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DEMONSTRATE ECOSYSTEM SERVICES ENABLING INNOVATION IN THE WATER SECTOR

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D22.5: Software for the evaluation of groundwater and surface water interactions: numerical model tool to identify links between MAR and water related systems

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D22.5: Software for the evaluation of groundwater and surface water interactions: numerical model tool to identify links between MAR and water related systems

SUMMARY

This deliverable reports the results of the numerical model developed to evaluate the impact of MAR in general, and ASR in particular, on identified ecosystem services.
This numerical model has two main objectives: to evaluate the interactions between groundwater and surface water media and to become a tool to show the benefits of this technology to implementers. The first objective is approached simulating a typical deltaic aquifer and evaluating the results of different MAR configurations. The latter is done through a web page with the results of the transient simulation in video format.

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Amphos 21	Jordi Font Capó Ester Vilanova Muset Martí Bayer Raich
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Amphos 21 Cetaqua	Salvador Jordana Oriol Gibert
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List of Acronyms and Abbreviations

ACA	Catalan Water Agency
ADIF	Administrator of Railway Infrastructures
ASR	Aquifer Storage and Recovery
CUADLL	Association of groundwater users in the Llobregat aquifer
CUACSA	Water users' community of Castellbisbal
ESS	Ecosystem Services
MAR	Managed Aquifer Recharge
SCC	Santa Coloma de Cervelló
SGAB	Barcelona's Water Supply Company
SVH	Sant Vicenç dels Horts

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Executive summary

Highly populated Mediterranean areas are undergoing an increase in environmental and water scarcity problems. Water resources are directly and indirectly affected by anthropogenic activities and by natural factors and, as a result, the ecosystem services related with water resources can change along time.

Managed Aquifer Recharge (MAR) is a very innovative technique to address both water scarcity and water quality problems. It consists in the introduction of water surplus in the aquifer to store it. These recharged water can be recovered during high demands periods or can be used to improve aquifer water quality.

This is a very site-specific technology and one of the main handicap in MAR implementation is the initial evaluation of aquifer positive and negative impacts derived from this practice. This evaluation represents an initial investment and does not ensure the final feasibility of the project. Furthermore, this uncertainty reduces the confidence on the technology of potential MAR implementers.

Positive impacts of this technology are related with an improvement of groundwater and surface water quality and quantity. Therefore, these changes in environmental conditions can be evaluated as changes in ecosystem services (ESS) and finally estimated using economic valuation.

Amphos 21 has developed a software tool to evaluate all water interactions when applying a MAR system in a typical and generic coastal deltaic aquifer. It is a groundwater flow numerical flow to be used as a decision making tool by non-experts in MAR to visualize the positive and negative impacts of the technology over water present status. It has to be taken into account that this software has been developed for a generic but common coastal Mediterranean aquifer type but can be easily adapted to other similar sites. As it is a generic model, the main impacts that can be visualized are related with water quantity (changes in potentiometric level) and saline intrusion (improvement of the salinity problem). There are other impacts related with MAR systems which are more site specific (flooding, wetlands maintenance, changes in private wells) that are out of the scope of this model as these require a specific model to reproduce it and to evaluate it.

To ensure the representativeness of the model, this has been based on Llobregat Delta area and the model reproduces the main problems and hydrogeological features of this aquifer. The conceptual model fits to water budget Llobregat delta.

The numerical model has been developed to simulate flow and transport in a typical delta aquifer. It has been built in MODFLOW 4.2 code using real data. Visual MODFLOW is a finite differences numerical flow model that allows to solve conservative transport using MT3DMS (Harbaugh, 2005). Flow and transport modeling have been assumed with constant density.

Model domain has been created using a pseudo-form that assimilates the deltaic form of the Llobregat Delta. The permeable area has also been divided in two aquifer separated by a low permeability layer (aquitard). The dimensions are 15 x 15 km and 70 m of thickness. The domain has been discretized in 80 files and 80 columns with a cell width of 20 m. The model has been divided vertically in three hydrogeological layers that represents a three-layer aquifer with a 23.33 m thickness per layer.

The state model situation results in an overexploited aquifer with an important saline intrusion problem in the deep aquifer (Abarca et al., 2006). This sea intrusion is similar to that recorded in Llobregat Delta aquifers which is related to delta overexploitation and to harbor construction.

The different management scenarios simulate deep injection of water through wells located at different distances from the sea and with variable injection flows. More specifically, the simulated scenarios are: 1) An injection barrier of five injection wells located at 1200 m of the coastline, 2) An

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injection barrier of five injection wells upstream the wells extraction area (3300 m from the sea), and 3) An scenario where all injection points are working and where the total injected volume is the double than in the previous scenarios (50 Hm^3/year).
The aims of these scenarios are to show the benefits that one can expect applying this technology in a typical ideal aquifer, and to help implementers to choose the best location for the injection wells.
What has been observed is that locating injection wells between the main extractions and the sea results in the best salinity improvements. Regardless the fact that this is very intuitive, the model has shown that it is not advisable to inject the water close to the extraction in order to avoid mixing and to obtain better salinity improvements. Additionally, higher injection volumes give better groundwater quality, although using the present planned injection flows of the Llobregat already leads to a recession of the saline intrusion plume. The volume of injected water to obtain the same improvements depends of the distance to the sea. The model allows to evaluate the correlation between the injection volume and the salinity improvements in order to help the implementer to evaluate the ratio economic investment- quality improvement.
The main purpose is to provide a tool to show the main positive impacts of the technique helping to overcome implementation barriers.
The actual deliverable D22.5 is a model (software) and its results have been synthetized in Amphos 21 web page. The specific results of the different MAR configurations can be visualized in an interactive way by clicking in preselected injection wells location and observing the video with the saline plume movement. Furthermore the files to run this model in other computers can also be downloaded in this same webpage : http://amphos21.com/vistas/dessin_project.php
This report is considered supporting material to provide background information about development and application of this software.

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Introduction

Mediterranean areas are undergoing rapid local and global social and environmental changes. All indicators are pointing out an increase in environmental and water scarcity problems.
The metropolitan region of Barcelona is facing change in urban development patterns, sociodemographic structures, and domestic water use and management. In recent years, several drought alerts have occurred and water restrictions applied, uncovering the fragile equilibrium between the demand and the supply of this resource (March and Saurí, 2010).
Water resources are directly and indirectly affected by anthropogenic activities (e.g. changes in land use) and natural factors (e.g. climate change), that is, global change. As a result, the ESS related with water resources can change along time due to these anthropogenic actions. At the same time, innovative measures can be implemented to tackle these negative impacts and to improve both water scarcity problems and related ecosystem services status.
Managed Aquifer Recharge (MAR) technique is a very promising tool in addressing water scarcity and water quality issues. Widespread application of MAR can help address water security problems to stimulate economic development, improve public health and well-being, and maintain ecological functions and biodiversity. MAR is intended to regulate groundwater recharge, increase water resources, improve water quality in subsurface horizons and regulate return flow from irrigated lands. Therefore, the use of MAR technologies can substitute the need for other, more energy-intensive water supply options, such as seawater desalination (MARSOL FP7 project). Indeed, MAR has the potential to be a major contributor to the UN Millennium Development Goals for water supply, especially for village supplies in semi-arid and arid areas (UNESCO, 2005).
Therefore, MAR is a very innovative technique that can help to face water scarcity and quality problems in Barcelona metropolitan area. The main technical handicap in MAR implementation is the initial evaluation of aquifer benefits as well as the identification of negative impacts derived from this practice. Usually, to evaluate both the positive and negative impacts requires costly modelling and site characterization works that can act as a barrier for its implementation. These works represent an initial investment and do not ensure the final feasibility of the project. Additionally, MAR is a very site-specific technology and it is difficult to evaluate the magnitude of the benefits before the site modelling works. Technology implementers are not always familiar with these technologies and all this initial uncertainty generates doubts and limits the technology implementation.
Amphos 21 has worked in the development of a software tool to evaluate all water interactions when applying a MAR system in a typical and generic detritic aquifer. This software is a decision making tool that allows non-experts in MAR to visualize the positive and negative impacts of the technology over water present status and to build confidence in the technology. Furthermore, this software has been developed for a simple but common aquifer type that can be easily adapted to other similar sites.
More specifically, the numerical model has been developed to simulate flow and transport in synthetic model that reproduces the conditions of a typical delta aquifer.
Note that DESSIN initial proposal indicated that deliverable D22.5 would be focused on developing a numerical tool to evaluate groundwater and surface water interactions. Due to the fact that finally the flexible ASR system is being tested in Cornellà wells where groundwater and surface water are disconnected, the model has been enlarged to the whole deltaic area to evaluate the impacts under different scenarios in the area as a whole. Llobregat deltaic area counts with two aquifers as it is explained in the following pages. From Cornellà to the sea both aquifers are disconnected and the deeper one (also called the main aquifer) becomes confined. Additionally, this model will be broadly

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applied in other sites as it has been developed taking into account the aquifer types in the most stressed areas: coastal Mediterranean aquifers.

This modelling tool does not intend to become a management tool. The main purpose is to provide a tool to quantify the impacts of the technique in a general view and to help to overcome implementation barriers related to the difficulty of showing the benefits of the technology to non-experts. At the same time this impacts could be related with ESS changes and quantified using economic valuation.

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1. STUDY DESCRIPTION

1.1 Managed Aquifer Recharge (MAR) Technique

The MAR technology has been established as a highly effective and affordable tool with respect to large hydraulic works in places where water availability is scarce and seasonal. Currently, it is widely implemented in several countries such as the Netherlands, United States, Australia and Israel.

Aquifer recharge can occur naturally through precipitation or accidentally by distribution network losses (Bouwer, 2002), irrigation and urbanization (Lerner, 2002), or intentionally by applying specific recharge methods. MAR is a technique designed for water infiltration into aquifers intentionally.

The MAR is a management activity that uses the storage capacity to introduce in the subsurface water from different sources and using variable technologies. The ultimate goal is to increase water availability, security of water supply and improve water quality.

Implementation of MAR requires available surplus of water and a suitable aquifer for inducing the recharge. Currently, there are many different techniques to carry out the aquifer recharge. They range from simple installations (small dams on rivers) to complex installations (barrier injection wells with regenerated or treated water). In addition, several innovations are being tested in these different installations in order to improve different aspects of this activity.

MAR offers a set of possibilities that should be adapted to the characteristics of the site, the source of available water resources and the needs of users. Consequently, local and national legislation and methodological guidelines derived from their analysis must be taking into account in each different country.

Depending on the type of recharge (direct or indirect), traditionally the MAR techniques can be classified in 2 main recharge methods: infiltration (or surface) and injection (or depth).

Superficial methods are based on the process of water infiltration through the permeable surface, percolating through the non-saturated zone and finally reaching the aquifer. These methods can be implemented in cases where the aquifer to be recharged is unconfined and is reasonable located near the surface. These methods include infiltrating ponds, ditches, canals, flooding fields, in-channel modifications, meanderings and dams, and permeable vessels. Surface spreading methods are among the simplest and most widely applied MAR techniques. Infiltration ponds are the installation type of surface recharge most widely implemented. In these basins infiltration occurs primarily through the bottom (Ortiz, 2012). In this method, the source water is spread over a land surface and allowed to percolate to the target aquifer. During point or line recharge, the source water is infiltrated either in elongated (e.g. shafts, drains) or punctual (e.g. abandoned dug wells, bore holes) structures. Additionally induced infiltration from stream or lake beds (bank- and lake filtration) is a specific type of infiltration method.

