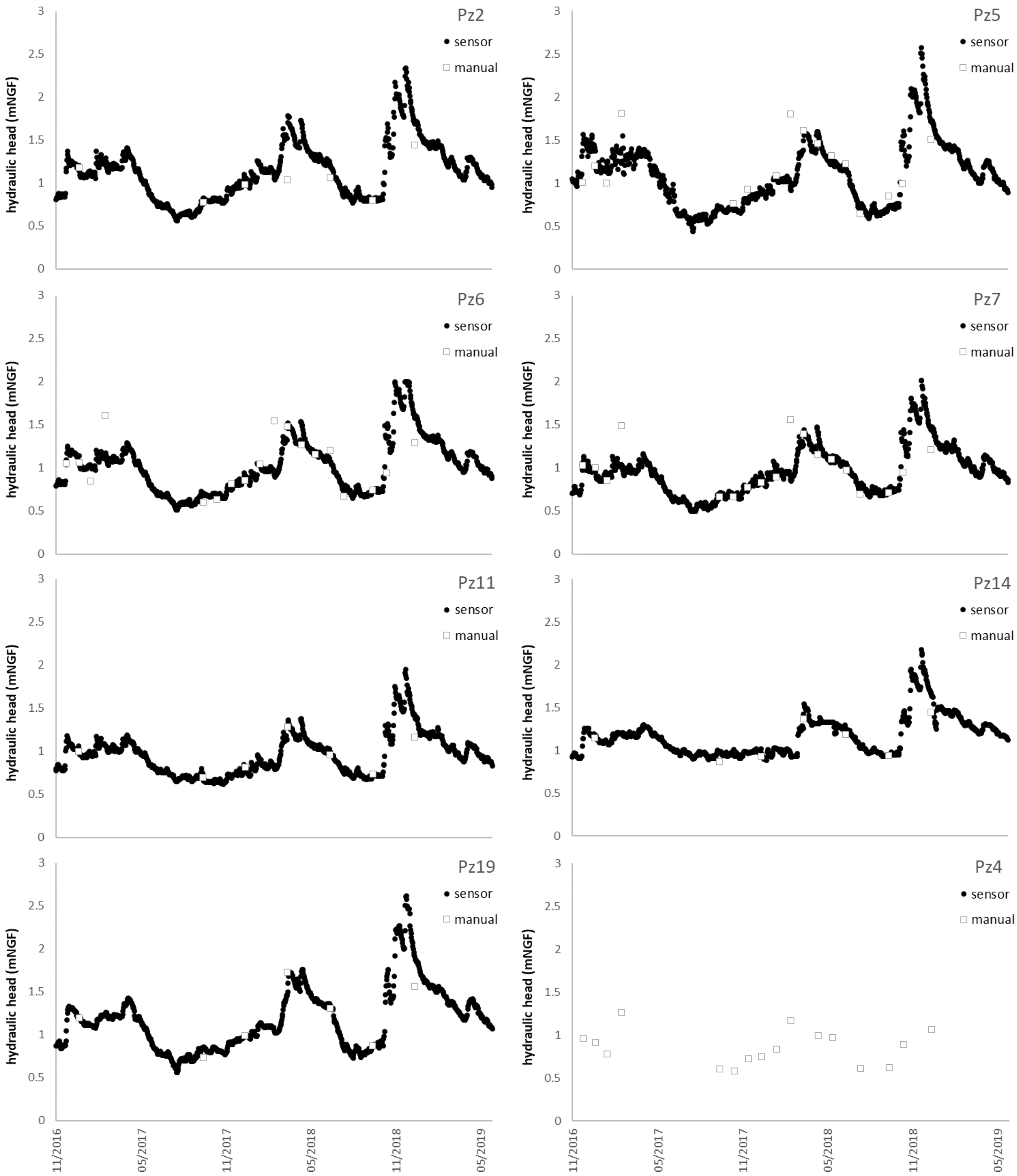


Figure 17: **Groundwater level measurements evolutions of the 9 observation wells (Pz2, Pz4, Pz5, Pz6, Pz7, Pz11, Pz14, Pz19) considered for the 910 stress periods in the model on the web-based SMART-Control platform.**

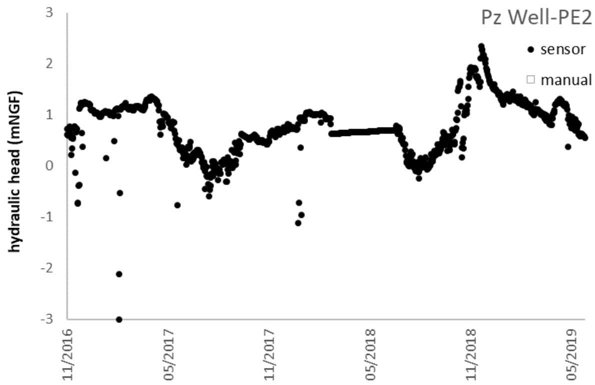


Figure 18: **Groundwater level measurements evolutions of well PE2 (relative to the "Père Eternel" pumping well) considered for the 910 stress periods in the model on the web-based SMART-Control platform.**

4.2 RESULTS

4.2.1. The reference model results - 2.5 years

The « Results » functionalities of the T03 web-based SMART-Control platform allows to view four main types of results of the simulation associated with the previous described model « aquarenova_small_v5-cal3 » as :

- Hydraulic heads at each time step on map and cross sections (Figure 19),
- Water budget : flow rates for each time step as well as cumulative volumes (Figure 20 and Figure 21),
- Time series of groundwater level of specific activated cells or observation wells (Figure 22),
- Statistics of the calibration based on the simulated hydraulic heads and the observed hydraulic heads (Figure 23).

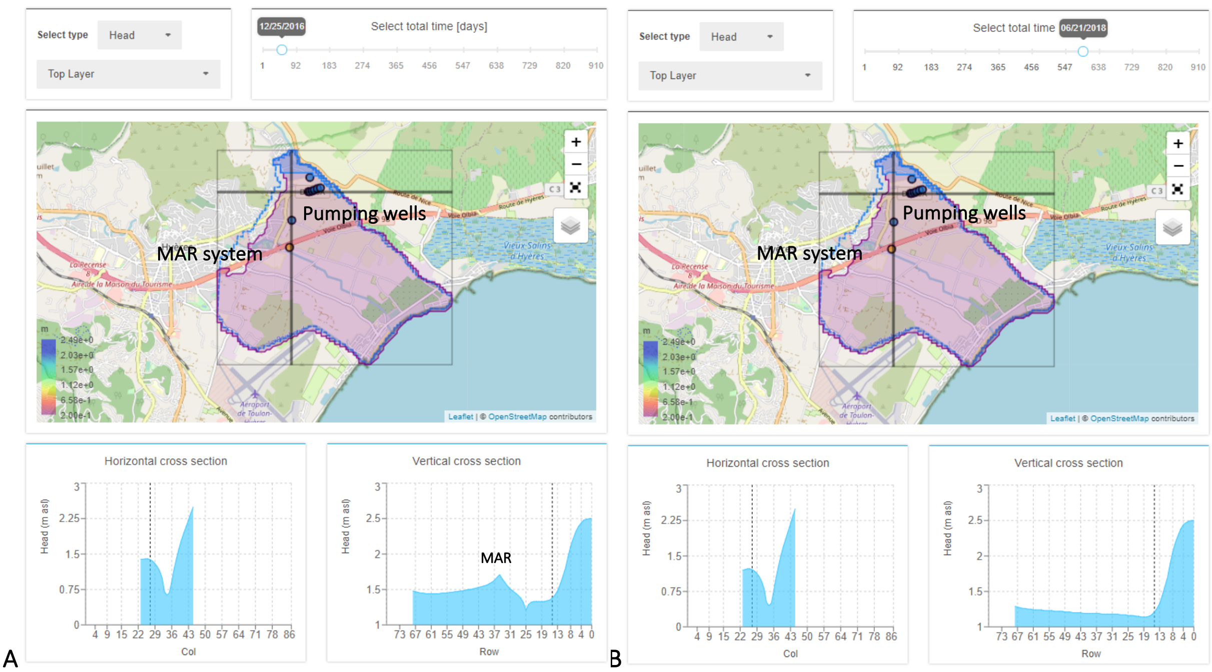


Figure 19: **Screenshot of the hydraulic heads calculated A) the 12/25/2016 (with MAR infiltration), B) the 06/21/2018 (without MAR infiltration) with the model "aquarenova_small_v5-cal3" run on the web-based SMART-Control platform (on map, horizontal cross section and vertical cross section).**

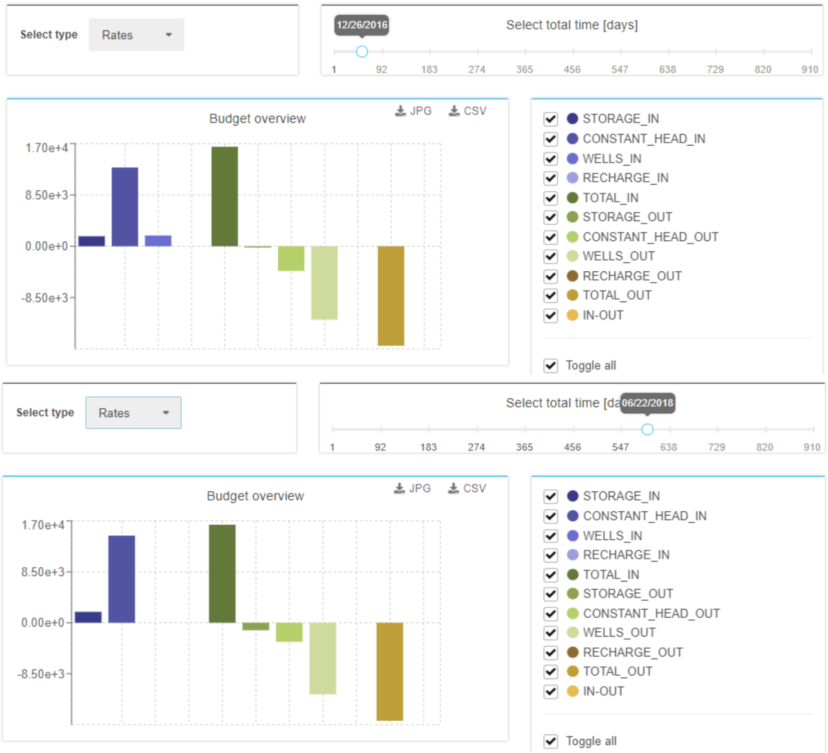


Figure 20: **Screenshot of the water budget "rates" calculated A) the 12/25/2016 (with MAR infiltration), B) the 06/21/2018 (without MAR infiltration) with the model "aquarenova_small_v5-cal3" run on the web-based SMART-Control platform (m³).**