Methods of deep recharge involve the direct introduction of water through injection wells, boreholes or sinkholes. These methods can be implemented in confined aquifers, when surface layers present low permeability and the aquifer is placed at that depth that allows the management of the system at affordable costs.

At the beginning of the recharge process, infiltration rates are higher as they are dependent on the "dry" permeability. However, once the materials have been wet, then permeability is conditioned by the hydraulic gradient and the transmission capacity of the aquifer (Darcy law). Over time, clogging

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processes can influence the permeability reducing infiltration rates. Table 1 summarizes the main MAR devices types.

Table 1 The main MAR installation types.

RECHARGE TECHNIQUE	MAR type	
Infiltration	Spreading methods (areal recharge)	Infiltration ponds
		Soil-Aquifer treatment
		Excess irrigation, ditches, trenches
	Point or line recharge	Well/borehole infiltration, Reverse drainage, shaft recharge
	No – closed to the public Limited (small surface) Limited (small surface)	Check dams
		Riverbed scarification
		Sand dams
	In-channel modifications	Riverbank filtration
		Lakebank filtration
Enhanced storage		Sub-surface dams
Injection	Well injection	Aquifer storage, transfer and recovery
		Aquifer storage (hydraulic barriers)
		Aquifer storage and recovery

1.2 Llobregat basin

Llobregat basin covers a large part of the Barcelona province where the Llobregat river has a total length of almost 170 km and with an average flow of around 10-15 m3/s.
Llobregat river is located in the North-East of Spain and has a typical Mediterranean climate regime. As a consequence, the river basin is characterized by irregular and heavy rain periods, followed by periods of severe droughts which occur in intervals of 8 – 10 years. The lower part of the river is located in most densely populated area of Catalonia, the metropolitan Barcelona area, where several and diverse anthropogenic activities have worsen the status of the basin (Sánchez-Vila et al., 2012).

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With the aim to improve the water availability and the groundwater quality, different MAR activities have been implemented in this lower part of the Llobregat basin (Hernández et al., 2011):

- Scarification of the Llobregat river bed.
- Deep recharge in Cornellà.
- Hydraulic barrier.
- Infiltration ponds (in Castellbisbal, Sant Vicenç dels Horts and Santa Coloma).

These activities have been carried out by the Catalan Water Agency (ACA), along with government agencies operating in the same area, Agbar S.A. and the Association of groundwater users in the Llobregat aquifer (CUADLL).

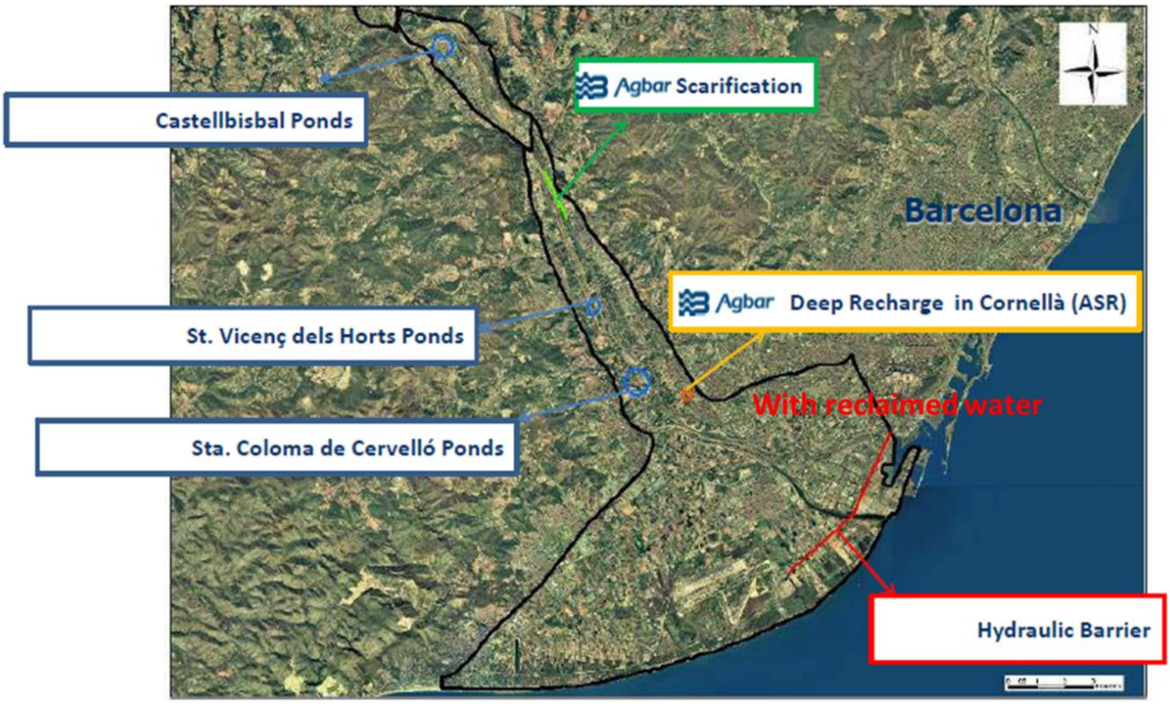

Figure 1: Different MAR facilities in the Llobregat Deltaic area.

SCARIFICATION

Scarification is a process which induces the aquifer recharge directly through the river bed by removing the silts and clays sedimented in the river bed. This activity is implemented upstream, in the upper part of the low valley. Silty sediments of the river bed are removed using a tractor to enhance the infiltration through sands and gravels.

This system of recharge has been used since the 1940's by Barcelona's Water Supply Company (SGAB). It is usually done in spring and autumn when the river flow is between 10 and 35 m3/s and the turbidity lower than 150 N.T.U. At higher discharges it is not safe for tractor operations.

DEEP INJECTION

Late in the 1960's SGAB built a treatment plant whose surpluses were used to be deeply injected into the aquifer through seven wells of 40 m depth. In a second stage, five more wells were drilled specifically for recharging purposes. Nowadays, these wells are still in use to inject treated water if they have surpluses. The amount of recharged water by deep injection ranges from 0 to 14 hm^3/year, as it depends on the availability of the resources.

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INFILTRATION PONDS

In the lower valley of the Llobregat, recharge ponds are being constructed in three areas, which can provide a total additional recharge of 6 to 15 hm3/year.

Castellbisbal recharge ponds were built in mid 1980´s and rebuilt in 2002 by ACA and the water users' community of Castellbisbal (CUACSA). These ponds were inaugurated in April 2010, and consist of 14.000 m^2 of wetland surface and 6.000 m^2 of infiltration pond. the total amount of recharge predicted is 1.8 hm^3/year (Hernández *et al.,* 2012). Infiltration water comes from the river when the amount of ammonia, conductivity and turbidity allows it.

Sant Vicenç dels Horts (SVH) recharge ponds were built in 2007 by ADIF as a compensatory measure for taking out the recharging ponds of Pallejà (1 Ha) during the construction of the high speed train railway (AVE). These ponds count with a settling ponds of 6000 m2 and an infiltration pond of 5600 m2. The connection is instrumented with a flowmeter to quantity the volume of water introduced in the infiltration pond (Cetaqua, 2015a). In 2011 infiltration pond was enhanced with a reactive organic layer compost-made. There are three possibilities for the sources of the recharged water but the recharging water mainly comes from the river when the quality is enough.

Santa Coloma de Cervelló (SCC) ponds are under construction and this depends on an agreement signed by CUADLL with ACA, the Environmental department of the Catalan government, Environmental Entity of the Metropolitan Area of Barcelona and SGAB. All the preliminary studies needed to create the project have been completed including the geologic, hydrogeologic and geophysical characterization (Luna *et al*., 2009). The selected location of this infiltration system was the municipality of Santa Coloma de Cervelló (Baix Llobregat region, Barcelona), in a 13 Ha of surface area placed in the right plane of Llobregat River between the river bed and the high speed train (AVE) platform, owned by ADIF (Administrator of Spanish Railway Infrastructures). This is an ambitious project with a total estimated cost of 8.0 million euros that will provide an extra infiltrated volume of 10 Mm^3 to the Llobregat aquifer.

HYDRAULIC BARRIER

The hydraulic barrier was also an ambitious project. The hydraulic barrier was created to raise the groundwater head near the coast to avoid seawater penetration. The hydraulic barrier consists of 15 wells into which highly treated reclaimed water from the waste water treatment plant of the Baix Llobregat is injected (Fraile and Garrido, 2012). Water is subjected, prior to the distribution to the injection wells, to secondary and tertiary treatments, and later to ultrafiltration, UV disinfection without chlorination, and salinity reduction through reverse osmosis in 50% of the water.

A preliminary pilot phase of the project was started in late 2007, with highly positive results. It consisted of 4 wells in the delta's area that inject water into the aquifer with an injection flow of 2.500 m3/day. The second phase started in mid 2010 and finished in 2011. It consisted on 14 wells with a total injection flow of 15.000 m3/day.

Hydrogeological and hydrochemical monitoring data indicate an efficient performance and aquifer improvement (Ortuño *et al*., 2012). The total investment for the construction of the Llobregat hydraulic barrier amounts to €23 million, including the treatment plant which produces 15.000 m^3/day of reclaimed water.

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1.3 MAR and modelling

Numerical models have become a very useful tool for MAR systems planning, optimization and management. Numerical models allow the site evaluation, the potential water recovery efficiency and the impact of the injected water on the ambient groundwater. Unsaturated flow models, solute transport models, reactive geochemical models as well as water balance models are also frequently applied and often coupled.
A numerical model is a predicting tool that has to be used for initial evaluations and, once the system is running, the model should be calibrated and updated with this new data. Then, the model can be also used as a management tool. Different scenarios can be included in the model in order to compare different system performances. Modeling also provides the distinctive possibility to include future climate change, water use and management scenarios into the feasibility study.
Finally, modeling is further used to predict possible long-term impacts regarding the geochemical processes and the potential impact on the local groundwater.

In the planning phase, classical assessments are often made on a regional basis, within which there may be limited data on complex surface and subsurface conditions and flows. This regional studies also need to determine how the impacts of MAR could vary with project location, size, and operating conditions. Some of these questions could be resolved doing field testing, but small scale pilot field studies can be expensive and may provide limited and scattered spatial information. Numerical models, are a reasonable tool in evaluating MAR scenarios and screening potential sites. Numerical models can be applied on regional spatial scales, allow testing of operational scenarios and hydrologic conditions, and combined with other management options.
As a result, in the planning phase, numerical modeling can help to identify sites amenable for MAR, and can be used to estimate the potential benefits of MAR projects on regional hydrologic conditions under a range of future climate, water use, and management scenarios (Munevar and Marino 1999). Groundwater models may be combined with an optimization algorithm to test water management strategies, including artificial recharge (Abarca et al. 2006). Thus, numerical modeling can be useful in pre-implementation evaluation of project options. The different exiting types of numerical models can help to conduct an MAR suitability analysis when selecting among potential sites and operating strategies.
Modeling can be used for scenario analysis and future predictions to compare different MAR techniques and operational schemes (Ringleb et al., 2016). Modeling is a valuable tool to evaluate the most suitable MAR technique in a given location. Given its flexibility, a model-based preliminary assessment is often recommended prior to pilot field experiments. But sometimes numerical models fail in the flow representation for different reasons as low availability data, unknown local processes, anthropogenic influences, software no suitable, … Some countries including Australia and the USA implemented guidelines that specifically regulate the requirements for risk assessment of new MAR facilities and advise the application of modeling during the planning phase (EWRI, 2001).
Ringleb et al (2016) analyzed 216 the studies that used numerical modelling to evaluate MAR performance. The papers included 188 modeling studies which evaluate field-scale MAR schemes or sites, 10 modeling studies which evaluate laboratory experiments and 18 assessing theoretical issues. The majority of modeling studies were performed for well, shaft and borehole recharge (57%) and spreading methods (29%)
The numerical models can try to reproduce the groundwater flow in the saturated and unsaturated zone and/or the chemical characteristics through the solute conservative transport or reactive transport. Additional, several works use water balance models to reproduce the whole watershed processes.

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The majority of modelling software nowadays applied are not specifically developed for MAR applications. The most commonly used groundwater flow model is MODFLOW (73 out of the 216 studies analyzed by Ringleb et al. (2016). Other quite common codes in saturated flow modelization are FEFLOW, SEAWAT, HST3D and FAST. To simulate unsaturated flow the most commonly used codes are MARTHE, HYDRUS, FEFLOW, MT3DMS, SEAWAT and CXTFIT. Som of these are free.

In the casae of reactive transport modeling the preferred codes are PHREEQC, MT3DMS, PHT3D and EASY-LEACHER

The results of these studies point out that existing modeling tools, regardless the fact that are not designed for MAR management, are mostly sufficient to meet the general needs observed for MAR modeling. These include unsaturated and saturated flow modeling, density-driven modeling and also geochemical modeling. Using well-established tools for MAR modeling such as MODFLOW and PHREEQC is generally of advantage due to their existing wide field of past applications and their comprehensive documentation. In case of complex systems it can be necessary to use other specific software in order to simulate those processes that are important in that site. For example when infiltrating in big coastal aquifers to evaluate the extent of the seawater intrusion and the precise location of the transition zone (mixing zone of freshwater and salt water) it can be necessary to develop a density dependent groundwater flow model. This allows to take into account the different salinity of the seawater and the freshwater and its influence in potentiometric level.

However, with rising complexity of applied models additional hydrogeological parameters and therefore a more detailed characterization of the study site is required. An accurate determination of site-specific parameters and an uncertainty analysis is important to predict the performance, design and operation of a MAR system more reliably by modeling. [241].

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2. METHODOLOGICAL APPROACH

Setting the objectives and characteristics

The context

The implementation of MAR is still subjected to different barriers that difficult its commercialization.

DEMEAU FP7 project evaluated the drivers and pressures for the implementation of different water technologies and among them, the MAR facilities in the Llobregat delta. The main conclusion of this study was that public opinion (contextual level) is the dominant barrier. Especially because of (unfounded) fear for environmental degradation, public opinion tends to be negative regarding these projects and are easily scared of negative impacts. Instead, MAR experts think that this is an optimal solution in most of the cases.

Additionally, the lack of regulatory embeddedness was also identified as an important barrier. As a consequence, administration poses very high (unnecessary) requirements that are very expensive to meet. This is caused by lack of knowledge (on MAR and case context) at public institutions.

Finally, MAR application is very context specific and is therefore not perceived as a valuable investment option for authorities and implementers (e.g. water utilities). Also, this non-generalized approach also makes it very difficult to learn from experience from other cases and develop shared expectations among cooperating stakeholders because the outcome is not certain.

This technology is well known among experts but generates considerable doubts in non-experts, including administration and implementers. There are numerous scientific studies that demonstrate the feasibility and the benefits of the technology. But these results rarely arrive to non-experts who still think that the technology is not totally ready to be implemented. The fact that it is site-specific hinders the demonstration of its feasibility.

As a consequence, a visualization tool of the technology benefits easy to understand can become a good demonstration tool to enhance its commercialization.

The model

The model that has been developed intends to reduce the uncertainty of these stakeholders, local people, implementers and administration, bringing visual information. The model is built in a typical coastal aquifer and reproduces the results of different recharging scenarios in order to offer a comprehensive example of the benefits of the technology.

The model is capable of reproducing the effect (flow and transport) of the pumping wells in the coastal aquifer (marine intrusion).

Different injection scenarios have been simulated in order to evaluate the better option to reduce the saline intrusion in the aquifer.

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This model is posted in Amphos 21 web page with an explanation of the technology. The web page offers an interactive visualization of the different simulated scenarios allowing the user to select different location and injection rates http://amphos21.com/vistas/dessin_project.php

Furthermore, in the same link, all model files can be downloaded in order to run the simulations in other computers and to develop additional recharging scenarios as required by each user.

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3. NUMERICAL MODEL

3.1 Introduction

A synthetic numerical model has been created to evaluate the performance of MAR installations in a detritical coastal aquifer. As the main objective is to offer an impact visualization tool, the model has been simulated in a generic aquifer but based on real data. This generic aquifer intends to reproduce the hydrogeological system of a coastal aquifer and uses the Llobregat river basin characteristics as an example to reproduce present conditions and to simulate realistic future management scenarios. As a consequence, real data from Llobregat aquifer has been used to define the aquifer in the model and to reproduce present status. It has to be taken into account that the model only approximates present status and reproduces observed behaviors and trends of the real aquifer. But the aquifer parameters have been simplified and, hence, local behaviors cannot be reproduced with this model.

Additionally, a bibliographic research has been conducted in order to obtain real values that can be incorporated into the model. Llobregat delta is a hydrogeologically well studied area where different flow models have been developed (UPC, 2003; ACA 2009, and CETAQUA 2015b –in DESSIN project-). The Llobregat bibliographic information that has been used comprises: aquifer type, permeable layers, approximated dimensions, hydraulic parameters, concentrations, recharge, pumping rates. These values have been adapted to a simplified configuration.

This aquifer is located in an area with high water demand (metropolitan area of Barcelona) where different MAR installations, by infiltration ponds and by wells, are placed. This area has held different research projects of MAR and aquifer management. It is expected to extrapolate this evaluation tool to other aquifer types

3.2 Conceptual model

Llobregat delta aquifer

The Llobregat Delta is located at the SW of the densely populated area of Barcelona City, in the NE of Spain (Figure 2). This area, formerly devoted to agriculture, now has important industrial settlements and cities with more than 50.000 inhabitants. The high water demand has lead an intense and continuous exploitation of surface and groundwater resources. Intensive groundwater exploitation until the late 1970s caused a significant advance of the saline intrusion interface. Saline intrusion still affects large areas of the delta. Nowadays, ACA together with CUADLL are trying to correct the present situation and are developing a groundwater management plan to recover groundwater quality and quantity.

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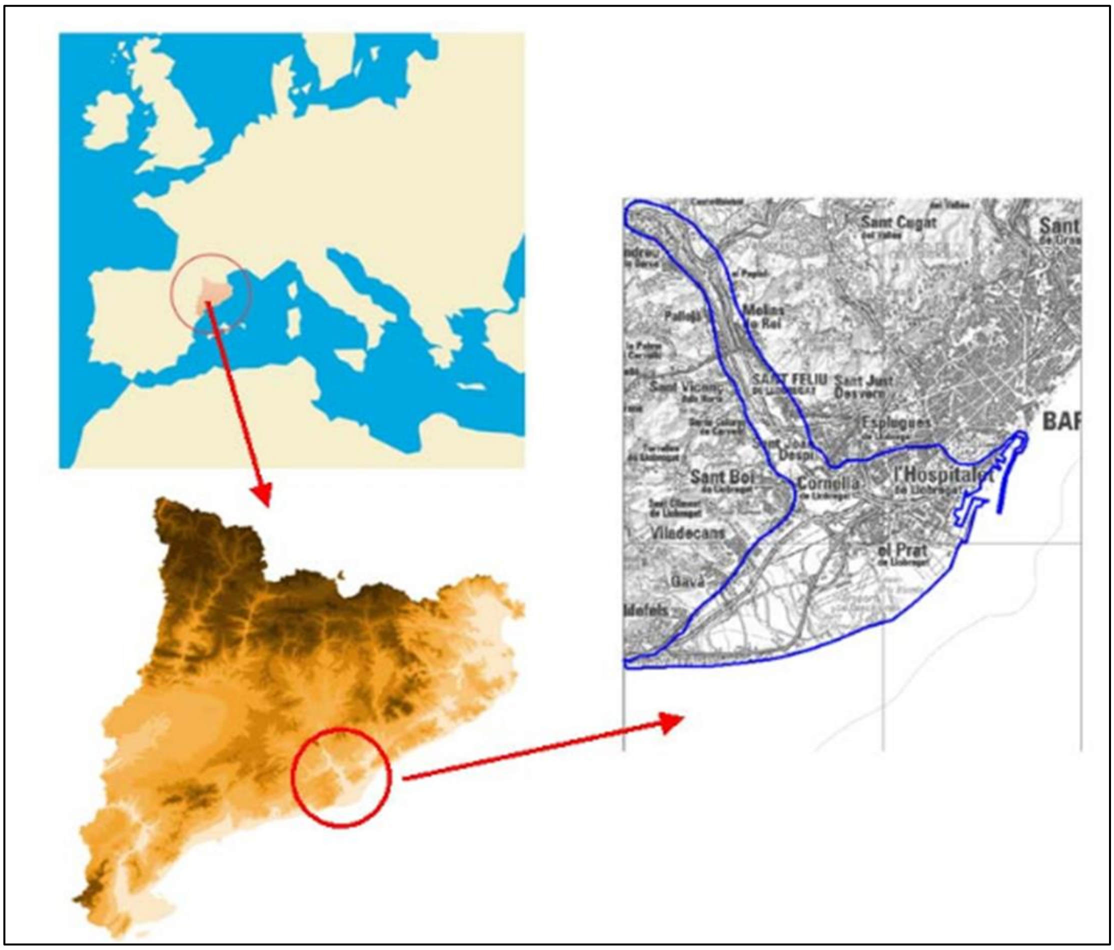

Figure 2: Location of Llobregat delta (Ortuño et al., 2009).

The Llobregat Delta is a well studied case of seawater intrusion. Numerous groundwater studies have been conducted in this area since the 1960s. Among others, the hydrogeological synthesis works by MOP (1966), PHPO (1985) and, more recently, Iribar and Custodio (1992) have been the reference for further studies. In the late 1970s, when salinization problems became more critical, hydrochemistry studies increased the knowledge of the aquifer systems and the mechanisms that cause seawater intrusion in the Llobregat Delta aquifers (Custodio et al., 1976; Custodio, 1981; Manzano et al., 1992; Bayó et al., 1977; Domènech et al., 1983; UPC, 2000,).