Figure 21: **Screenshot of the water budget "cumulative volumes" calculated from the 11/01/2016 to A) the 12/25/2016, and to B) the 06/21/2018 with the model "aquarenova_small_v5-cal3" run on the web-based SMART-Control platform (m³).**

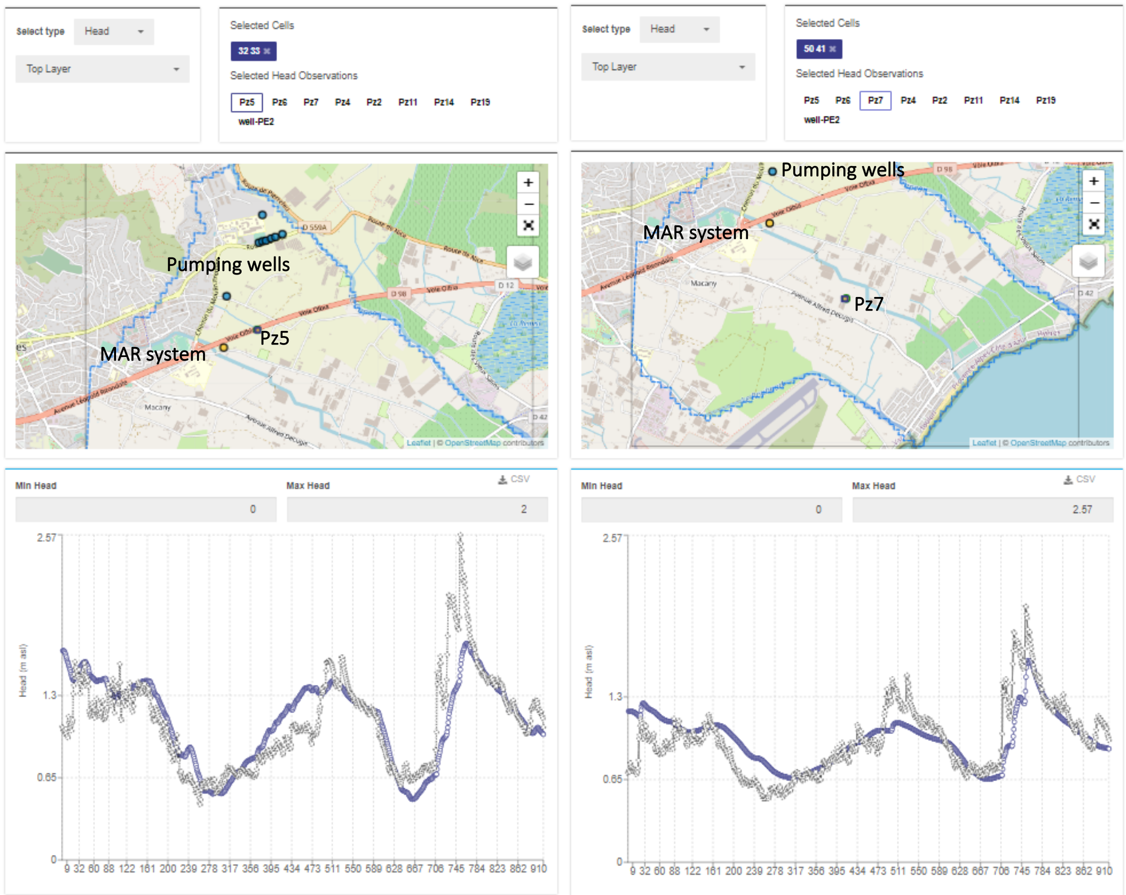
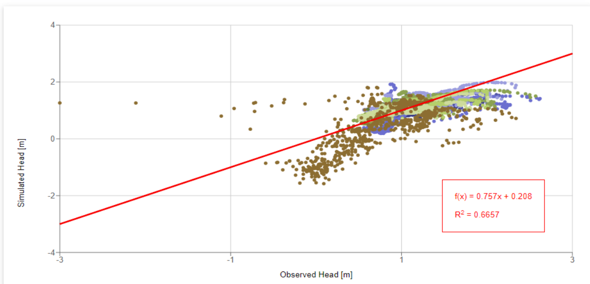


Figure 22: **Screenshot of the time series of groundwater level « head » (mASL) calculated, in blue, for the two of the nine observation wells with the model "aquarenova_small_v5-cal3" run on the web-based SMART-Control platform compared to measurements, in grey (on the right Pz5, on the left Pz7).**

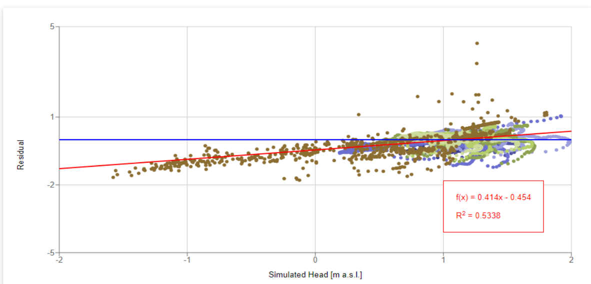
Calculate statistics

Name	Symbol	Value	Unit
Number of data points	n [-]	7304	-
Maximum Absolute Residual	R_{MAX}	4.263	m
Minimum Absolute Residual	R_{MIN}	0.000	m
Residual Mean	R_{MEAN}	-0.044	m
Absolute residual Mean	$\lvert R_{MEAN} \rvert$	-0.044	m
Standard error of estimation	SSE	0.004	-
Root Mean Squared Error	RMSE	0.327	m
Normalized Root Mean Squared Error	NRMSE	0.058	-
Correlation Coefficient Pearson R	R	0.666	-
Coefficient of determination	R^2	0.443	-

Simulated vs. Observed Values



Weighted residuals vs. simulated heads



Ranked residuals against normal probability

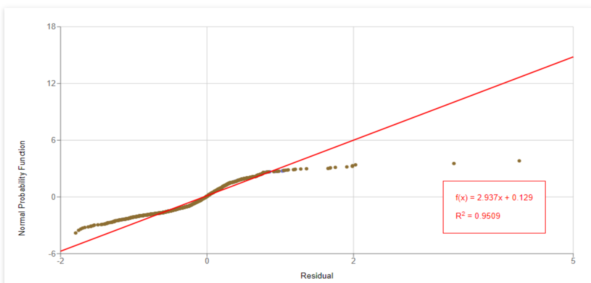


Figure 23: **Screenshot of the statistics of the calibration based on the observed hydraulic heads and the hydraulic heads simulated with the model "aquarenova_small_v5-cal3" run on the web-based SMART-Control platform.**

The hydraulic heads simulated for each time step on map and cross sections (Figure 19) and the water budget (Figure 20 and Figure 21) show first, groundwater levels are quite flat over the entire domain at elevations of about +1mASL (Table 2), except close to the boundaries due to fixed « constant heads » conditions to the north and west around +2 to +2.5mASL and close to the pumping well areas where the groundwater elevation is simulated below +1mASL. Second, the volumes of water inflow through the boundary conditions « Constant heads » imposed to the north and west dominate the flows due to pumping well effects correctly reproduced in this model.

The inflow trough the boundary conditions (~13000m^3.d^{-1}) is higher than the outflow (~4000m^3.d^{-1}) but these calculated volumes depend on the « Constant heads » fixed values and also on the permeability value selected for the calculation, all driven by pumping. As we do not have detailed information on these two quantities (flow from boundaries and permeability values), only the comparisons between the measured and simulated water levels can inform us if they are correctly evaluated. According to the Figure 22, the simulation represents quite well the measured levels for Pz5 and Pz7. However, according to the calculated statistics if we consider the 9 piezometers (Figure 23), there are discrepancies between the two, especially for the piezometers located close to the boundaries (Pz2 and Pz14) and those located near the pumping areas (Pz19 and PzWell-PE2), as shown in the Figure 24.

Table 2: Statistical information of the measured groundwater level (Head) on the 9 observation wells

	Sensors								*Manual*	
mASL	**Pz14**	**Pz19**	**Pz11**	**Pz7**	**Pz6**	**Pz2**	**Pz5**	**Pz_well-PE2**	*Pz4*	ALL Pz
Max	**2.18**	**2.62**	**1.95**	**2.01**	**2.00**	**2.34**	**2.57**	**2.34**	*1.26*	2.620
min	**0.88**	**0.56**	**0.62**	**0.50**	**0.51**	**0.56**	**0.44**	**-3.00**	*0.58*	-3.000
Mean	**1.17**	**1.18**	**0.96**	**0.96**	**1.02**	**1.13**	**1.10**	**0.77**	*0.85*	1.053
Median	**1.14**	**1.14**	**0.95**	**0.94**	**1.01**	**1.13**	**1.11**	**0.72**	*0.86*	1.040

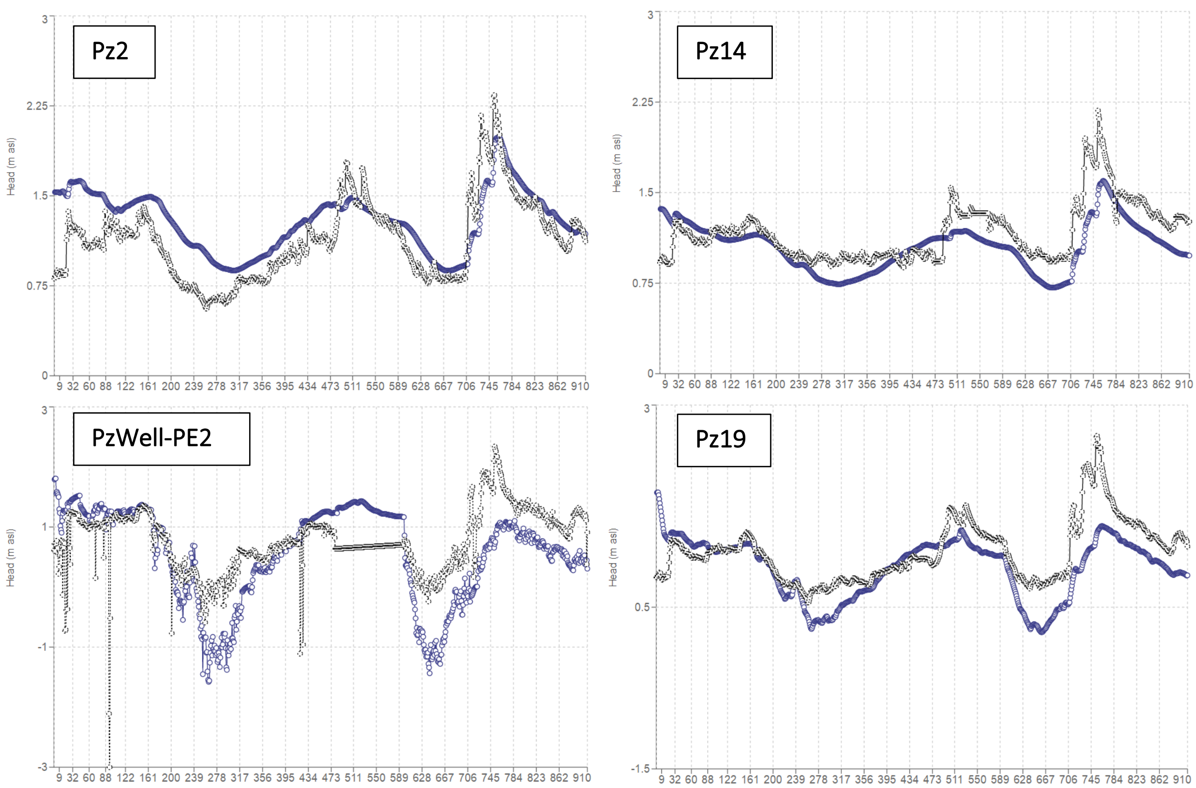


Figure 24: Screenshot of the time series of groundwater level « head » (mASL), calculated in blue, for the Pz2 and Pz14 close to boundaries and PzWell-PE2 and Pz19 close to pumping areas, with the model "aquarenova_small_v5-cal3" carried out on the web-based SMART-Control platform compared to measurements in grey.

Concerning the recharge of the aquifer, the volumes coming from the atmospheric recharge and the infiltrated volumes through the MAR system are low compared to the other terms of the water budget on the modelled period. They represent respectively 5.5% and 4.0% of the volume of inflow in the aquifer while the upstream regional flow represents 81.0% and the pumping volumes represent 73.0% of the total outflow. Finally, the proportion of volume discharged by natural flow (to the sea) is 20% in this model.

Even if the infiltration MAR system seems to be negligible in volumes, it is nevertheless visible locally on the simulated hydraulic head (sea cross section on the Figure 19) and certainly also on the observed piezometry. On the latter, it is less obvious because it is often confounded with the increase in level due to winter recharge and the decrease of pumping rate at the PE1PE2 wells occurring at the same periods (Figure 25).

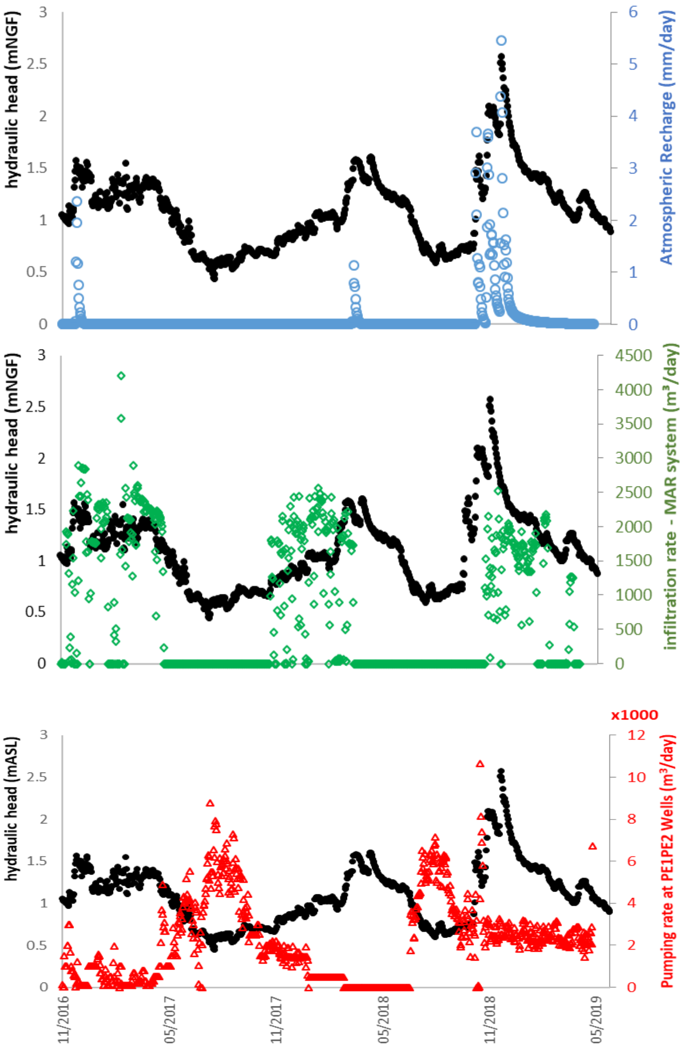


Figure 25: Time series of groundwater level « hydraulic head » (mASL) measured for the Pz5, in black, compared to the atmospheric recharge, in blue, the infiltration through MAR system, in green, and the pumping rate at PE1PE2 wells, in red.

4.2.2. The scenario results – 2.5 years

The simulated results show that boundaries and hydrodynamic parameters should be better evaluated adding measurements on field particularely on regional groundwater flow knowledge (upstream and downstream), considering the groundwater-river exchanges and of course optimising the calibration of the model.

However, the application of the modeling tool, even considering a simplified version of the hydrosystem, allows the identification of major processes but especially the simulation of the impact on groundwater of alternative groundwater management practices. For example, four scenarios of infiltration through the MAR system are tested to be compared to the current situation – reference model « aquarenova_small_v5-cal3 » (all other conditions remaining equal) :

- same MAR system duplicated at the same location « SCENARIO-1 »,
- no MAR system « SCENARIO-2 »,
- same MAR system duplicated upstream of the PE1PE2 pumping wells « SCENARIO-3 ».

Other scenarios could be tested to evaluate the effect of the fixed boundary conditions « Constant heads » or also test several hypothesis on the calculation of atmospheric recharge for example.

The « Results » functionalities of the T03 web-based SMART-Control platform allows to view the main results of the simulation of each SCENARIO as presented previously for the reference model « aquarenova_small_v5-cal3 ». In order to quickly compare the scenarios between them but also to the reference model, the tool T07 – MODFLOW model scenario manager developed on the web-based SMART-Control platform is applied[4].

When analysing the results while the system is active, the comparison of the results of these three MAR Scenarios shows that the groundwater level increases with the action of the MAR system (Figure 26, Figure 28, Figure 29) and the closer to the infiltration system, the greater the variation in the hydraulic head (Figure 30). It is of the order of several tens of centimetres near the basins and only a few centimetres near the sea.

On the other hand, when the system is inactive (06/21/2018), no significant difference is observed on the calculated hydraulic heads between the different simulations (Figure 27), which indicates that the effect of the MAR on groundwater level is not very inertial in this specific case due to the high permeability of the aquifer.
These simulations do not however indicate anything about water quality and the beneficial effect of MAR systems on groundwater salinity. This model would have to be completed by a calculation of convection and dispersion of solutes (and possibly take into account the associated density phenomena). It is more probable that the effect of MAR on groundwater quality is much more inertial in this aspect.

The results of the Scenario-2 (no MAR system) show that the infiltration MAR system is visible on the simulated hydraulic head and explain better the piezometry measured on the observation wells (Figure 30). Indeed, the scenario-2 with no MAR compared to the reference model with MAR system indicate that the increase is not only due to winter recharge and lower PE1PE2 pumping but also to the MAR system.

For the moment, no comparison of the water budget between the four simulation is possible at this stage of the platform's development, which does not allow us to identify the impact of the MAR system on the groundwater inflow and outflow through the boundary conditions fixed as « Constant head ».