In this area two overlayed aquifers can be differentiated (Figure 3). The Main Aquifer is an essentially confined horizontal aquifer of around 100 km^2 and with 15–20 m of thickness. It corresponds to alluvial sediments of Llobregat River and has hydraulic continuity with lower permeable sedimentary materials of the Delta. The Upper Aquifer is non-confined and is present in the upper part of the delta. These two aquifers are separated by an aquitard formed by silty clay sediments.

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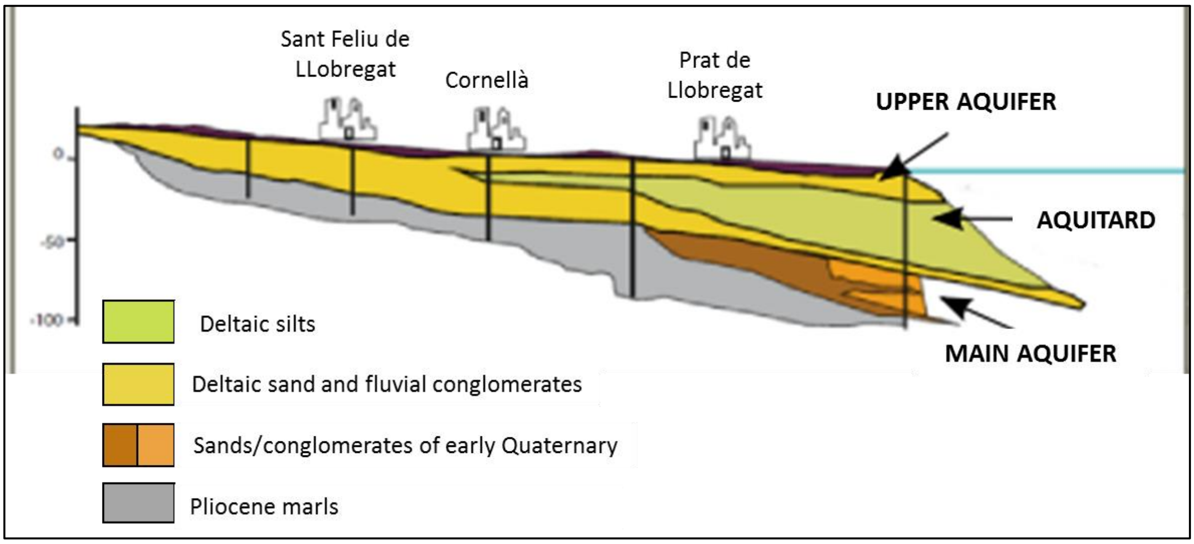

Figure 3: Cross section of Llobregat Delta Aquifer (MOP, 1966, Manzano et al , 1992; modified by UPC, 2002).

One of the most difficult variables to obtain in this area is the groundwater recharge, which depends on soil use and varies with time, and groundwater extraction. Furthermore lateral recharges from other aquifers are also difficult to estimate.

The information about pumping is diverse and variable. The most important groundwater abstractions are known but there are small pumpings that are not being recorded. Groundwater pumping has changed over time and this was largest in the 1970s, when it reached values higher than 130 Hm^3/y (Vázquez-Suñé et al., 2006). As a result heads dropped below 25 m.b.s.l. in the central part of the delta.

More specifically, historical maximum of low groundwater levels was recorded in 1975. Usually differences between minimum and maximum level were between 2 and 5 meters. Instead, in 1975 this difference was more than 7 meters. The main groundwater exploitation was carried out by different local companies or factories and drinking water production operators.

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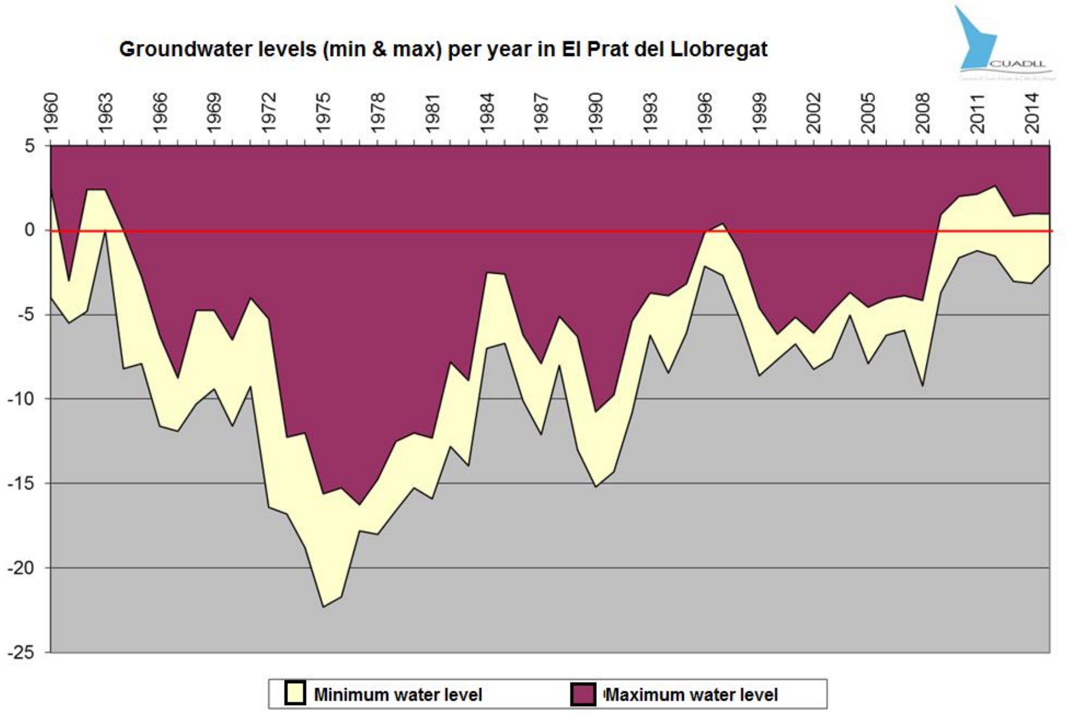

Figure 4: Groundwater levels (min& max) per year in El Prat del Llobregat (Cetaqua, 2016)

Table 1: Maximum differences in groundwater level per year (Cetaqua, 2016)

Year	Difference of level (min – max) [m]	Year	Difference of level (min – max) [m]
2005	3.34	2011	3.35
2006	2.16	2012	4.17
2007	2.05	2013	3.86
2008	5.06	2014	4.13
2009	4.62	2015	2.98
2010	3.64		

The overexploitation has a direct impact in coastal areas in groundwater salinization. The decrease of potentiometric levels places the potentiometric aquifer surface below sea level facilitating the penetration of saline water in the aquifer. The coastal equilibrium depends on the aquifer discharge to the sea as inland outputs are balanced out with marine intrusion. Once salinity has reached the aquifer, it is very difficult to return to previous salinity values due to dispersion processes. In that sense, electrical conductivity measured in production wells can be an additional indicator of this pressure in coastal zones (Delta of Llobregat, for example). Figure 5 shows the high chloride concentration in mg/L in two ACA monitoring points from 2008 to 2015 located in El Prat de Llobregat (deep aquifer), close to the coastal line. Chloride concentrations were higher than those recommended for human consumption (which is 250 mg/l). Droughts periods resulted in a chloride concentration increase in deltaic aquifer.

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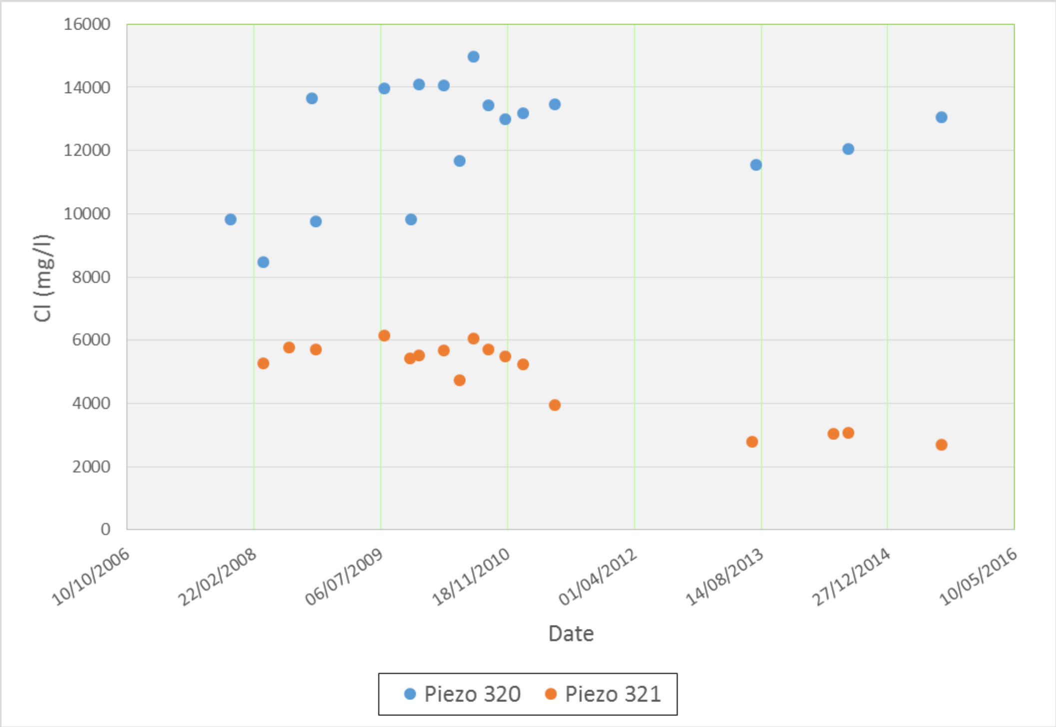

Figure 5: Chloride concentration in two ACA monitoring points (source: www.gencat.cat/aca)

High past groundwater exploitation together with some anthropogenic modifications in the area, led to a quick progression of seawater intrusion. In the middle 80s saline intrusion reached the central part of the delta, where some of the main pumping areas were located. Figure 6 shows the chloride distribution in the Delta in 2007 just before the implementation of corrective measures to prevent further saline intrusion.