[4] https://dss.smart-control.inowas.com/tools/T07/ « Scenario analysis aquarenova_small_v5-cal3 »

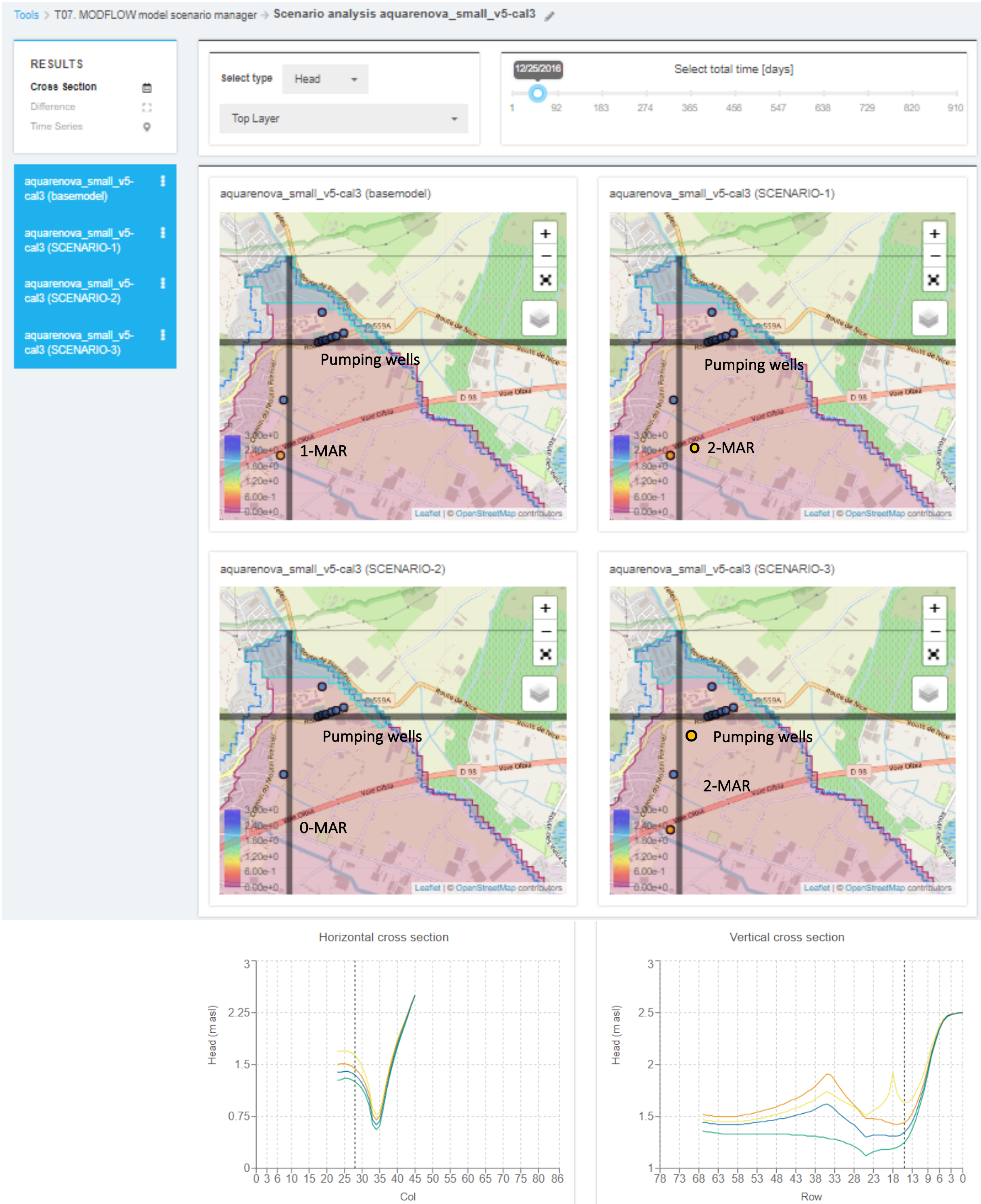


Figure 26: **Screenshot scenario analysis of the hydraulic heads calculated the 12/25/2016 (with MAR infiltration active) for the reference model "aquarenova_small_v5-cal3", in blue, and the three MAR SCENARIO (SCENARIO-1 in orange; SCENARIO-2 in green, SCENARIO-3 in yellow) carried out on the web-based SMART-Control platform (on map, E-W cross section and N-S cross section).**

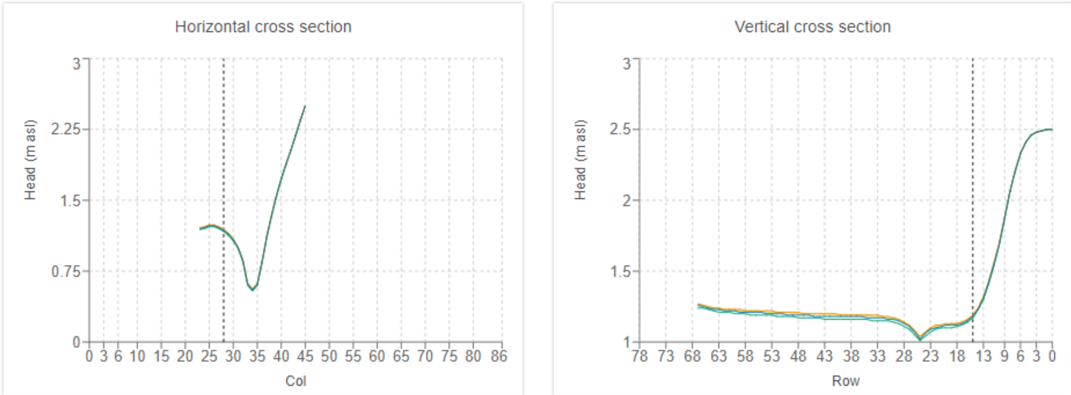


Figure 27: **Screenshot scenario analysis of the hydraulic heads calculated the 06/21/2018 (with MAR infiltration inactive) for the reference model "aquarenova_small_v5-cal3", in blue, and the three MAR SCENARIO (SCENARIO-1 in orange; SCENARIO-2 in green, SCENARIO-3 in yellow) carried out on the web-based SMART-Control platform (E-W cross section and N-S cross section).**

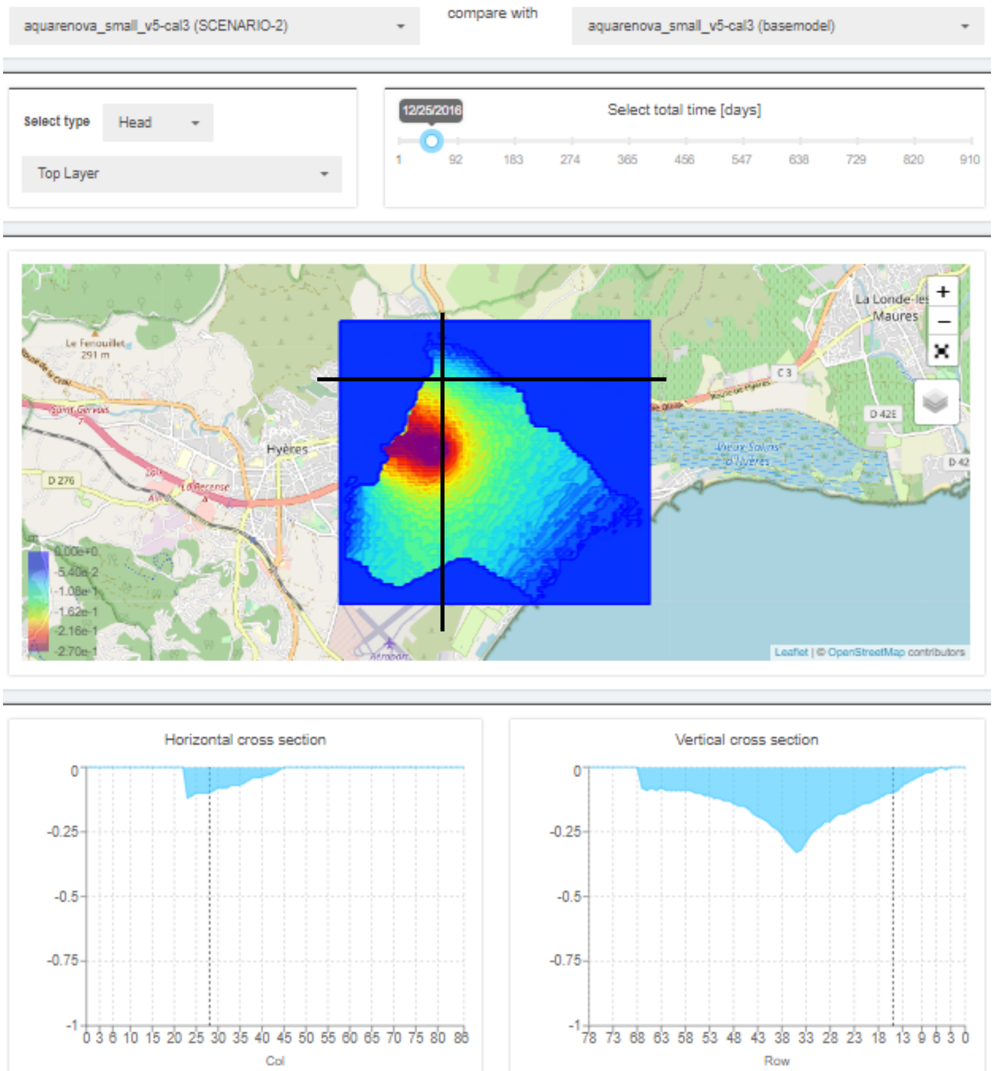


Figure 28: **Screenshot scenario analysis of the drawdown calculated the 12/25/2016 (with MAR infiltration active) between the SCENARIO-2 and the reference model "aquarenova_small_v5-cal3" carried out on the web-based SMART-Control platform (on map, E-W cross section and N-S cross section).**