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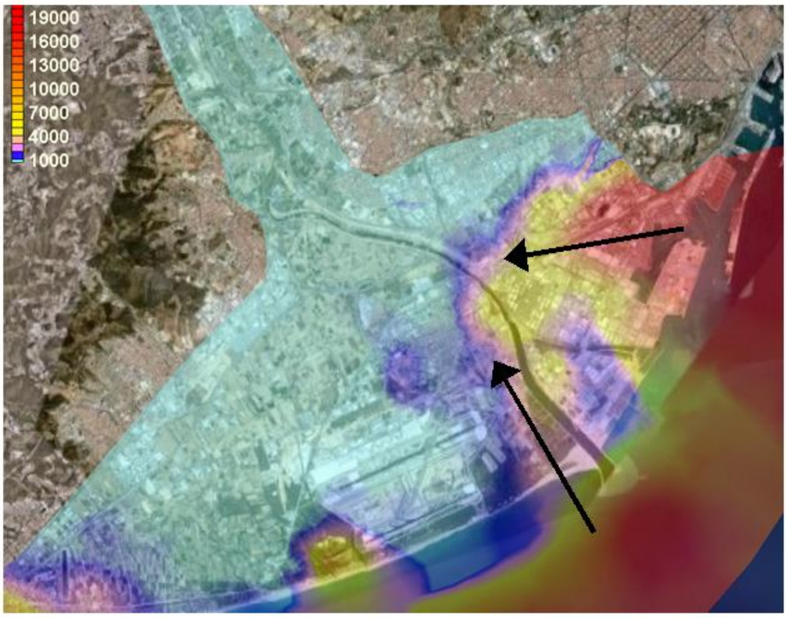

Figure 6: Chloride concentration distribution of Llobregat Delta in 2007 (ACA, 2009).

Groundwater numerical modelling allows the integration and validation of the conceptual model and becomes a useful management tool. The model allows the simulation of different management scenarios and to predict the effects of potential future policies to be implemented in these aquifers. Also, it is possible to add in the model different management infrastructures and to visualize the benefits and impacts (Figure 7). Groundwater flow models had been already developed for the Main Aquifer, referred to as Lower Aquifer in previous works (Custodio et al., 1971; Cuena and Custodio, 1971; PHPO, 1985; Iríbar et al., 1997) and, more recently, as the Main aquifer (UPC, 1997). Upper aquifer has also been simulated in different works (UPC, 1998). The detail reached in each of these models is different and the most recent include all human infrastructures in the area. This is out of the scope of this work as in this case only the general behavior is being simulated. These previous models are used to corroborate the results of this present generic modelization work.

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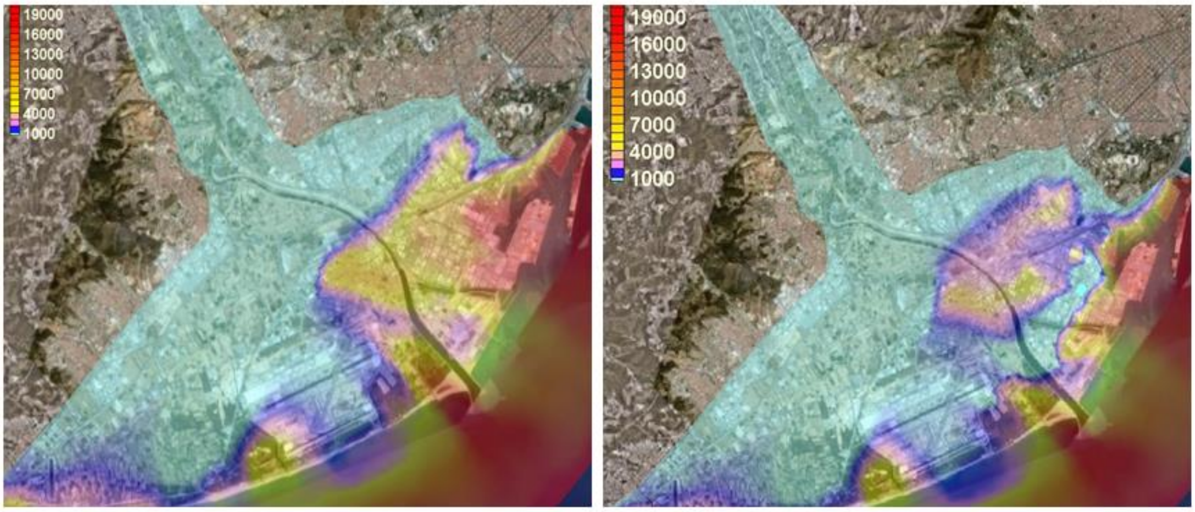

Figure 7: Simulated chloride concentration distribution in Llobregat Delta in 2035 without prevention measures (left) and considering managed recharge facilities (right) (Vázquez-Suñé, 2006).

Water budget

Basically the recharge in the Delta aquifer comes from surface infiltration, external contributions from other aquifers, water intrusion from the sea and river infiltration. Additionally, also MAR facilities have to be taken into account as recharge inputs.
On the other hand, the main water outputs are through pumping extractions and exits into the sea.
All the data shown below have been obtained from bibliographic works.

Inputs

Average precipitation in the Llobregat Delta Area is around 550 mm/year. Infiltration rate can be considered between the 10-20 % of the precipitation, resulting in a mean aquifer recharge of 100 mm/year (Jordana et al, 2008).

The input from river infiltration has been calculated in previous numerical models and ranges between 3 Hm3/year and 15 Hm3/year (Vazquez-Suñé *et al*., 2006; ACA, 2009 and Cetaqua, 2015b).

Other external contributions that are considered in this area are:
- Lateral contribution from the rock materials located at the lateral sides of the delta (lateral recharge).
- Contribution by the aquifer located upstream of the aquifer (upstream aquifer recharge).
- Contribution undertaken by the seawater intrusion.
- Recharge from the MAR installations and activities.

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Outputs

The main groundwater outputs are through wells abstraction and discharge to the sea. Figure 8 shows the registered groundwater abstraction through the years disaggregated per types of users.

The sustainable exploitation rate to avoid further groundwater deterioration is calculated to be around 40Mm^3 (Vázquez-Suñé *et al.,* 2006) which is usually exceeded.

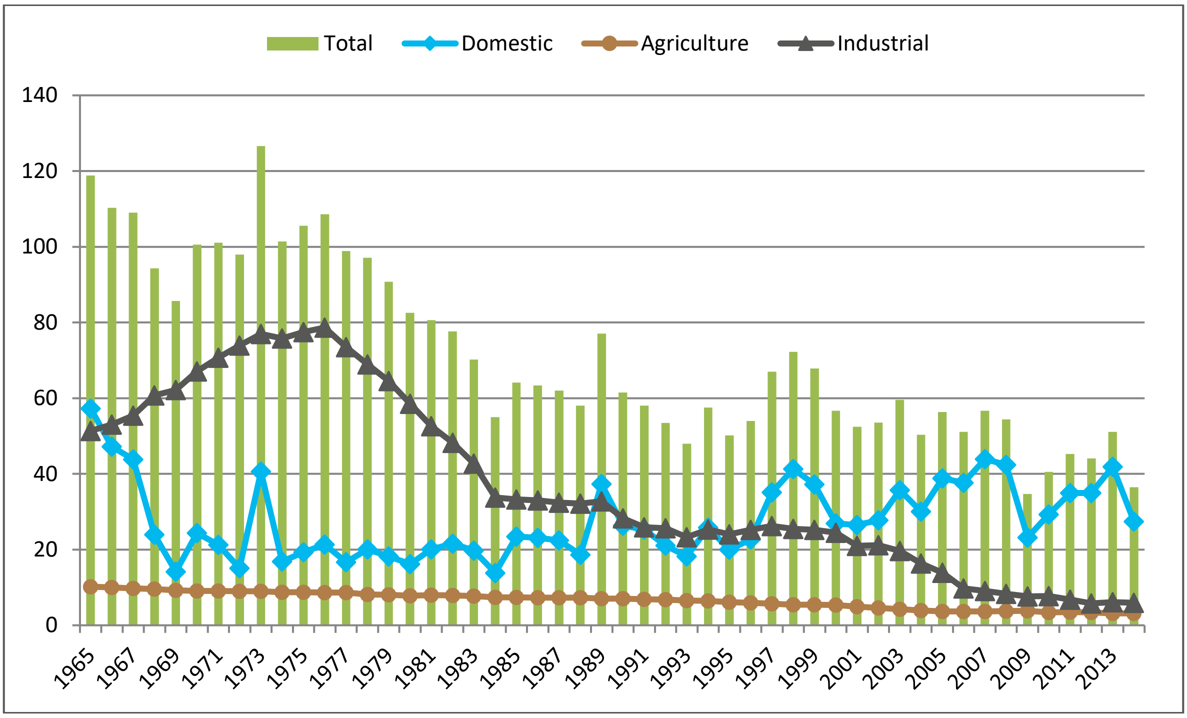

Figure 8: Record of abstractions (Mm^3) from the aquifer registered by CUADLL (from Cetaqua, 2016)

Budget calculations

The calculation of total water budget of the area differs among different authors. This is attributed to the fact that the abstractions in each area are not very well known, some of the parameters are calculated using different methods and approaches and besides, some parameters of the budget can be estimated individually or grouped.

Cetaqua (2016) calculated the water budget between the years 1965-2013 (Table 2). All inputs contributions (surface recharge, external contributions, water intrusion contribution, river infiltration and artificial recharge and contribution by the aquifer located upstream) were taken into account separately. Outputs were grouped without any differentiation between pumping extraction and sea outputs. In addition inputs and outputs have the same value, with the result that there is no variation in the aquifer storage.

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Table 2: Water Budget calculated by CETAQUA (2016)

	PARAMETER	Hm^3
Inputs	Lateral contributions	14
	River infiltration	21
	Surface infiltration	34
	Aq. upstream contributions	7
	Seawater intrusion	6
	Artificial Recharge	3
Total		**85**
Outputs	Well pumpings + sea outputs	**85**
S (Hm3)		0

Vazquez Suñé et al. (2006) calculated the budget for the period 1966-2001 (Table 3) . Authors summarized all inputs in river infiltration, lateral contributions and seawater intrusion, Outputs were also grouped. In this case the storage variation of the aquifer presented a positive variation

Table 3: Water Budget calculated by Vázquez Suñé et al. (2006)

	PARAMETER	Hm^3
Inputs	Lateral contributions	30.25
	River infiltration	19.74
	Seawater intrusion	7
Total		**56.99**
Outputs	Well pumpings	**52.1**

Finally the water balance undertaken by ACA (ACA, 2009) for the period 1966-2006 has been also considered (Table 4). In this balance inputs parameters were separated into river infiltration, lateral and upstream contributions from other aquifers and artificial recharge. Only pumping extraction was taking into account as outputs and the budget was not closed. Sea water interactions have not been taken into account.

Table 4: Water Budget calculated by ACA (2009)

	PARAMETER	Hm^3
Inputs	Lateral + upstream contributions	21.5
	River infiltration	16
	Surface infiltration	5.2
	Artificial Recharge	5
Total		**47.7**
Outputs	Well pumpings	**13.6**

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3.3 Numerical model

Introduction

A synthetic numerical model of a deltaic aquifer has been developed in MODFLOW 4.2 code using real data obtained previously from the bibliography. Visual MODFLOW is finite differences numerical flow model that allows solve conservative transport using MT3DMS (Harbaugh, 2005). The election of this code was based on its worldwide popularity. It is a useful and user-friendly software where the introduction of geometries and parameters is easy as well as to obtain results and balances.
Using the conceptual model described before, a synthetic deltaic aquifer was created, and this aquifer reproduces the main characteristics of a coastal overexploited aquifer. The aquifer characteristics and subsurface flow have been based on the Delta del Llobregat Aquifer. Flow and transport modeling have been assumed with constant density because MODFLOW does not allow to solve variable density.