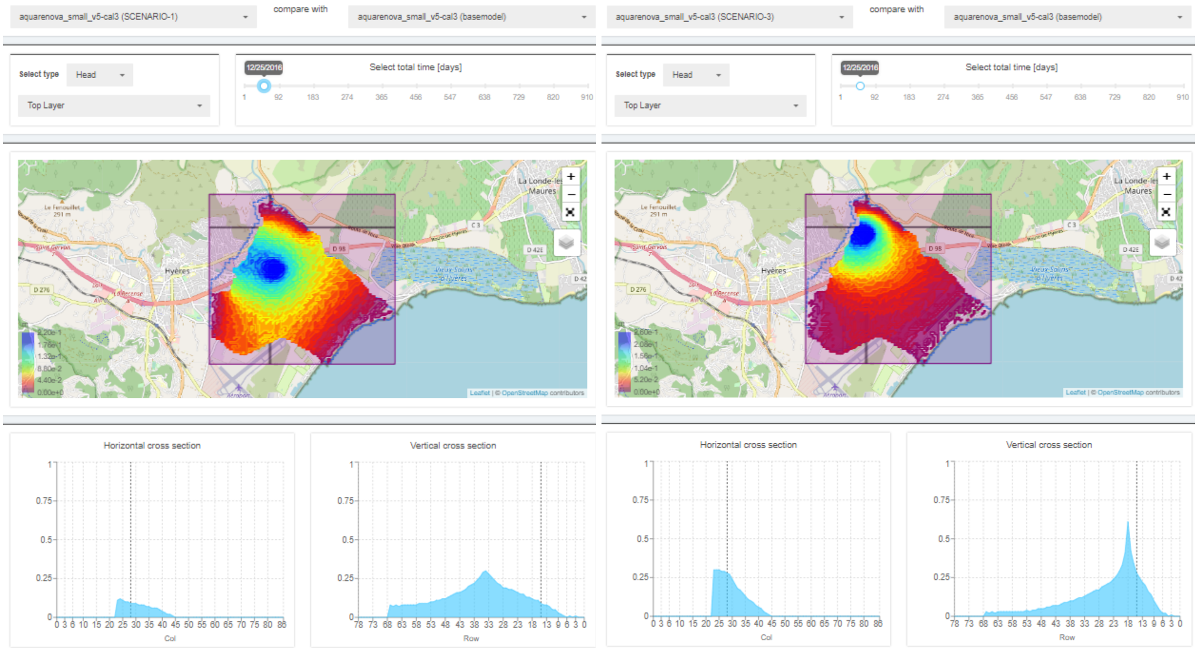


Figure 29: **Screenshot scenario analysis of the drawdown calculated the 12/25/2016 (with MAR infiltration active) between the SCENARIO-1 and the reference model “aquarenova_small_v5-cal3” (left) and between the SCENARIO-3 and the reference model “aquarenova_small_v5-cal3” (right) carried out on the web-based SMART-Control platform (on map, E-W cross section and N-S cross section).**

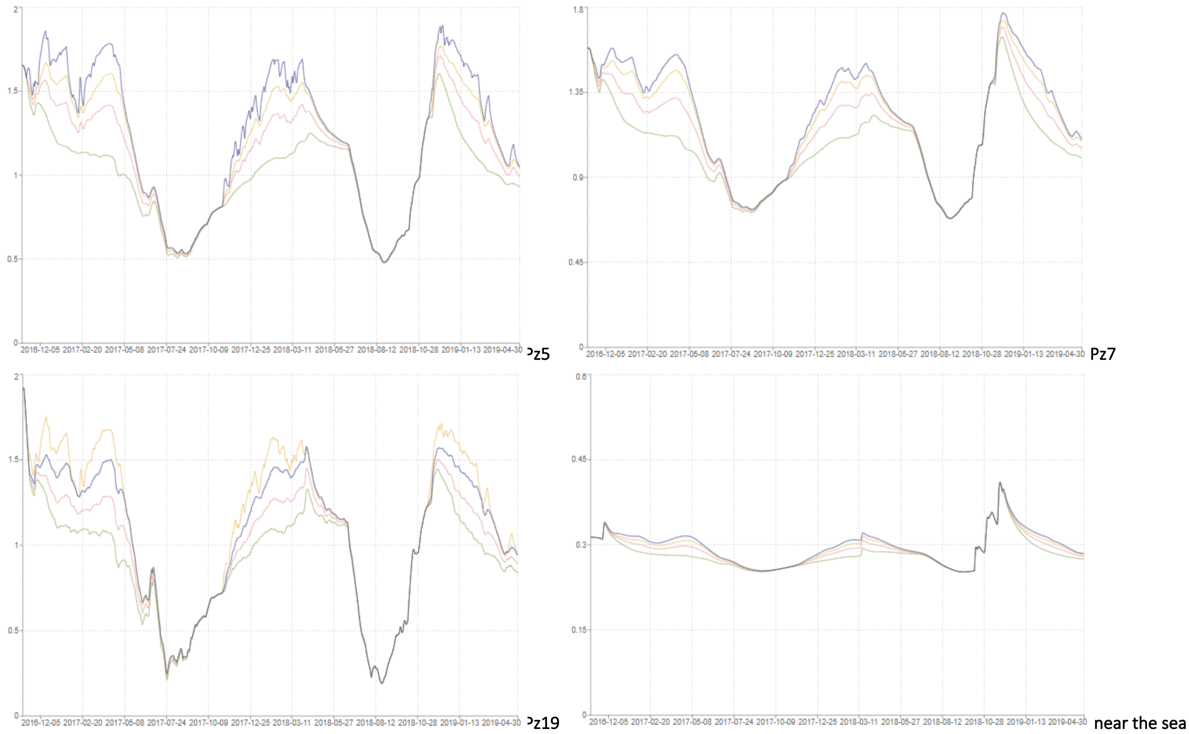


Figure 30: **Screenshot of the time series of groundwater level « head » (mASL) calculated for the reference model “aquarenova_small_v5-cal3”, in red, and the three MAR SCENARIO (SCENARIO-1 in blue; SCENARIO-2 in green, SCENARIO-3 in yellow) carried out on the web-based SMART-Control platform for the two of the nine observation wells.**

5. ANALYTICAL SOLUTION APPLICATION

This section presents the use of an analytical solution to describe the groundwater mound due to the infiltration of water into the recharge basin from the Roubaud river, and its impact in term of groundwater flow downstream into the Mediterranean sea. The following paragraphs present the analytical solution and its use on an infiltration test performed in November 2016 during 5 days (10-16/11/2016).

5.1. USED ANALYTICAL SOLUTION

This mathematical model allows computing the groundwater mound and decay caused by a recharging basin and a pumping well located near a river or the sea. The sketch of the solution is presented in Figure 31, detailed of the solution can be found in Dewandel et al. (2021). The solution assumes a rectangular recharging area of length 2xL (along the x-axis) and width 2yL (along the y-axis) at a distance d from the sea (or a river), modelled as a constant head boundary. The infiltrated water from the basin directly enters an homogenous, unconfined and isotropic aquifer (i.e. absence of vadose zone) of thickness h0, hydraulic conductivity K, and storage coefficient S. The pumping well is located at coordinates xw and yw and pumps water from the same unconfined aquifer as that intended to be artificially recharged. x=y=0 at the centre of the recharging area.

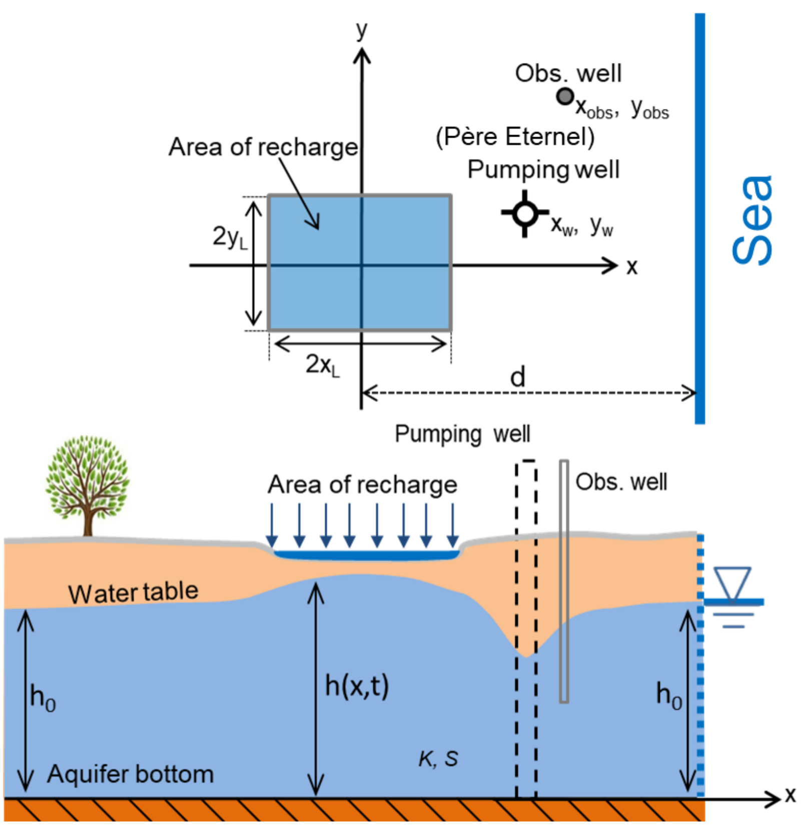


Figure 31: Sketch of the analytical solution used for modelling the groundwater mounding at MAR site in the Gapeau Plain (Dewandel et al., 2021)

5.2. APPLICATION TO THE MAR SITE IN THE GAPEAU PLAIN

5.2.1. Available data

Figure 32 presents the available data (Suez database) during the experiment conducted by Suez in 2016, where only the Basin 1 (1.1 on Figure 32) has been put in water. Data are: the water level within the basin (PzB1.1, Figure 32), the water inflow entering the basin (deviated from Roubaud river), the water levels recorded within the aquifer: at Pz1 and Pz2 (Pz N1.1 and Pz N1.2 onFigure 32) located about 9 m and 58 m meters from the centre of the basin respectively and at a farest well Pz5 located at about 330 m from the basin, and the flow rate at the pumping well Père Eternel located within the same aquifer and at about 530 meters from the basin (only average daily flowrates are available). Figure 33 shows the location of Pz1, Pz2, Pz5 and Père Eternel according to the recharging area (Basin 1). As shown on the Figure 32, water level in Pz1 and Pz2 increased of about 0.27 m and 0.15 m respectively during the experiment, whereas Pz5 did not show any significant response. After stopping the artificial recharge, the water levels returned to their original levels in about 5 to 6 days. Note also that groundwater level data are characterized by daily fluctuation, probably to due pumping at Père Eternel. However, the available data for flowrate at Père Eternel (daily average) does not allow to confirm this hypothesis.