Spatial discretization

Model domain has been created using a pseudo-form that assimilates the deltaic form of the Llobregat Delta (Figure 9). The permeable area has also been divided in two aquifer separated by a low permeability layer (aquitard). The dimensions are 15 x 15 km and 70 m of thickness. The domain has been discretized in 80 files and 80 columns with a cell width of 20 m. The model has been divided vertically in three hydrogeological layers that represent a three-layer aquifer with a 23.33 m thickness per layer. In order to obtain more precise results, the intermediate layer has been discretized more accurately. The topography has been simplified using a constant slope for all layers. The used slope has been 0.06º.

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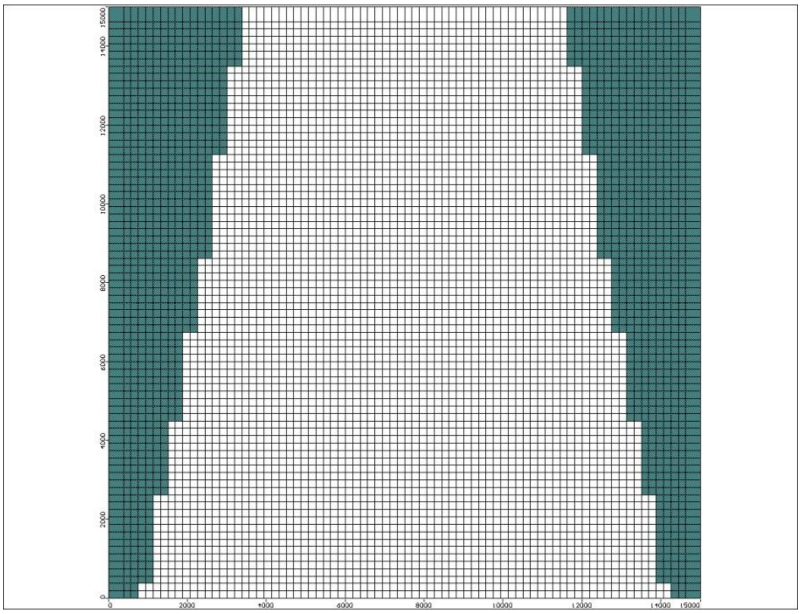

Figure 9: Geometry and domain of the model

To simulate the groundwater abstractions and the impacts of the MAR, the total main aquifer pumping has been grouped in 5 wells. These are the extraction wells E-1 to E-5 in Figure 10. The wells that are used to simulate groundwater recharge have been distributed both upstream (from I-6 to I-10) of the extraction wells and downstream (from I-1 to I-5).

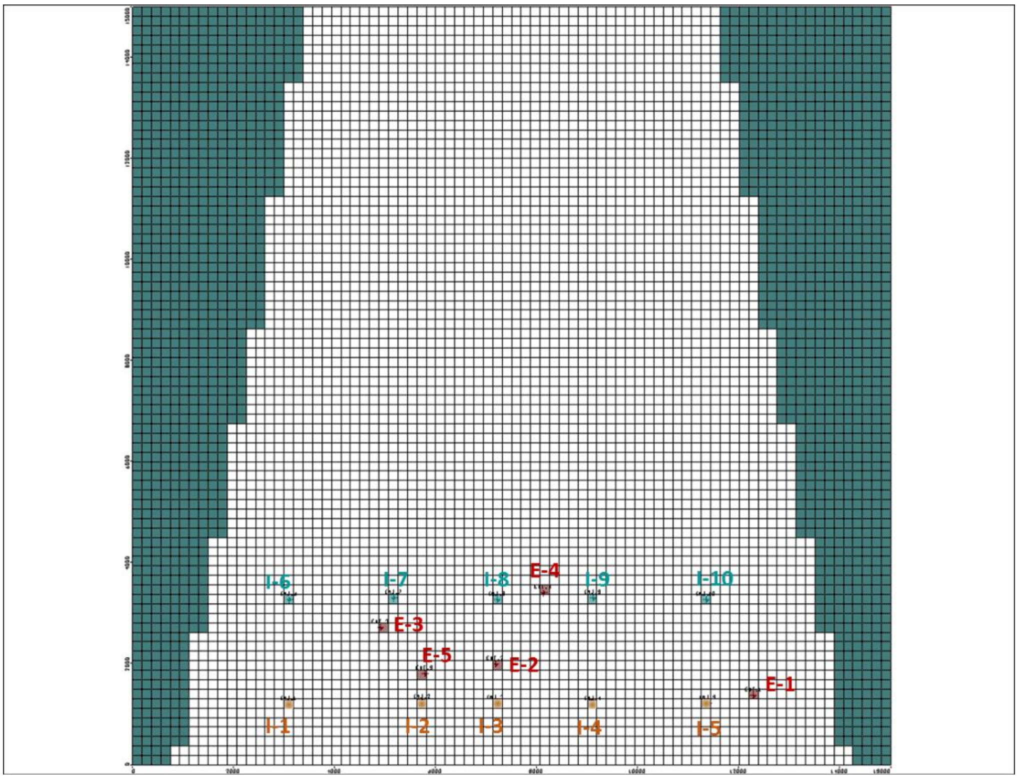

Figure 10: Location of wells (E: extraction, and I: injection) in the model

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Flow and transport parameters

The hydraulic parameters found in the literature have been simplified and averaged values have been used.

Numerical model requires the introduction of the following values: Conductivity (Kx, Ky, Kz), total porosity, effective porosity, specific storage and specific yield.

Two conductivity zones have been differentiated into the model. The first conductivity zone has been assigned to the aquifer layers (layer inferior and superior) with a value of 400 m/d in Kx and Ky. Instead, the Kz permeability is lower and the entered value has been 1/10 in order to simulate the vertical variation of permeability in layered sedimentary aquifers. The layer located between the two aquifers has been considered as an aquitard and a value of 0,001 m/d has been used for Kx and Ky while vertical conductivity has been of 0,0001 m/d.

Porosity and storage parameters have been implemented taking into account the aquifer material and its position into the aquifer (shallow and deep aquifer versus unconfined aquifer and confined aquifer) (Table 15). The two aquifers are connected in the upstream sector, where aquitard does not exist (simulating the conditions of the Delta del Llobregat) (Figure 3 and Figure 11).

Table 5: Porosity and storage parameters

Aquifer	Ss	Sy	Effective porosity	Total porosity
Shallow aquifer	0.017	0.015	0.015	0.3
Aquitard	0.001	0,002	0.001	0.3
Deep aquifer	1 E-06	1 E-06	0,01	0.3

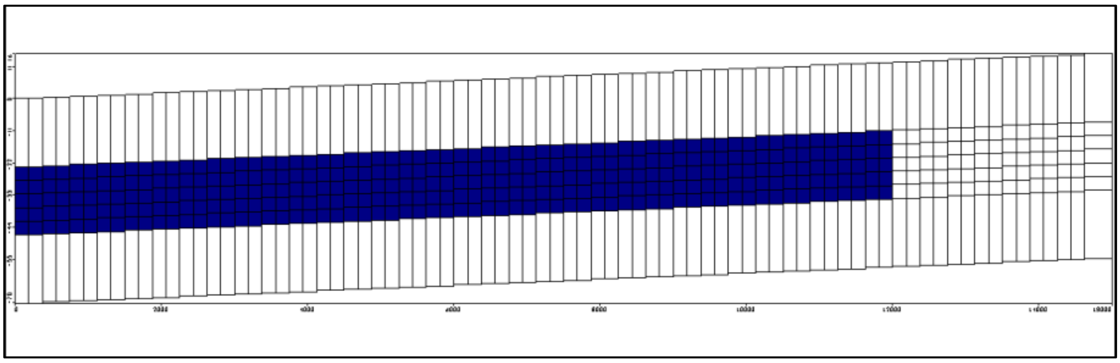

Figure 11: Cross-section of the aquifer. Aquitard materials are indicated in blue color while shallow and depth aquifer are in white color.

To simulate transport of seawater intrusion not only porosity needs to be taken into account. Dispersion of solute elements into the aquifer has also to be considered. A value of longitudinal dispersivity of 37 m has been implemented while the transversal dispersivity has a value of 1/10 of longitudinal dispersivity and the vertical dispersivity a value of 1/100 of longitudinal dispersivity.

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Boundary conditions

Flow from lateral boundaries (east and west sides) has been considered zero (rocky boundaries), no flow boundary condition has been implemented into the model.

To simulate natural recharge by precipitation, fixed flow has been imposed above model surface. This recharge has been assumed constant and homogeneous in the entire domain (separation between urban, agricultural, etc areas has not been taken into account due to the generic approach). The value of the total recharge implemented in the numerical model is very similar to that value of the Llobregat conceptual model (100 mm/year).

The relationship with the upstream aquifer has been simulated using a constant head boundary condition (5 m of head level). This boundary condition has allowed the simulation of the lateral contribution of the upstream aquifer. The sea is located downstream of the aquifer, a constant head boundary condition has been also used to simulate the sea level. In the eastern side of the model the boundary head condition is also located in three cells of the east lateral boundary (to simulate the harbour area). Coastline has a head of 0 m but this level has been corrected in order to take into account the value of salt water density (1.025 g/cm3), after multiplying this value by the depth of the aquifer (70 m) the value of head in the coastline was corrected to 1.75 m.

Cauchy boundary condition has been implemented to simulate the river effect (reproducing the similar behavior observed in the Llobregat River). *River Package option* has been used and this method allows the simulation of the interaction between the river and the aquifer across a permeable riverbed. To calculate this boundary condition Visual MODFLOW uses the following parameters:

$$C = \frac{KLW}{M}$$

Where:

- C is the value of conductance,

- K the vertical conductivity of the riverbed material,

-L is the length of the cell and

- W is the width of the river in a model cell.

M has value of 0.5 m, and the conductivity of the riverbed materials has a value 0.01 m/d (Jordana et al, 2008).

Modflow parameter STAGE has been used to calculate the head level of the river. More specifically, the maximum value in the northern boundary is 16 m while the minimum value is 0 in the sea. River Bottom parameter has an initial value of 14 m and -2 m in the sea connection.

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Recharge water from precipitation has a constant chloride concentration of 10 mg/l. River concentration is around 297 mg/l (based on real values). Sea boundary condition has constant concentration boundary condition of 13000 mg/l and upstream boundary condition has a fixed concentration of 364 mg/l. All these values have been extracted from bibliographic works and monitoring data in the Llobregat area.

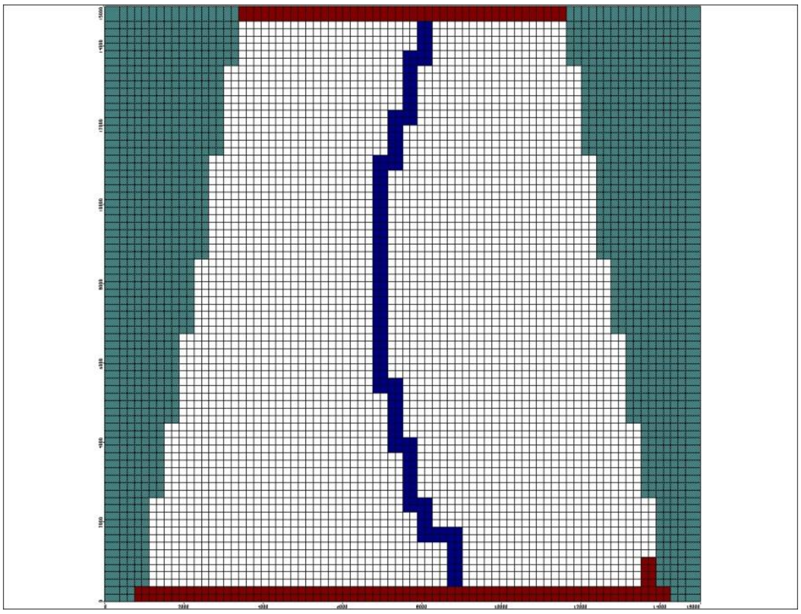

Figure 12: Boundary conditions. River boundary condition (blue), upstream constant head boundary condition and downstream or sea coastline boundary condition (brown). Green cells are not activated and the contact of these green cells with the aquifer is of no flow boundary condition.

Base case (Steady state)

The steady state case considered as the Base Case has been developed. The results of this simulation have been approximated to Llobregat present conditions. As a consequence, this scenario shows the over-exploitation conditions where the aquifer has severe seawater intrusion due to all groundwater abstractions and harbor construction.

The total present groundwater pumping has been divided in 5 wells distributed roughly around the main present exploitation focus (Figure 13). As a result, five zone wells have been implemented in the model mainly close to the sea coastline except one that has been located in the eastern sector, near the harbor area. Wells are exploiting the main (deep) aquifer and total pumping flow considered in the model is 51.1 Hm3/year, representing an important overexploitation. The initial chloride concentration of the aquifer is 297 mg/l (based on real values).

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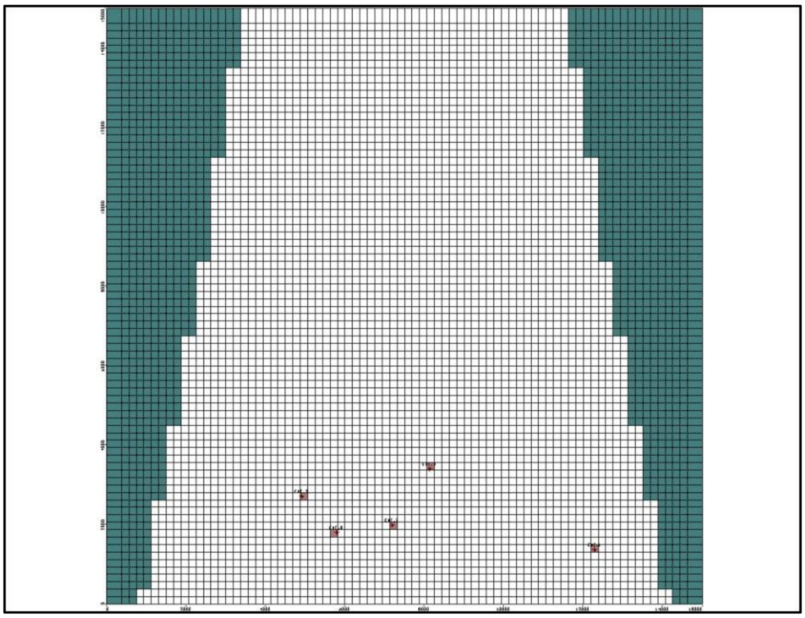

Figure 13: Location of the five extraction well areas.

Figure 14 shows head and chloride concentration variations in the deep aquifer. Salinization of the aquifer reaches the wells located near the coast, between 1700 and 2000 m. Eastern boundary presents a more penetrating seawater intrusion due to the harbor construction that connected both aquifers and changed natural hydraulic parameters.

Figure 15 shows a cross section from the coastland to the extraction well E2 (Figure 10). As it can be observed in this figure, the effect of the salinization into well is also noticeable and this is the most inland position of the saline interface. The effect of the seawater intrusion is more restricted in the shallow aquifer. This is attributed to the fact that all well extractions are located in the deep aquifer, decreasing the intrusion effect in the shallow aquifer. Also aquifer discharges to the sea are more important in the shallow aquifer. Contribution of the river into the shallow aquifer (upstream sector) can also be observed in Figure 16.

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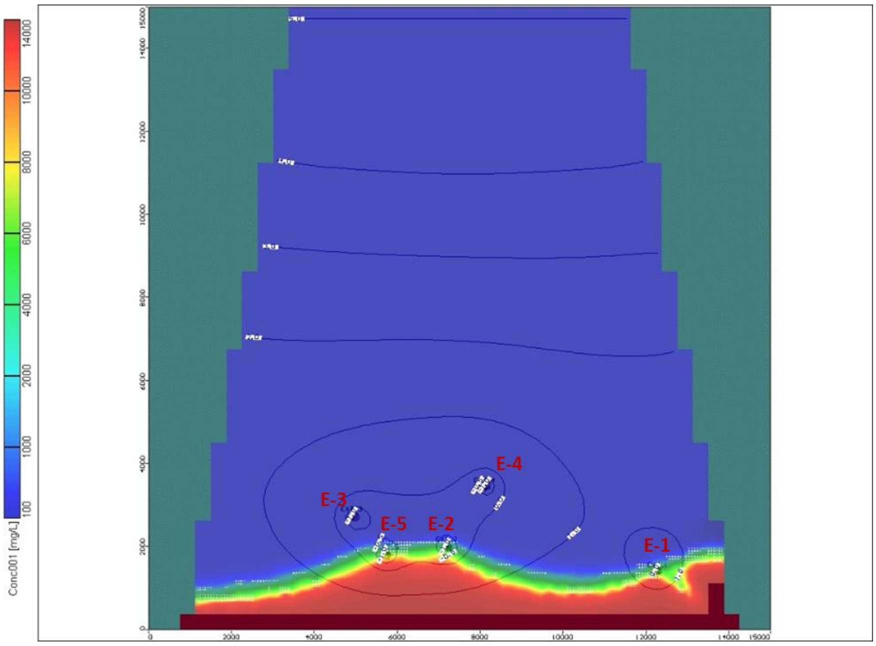

Figure 14: Head and Cl concentration levels simulated in the deep aquifer.

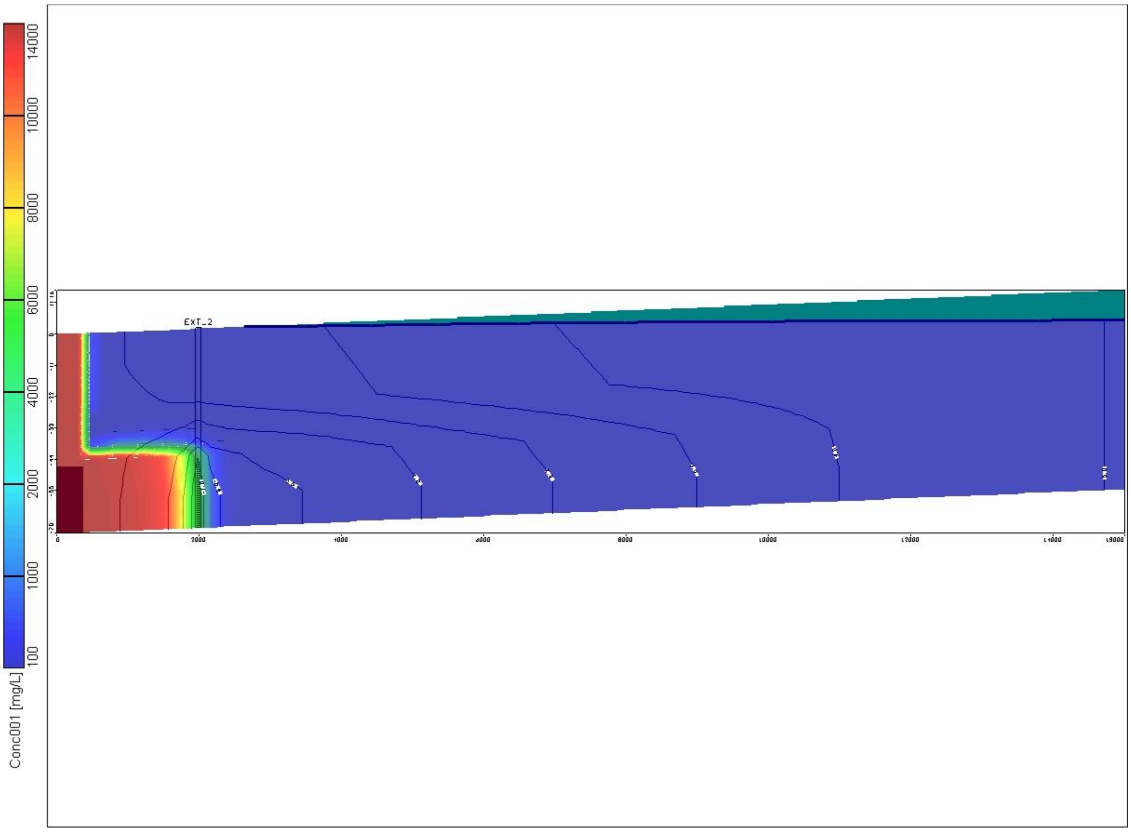

Figure 15: Cross section of simulated head and concentration levels in extraction well E2.

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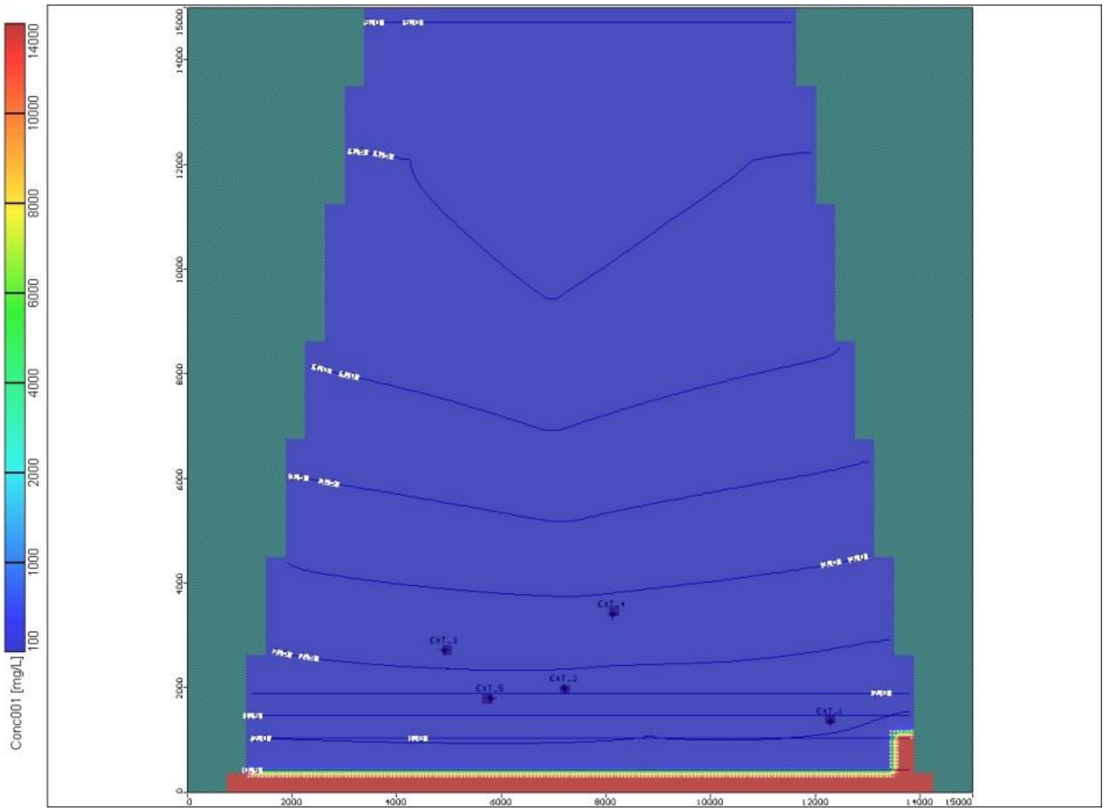

Figure 16: Head and Cl concentration levels simulated in the Shallow aquifer.