The basin is located at about 2.4 km from the sea (Mediterranean sea). According to the Figure 33, the geometry of the basin is assumed rectangular (43.2x9.2 m) and, according to geological data the aquifer thickness is 17.0 m. The water percolating though the bottom of the basin has been computed from inflow data and water level within the basin (inflitration rate= [volume of water entering the basin – water level variation in the basin x basin area]/time]). From 10th to 15th November 2016, it was about 80 l/s, and is rapidly equivalent to the water inflow into the basin (Figure 34). For the purposed of the modelling and as Père Eternel is pumped throughout the year only the flow rate variations according to the mean flow rate before the recharge experiment started (about 16 l/s) were considered in the following computation (Figure 35). The flow rate variations ranged between -10 and 30 l/s during the recharging period.

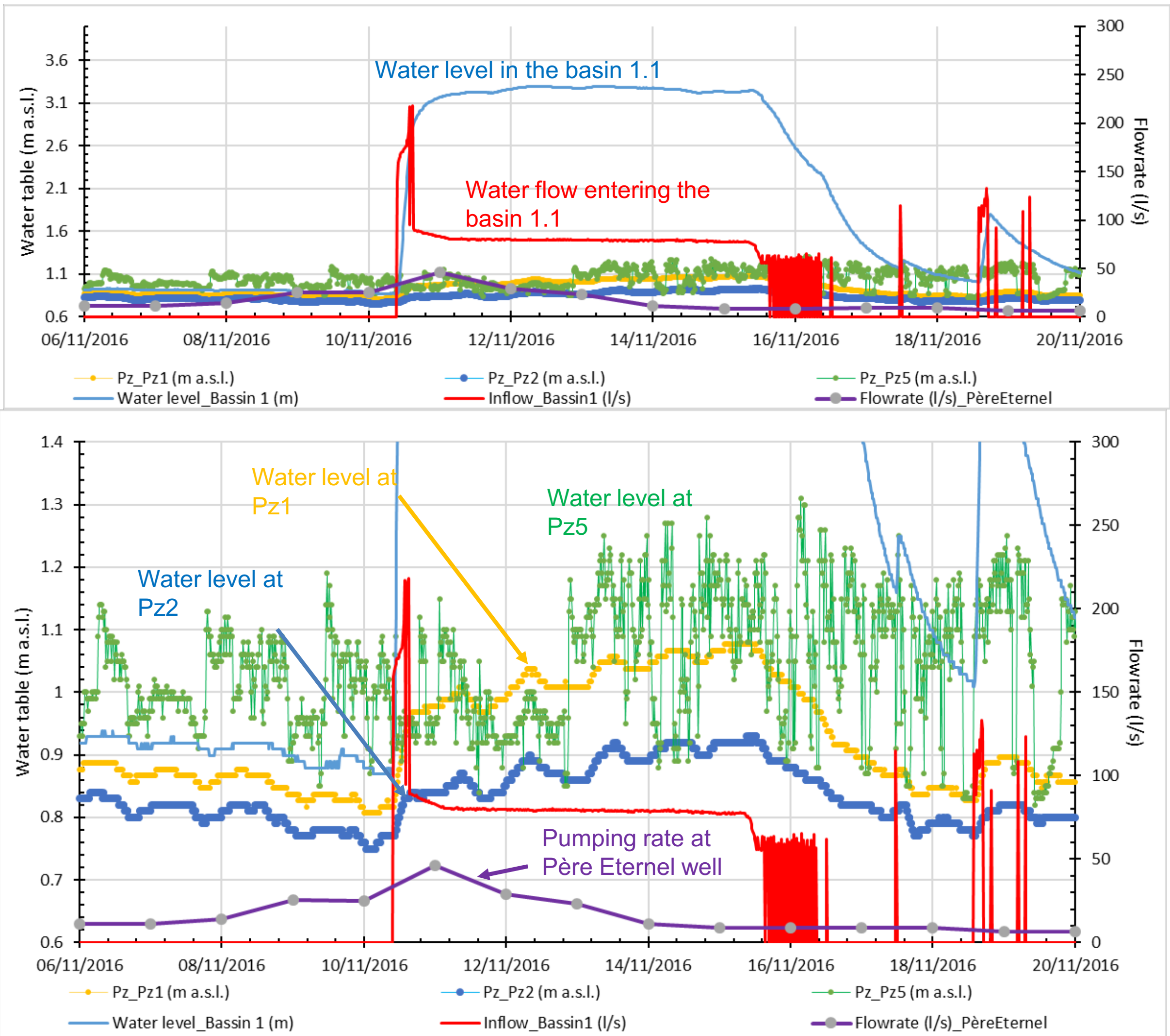


Figure 32: **Available data (Suez database). Bottom figure: detail from the top figure**

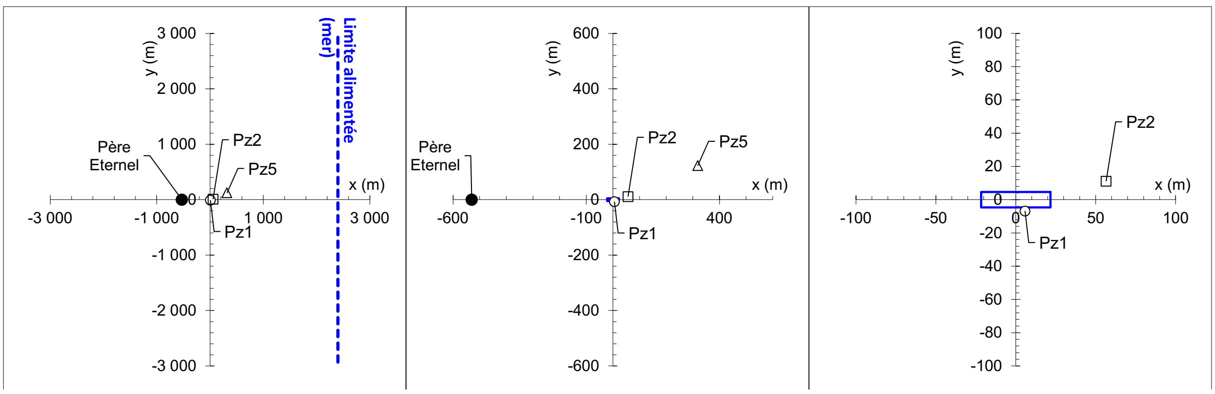


Figure 33: **Location of Pz1, Pz2, Pz5, Père Eternel according to the recharging area (Basin 1); 10-21/11/2016. The sea is the Mediterranean Sea**

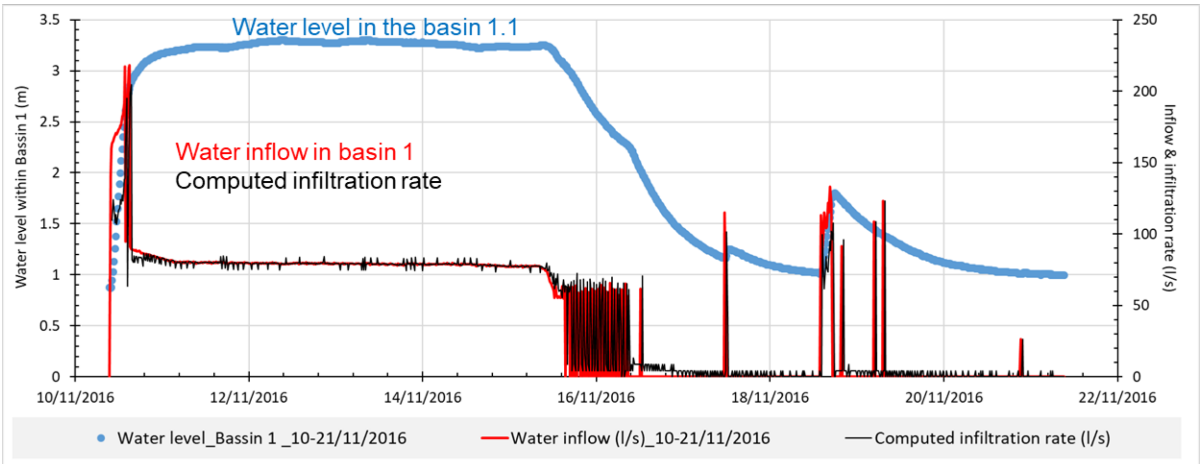


Figure 34: Computation of the infiltration rate, 10-21/11/2016

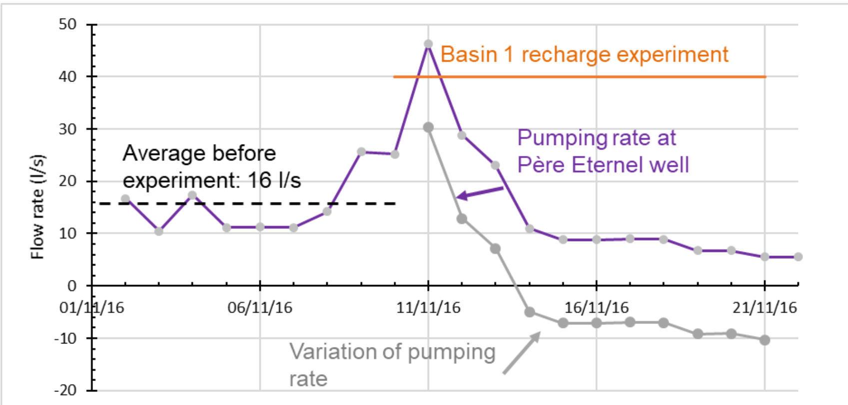


Figure 35: Variation of pumping flow rates at Père Eternel during the recharge experiment ; 10-21/11/2016

5.2.2. Results

Figure 36 presents the results of the modelling for water level rises at the location of the three observation wells within the aquifer (Pz1, Pz2 and Pz5), and Table 3 the deduced aquifer parameters. The model satisfactorily reproduces water level rises at Pz1 (9 m from the basin) and Pz2 (58 m from the basin). At Pz5, the noise of observed data is larger than that of the impact on water level due to the artificial recharge experiment. Hydraulic conductivity of the aquifer is high, 1.6×10^{-2} m/s and storage coefficient is evaluated at 0.10. These values are typical of an unconfined aquifer in alluvial deposits.

Figure 37 gives an evaluation of the theoretical impact in term of groundwater flux at the sea. However, this is a relative assessment as the absolute outflow of the aquifer to the sea is unknown, results gives thus the additional outflow along the costline created by the artificial recharge experiment. The graph describes flow changes in comparison to the initia state, induced by the MAR scheme infiltration and pumping rates changes. The graph presents the impact of the artificial recharge only (max. 55 m^3/h or 15.3 l/s), the one due to the variations of flow rate induced by the Père Eternel pumping well (min: -2.8 m^3/h or -0.8 l/s; fluxes are negative as water from the sea may enter into the aquifer) and the impact of the whole device (artificial recharge + pumping well; 52 m^3/h or 14.4 l/s) along the costline. This computation shows, due to the aquifer properties and the distance to the sea, that the maximum impact occurs about 3 days after stopping the infiltration in the basin and continues for about 15 days (not shown on the figure).

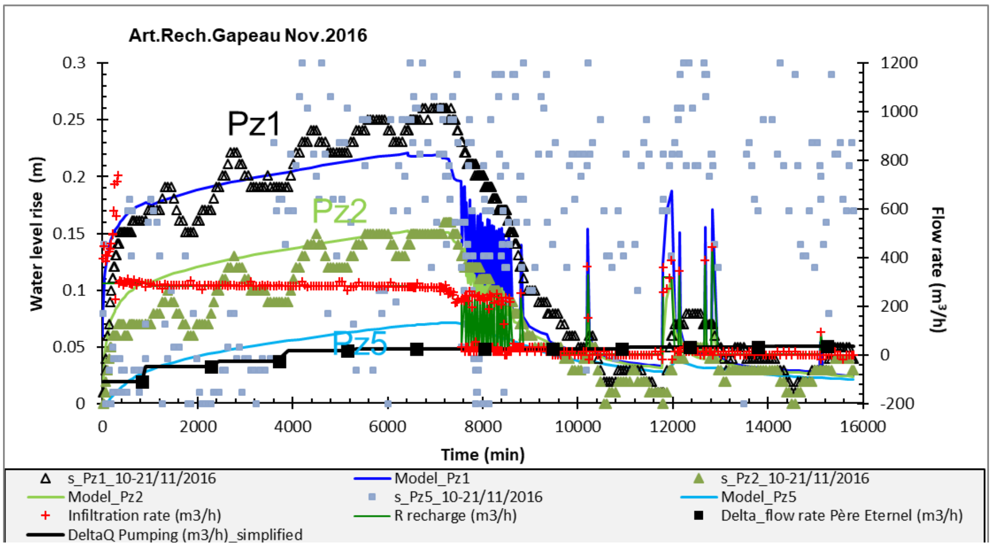


Figure 36: **Modelling of the groundwater mound at Pz1, Pz2 and Pz5 during the artificial recharge experiment conducted in November 2016 (10-21/11/2016)**

Table 3: **Aquifer properties deduced from the modelling. Artificial recharge experiment conducted in November 2016 (10-21/11/2016). r: distance to the centre of the basin (m), x and y: location (m), K: hydraulic conductivity (m/s), S: storage coefficient, h0: initial saturated thickness (m), d: distance to the sea (m), and 2xL and 2yL: length and width of the recharging area (m).**

Well	r (m)	x (m)	y (m)	K (m/s)	S (m)	h0 (m)	d (m)	2xL	2yL
Pz1_10-21/11/2016	8.9	5.8	-6.8	1.60E-02	1.0E-01	17	2400	43.4	9.2
Pz2_10-21/11/2016	57.7	56.6	11.1	1.60E-02	1.0E-01	17	2400	43.4	9.2
Pz5_10-21/11/2016	341.3	318.6	122.6	1.60E-02	1.0E-01	17	2400	43.4	9.2

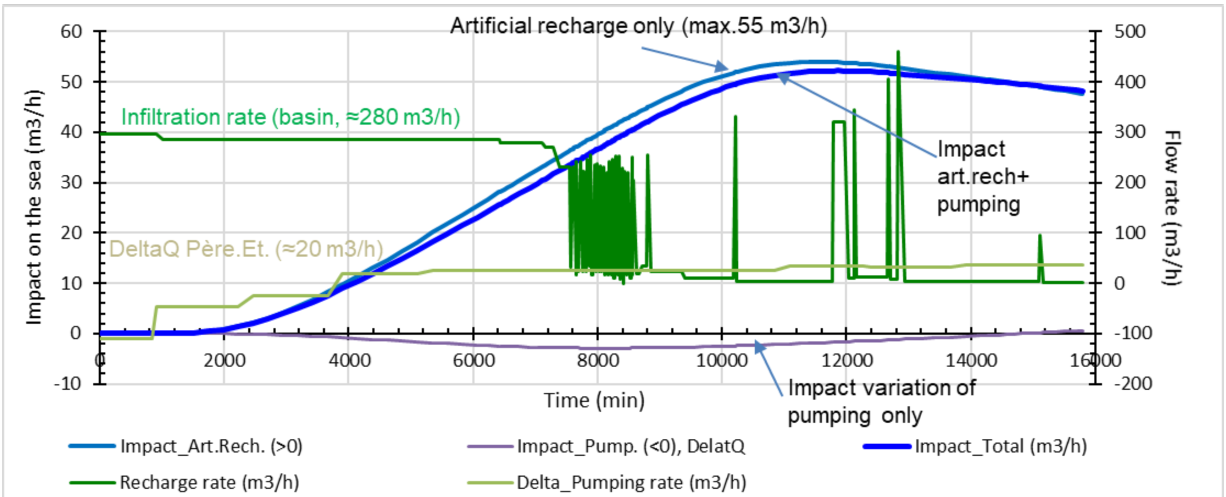


Figure 37: **Relative impact in term of flow rates between the aquifer and the sea during the artificial recharge experiment conducted in November 2016 (10-21/11/2016). Positive flow rates designate flow from the aquifer to the sea while negative flow rates designate sea intrusion into the aquifer.**

5.2.3. Simulation of a one-year scenario

Based on the above model and deduced aquifer parameters, a one-year scenario has been created based on field data and Suez information. The MAR scheme is put in water from November to April (six months) with a flow rate of 50 l/s during 20 h each day, and the pumping flow rates at Père Eternel are the ten-day average of 2019-2020 records. The objective of this modelling is to assess at a year-scale the relative impacts on the water levels and on the outflows along the costline of the recharge scheme. Impacts are given in terms of relative values with respect to the average present water table (i.e. the natural groundwater recharge is not considered) and the present discharge of the aquifer along the sea. For example, the variations in hydraulic head (reference level: 17 m) can be added to the hydraulic head profile deduced from water level level measurements, and the same can also be done for the impact to the sea along the costline.

Figure 38 presents the hydraulic profiles through the Père Eternel pumping well and the recharging area up to the sea (line y=0 in the Figure 33). Results show that rapidly after the infiltration stopped (after 6 months – 180 days) the groundwater mound decays rapidly, which is a consequence of the high aquifer diffusivity (T/S is about 2.7) and because of the pumping at Père Eternel that reduces the size of the groundwater mound, particularly in summer due to the high level of pumping (Figure 39). So, about 5 days after stopping the infiltration, the groundwater mound disappeared. In term of impacts to the sea (Figure 39), the recharging area produces significant impacts even 2.5 months after stopping the infiltration (t=250 d; impact: 22 m3/h or 6 l/s), thus up to mid-July during the dry season. After, the additional flow brought by the recharge scheme continues to decrease down to 11 m^3/h (or 3 l/s) at the end of September (about t=330 d). These created flows contributes thus to decrease the impact due to the pumping at the Père Eternel well, from which flowrate increases by a factor up to 2.5 during the summer period (max: 260 m^3/h or 72 l/s). Note, that this increase in pumping rate explains also the rapid decrease of the impacts along the costline of the whole device (artificial recharge + pumping). On Figure 39, the hatched part (purple) corresponds to the benefit created by the artificial recharge device (MAR system, Gapeau Plain). The cumulative volume of water (Figure 40) corresponding to the outflow of the recharge device to the sea is about 0.54 Mm^3 at the end of the simulating period (one year), meaning that most of the infiltrated water into the basin has be evacuated to the sea (vol. of infiltrated water: 0.65 Mm^3). Compared to the 1.25 Mm^3 abstracted by the Père Eternel well, therefore, the MAR scheme has decreased by a factor of about 2 the impact of the Père Eternel well on the aquifer but also has significantly increased the contribution of the aquifer to the sea (annual impact of Père Eternel to the sea is about -0.87 Mm^3 in the absence of artificial recharge), reducing thus the chance to directly infiltrates sea water into the aquifer.

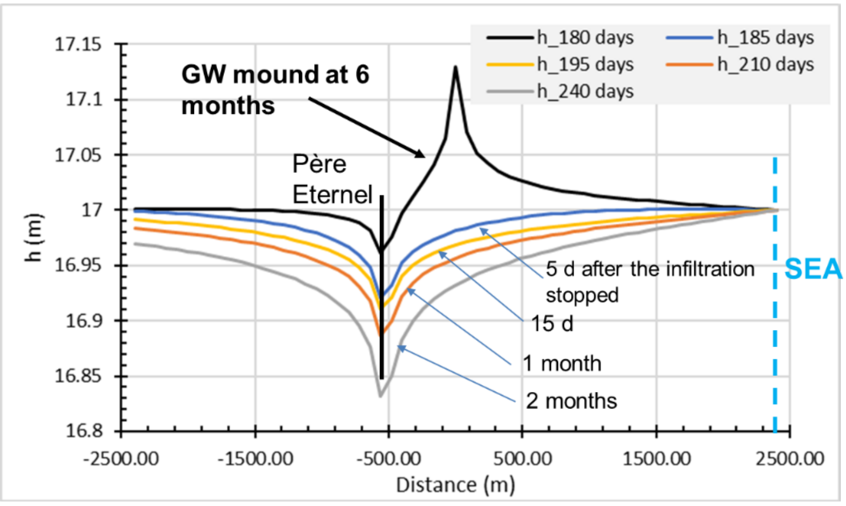


Figure 38: Hydraulic head profiles (with respect to the actual water table) along a line Père Eternel – infiltration basin – Mediterranean sea, at the end of the recharging period (6 months), 5, 15, 30 and 60 days after the infiltration stopped

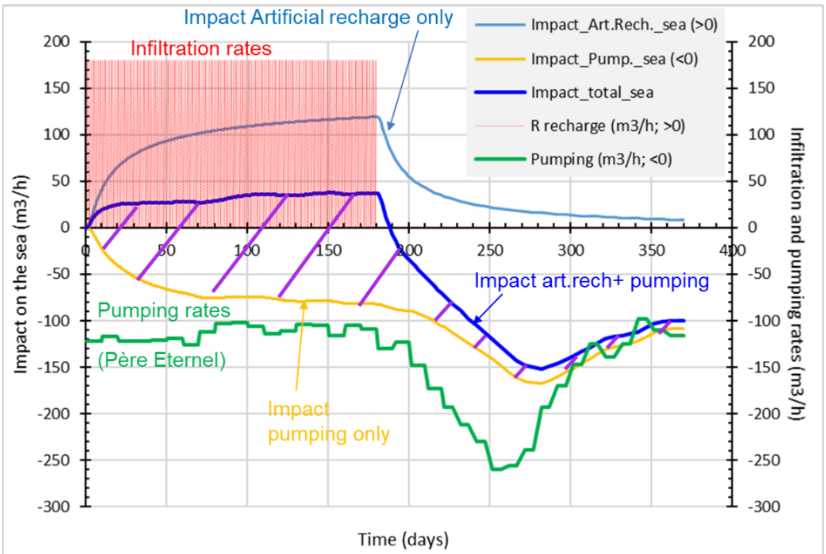


Figure 39: **Theoretical relative impact in term of flow rates at the sea, one-year scenario. The hatched part (purple) corresponds to the benefit created by the managed recharge scheme (MAR system, Gapeau Plain)**

The developed model gives thus a first assessment at the aquifer plain scale of the benefit, in term of flow and volume of water into the aquifer and at the limit between the aquifer and the sea, of the MAR structure in the Gapeau Plain. To go further in analytical modelling, several other elements could be considered such as: the upstream aquifer limit, the natural recharge, the pumping at the Golf Hotel (far but not considered here), the Roubaud and Gapeau rivers.

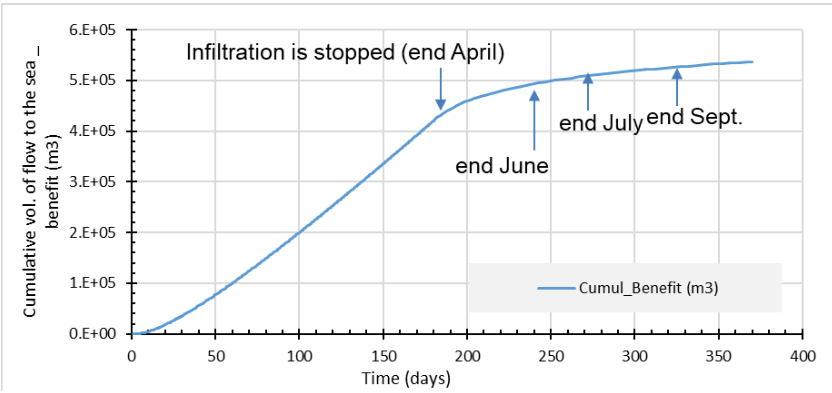


Figure 40: **Cumulative volume of outflow to the sea. Its corresponds to the hatched part (purple) within the previsou figure; MAR system, Gapeau Plain**

5. SUMMARY AND OUTLOOK

The real-time monitoring and modeling INOWAS platform (Smart-Control tool) has been succesfully applied to the Gapeau case study.

For the real time monitoring operation as well as modeling applications, data from the monitoring networks devoted by SUEZ to MAR operations, seawater intrusion prevention and regional monitoring were combined on the INOWAS platform. The time series shows the fluctuating daily groundwater levels which reacts to the annual artificial recharge time periods between November and April and to weather events such as rainfall and droughts. The data can be now vizualised on the platform and sevral tools can be applied to them.

A MODFLOW numerical model of the Gapeau aquifer has been implemented on the platform. It is a simple model with one layer, only simulatioin of the flow, developed under transient conditions. The calibration is quite satisfactory regarding the assumptions. The model includes the MAR scheme. Apart the reference scenario, three scenarios have been simulated on a 2.5 year duration, based on several assumùptions on MAR scheme numbers and location.

New analytical solutions have been developed inb order to simulate the grounwater mound and flows below an infiltration basin. They have been aplied to the Gapeau case study. More simple than a complex numerical model, they allow computing the impact of the MAR scheme on the aquifer.

The numerical model developed on the web-platform constitutes at this stage a feasibility demonstration : it cannot be used as a management tool without further improvements. The next step are a better evaluation of surface water / groundwater interactions close to the pumping wells field. Considering solute transfer and density processes relted to saline intrusion is required in order to properly simulate the impact of MAR schem of salt water intrusion.

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7. ANNEX

Table 4: Summary of monitoring variables and sites in the Gapeau aquifer in Hyères Les Palmiers site (France)

Network	Site	Ref. INOWAS	Variable (Type - Unit)	Sampling freq.	Sync. SFTP
	PZ 2	FRA1_72523	SpC [µS/m]	15 min	daily
		FRA1_72523	Water level [m]		
	PZ 6	FRA1_72526	Water level [m]	15 min	daily
Regional	PZ 10	FRA1_72529	Water level [m]	15 min	daily
monitoring	PZ 14	FRA1_72531	SpC [µS/m]	15 min	daily
		FRA1_72531	Water level [m]		
	PZ 15	FRA1_72532	Water level [m]	15 min	daily
	PZ 19	FRA1_72533	Water level [m]	15 min	daily
	PZ 5	FRA1_72525	Water level [m]	15 min	daily
	PZ 7	FRA1_72527	Water level [m]	15 min	daily
Seawater intrusion	PZ 11	FRA1_72530	SpC [µS/m]	15 min	daily
monitoring		FRA1_72530	Water level [m]		
	PZ 20	FRA1_72534	Water level [m]	15 min	daily
	Withdrawal	FRA1_88320	SpC [µS/m]	15 min	daily
	Roubaud river	FRA1_88320	Flow-rate pump in river [m3/d]	15 min	daily
Managed Aquifer	MAR pz1	FRA1_88321	Water level [m]	15 min	daily
Recharge operations	MAR pz2	FRA1_88321	Water level [m]	15 min	daily
	MAR H1	FRA1_88321	Water height [m]	15 min	daily
	MAR H2	FRA1_88321	Water height [m]	15 min	daily
	Withdrawals	FRA1_72480	Water level [m]	15 min	daily
	Pere	FRA1_72480	Flow-rate Pump 3 [m3/d]	30 min	daily
	Eternel	FRA1_72480	Flow-rate Pump 4 [m3/d]		
	F2	FRA1_72480	Flow-rate Pump 5 [m3/d]		
Withdrawals operations		FRA1_72480	Sum flow-rates [m3/d]		
	Withdrawals	FRA1_72481	SpC [µS/m]	15 min	daily
	Golf	FRA1_72481	Water level [m]	15 min	daily
	Hotel	FRA1_72481	Flow-rate Pump 1 in F1 [m3/d]	30 min	daily
	F1 and F5	FRA1_72481	Water level in F5 [m]	15 min	daily
		FRA1_72481	Flow-rate Pump 5 in F5 [m3/d]	30 min	daily
		FRA1_72481	Sum flow-rates [m3/d]		