The total water budget of the model has been calculated in this steady state solution. This calculation includes both aquifers.

There are four main different water contributions into the model:

- The constant head condition located upstream of the model is considered as an input to the model (from other upstream aquifers)
- The river has a permanent influent (recharging) condition
- The surface recharge from precipitation
- The seawater intrusion to the deep aquifer.

The main outputs estimated in this model are two:

- Output to the sea (shallow boundary condition) through the shallow aquifer
- Wells withdrawals.

One of the most relevant issues that can be observed in this budget is the relationship between the wells extraction and seawater intrusion. It has been estimated that in these 5 extraction wells, the

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71.2 % of the pumped water comes from the sea. The influence of the river on wells located nearby is noticeable minor.

Table 6: Warter budget parameters

	CONTRIBUTION	RATES (m3/day)	Rates (Hm3/year)
INPUT	Constant head	23988	8.8
	River	15905	5.8
	Recharge	41378	15.1
	Seawater	99856	36.4
	TOTAL	**181130**	**66.1**
OUPUT	Sea Shallow boundary	39250	14.3
	Wells	140000	51.1
	River	1854.2	0.7
	TOTAL	**181100**	**66.1**

Scenarios

The base case is the steady state solution with seawater intrusion due to well extractions. This represents almost the present situation in Llobregat Delta.

Time simulation has been fixed in 20 years in order to arrive at pseudo-steady state conditions. The time step has been fixed at one month (30 days).

The objective of the different scenarios is to test the feasibility of MAR to avoid saline intrusion in the aquifer and to visualize the positive impacts. This simulation has been done using injection points (Figure 10) with variable injection volumes.

After testing different injection volumes a total volume of 25 Hm3/year has been implemented in the scenarios 1 and 2. This recharging volume represents the 50 % of the extracted water by wells. In addition volumes around 20 Hm3/years were injected in the Delta del Llobregat in different MAR facilities.

Scenario 1

An injection barrier of five injection wells located at 1200 m of the coastline has been simulated. These are the points I-1, I-2, I-3, -I4 and I-5 of the Figure 10.

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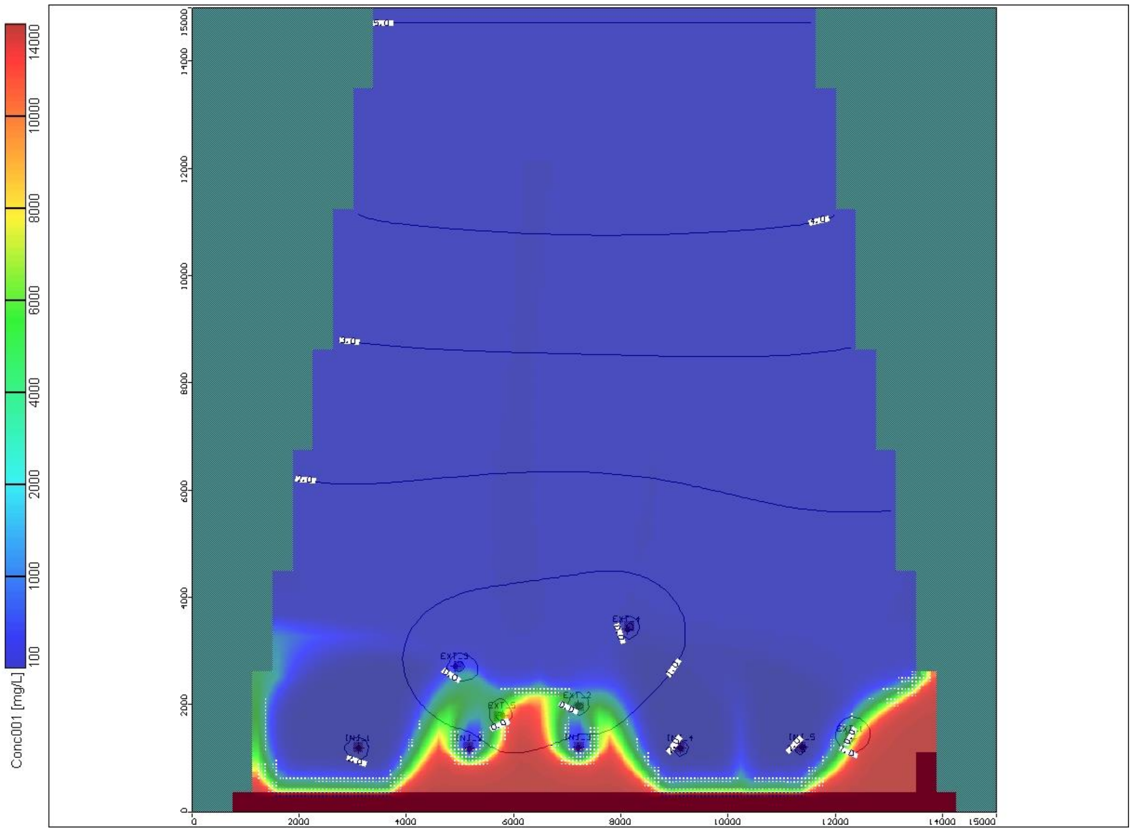

Figure 17: Head and Cl concentration levels simulated in the deep aquifer in the scenario 1 (after 20 years).

When there are no extraction wells between the injection and the coast, the recharge creates a real barrier and a real backward movement of the seawater intrusion. On the other hand, wells located directly between extraction wells and the seacoast create apparently only a local effect on the chloride concentration.

After the 20 simulated years of injection in these five wells, a real change can be observed in the budget (Table 7). Sea water intrusion has decreased from 36 Hm3/year (Base case) to 12 Hm3/year and a total of 24 Hm^3 (representing 94% of the injected water as it is 25.5 Hm3) has been enough to stop the water intrusion.

Table 7: Water budget parameters for scenario 1

CONTRIBUTION	RATES (m3/day)	Rates (Hm3/year)
Storage variation	0.17278	0
Constant head	28349	10.35
Wells	70000	25.55
River	16022	5.85
Recharge	41378	15.10

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Seawater	33072	12.07
TOTAL	**188820**	**68.92**
Storage variation	0.41466	0
Constant head	43459	15.86
Wells	140000	51.10
River	2176.4	0.79
Seawater	3185.3	1.16
TOTAL	**188820**	**68.92**

Scenario 2

An injection barrier of five injection wells has been implemented upstream the wells extraction area (3300 m from the sea). These are the wells I-6 to I-10 in Figure 10.

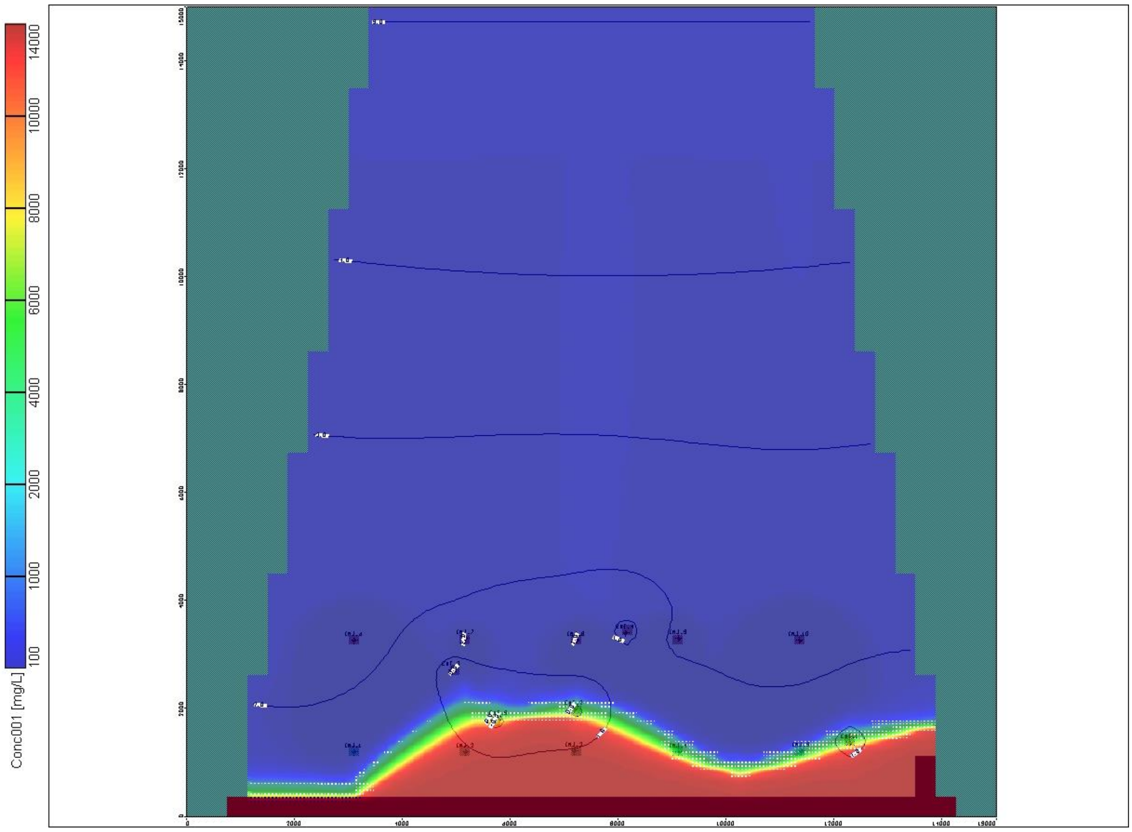

Figure 18: Head and Cl concentration levels simulated in the deep aquifer in the scenario 2 (after 20 years).

Main changes are observed in heads after 20 years of injection with a decrease of the extraction cone (Figure 18). On the other hand, the seawater intrusion does not show evident changes in terms of salinity areal distribution in the deep aquifer.

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After the implementation of the five injection wells (after 20 years of injection) a real change can be also observed in the water budget. Seawater intrusion has decreased from 36 Hm^3/year (Base case) to 15 Hm^3/year. In this case, 21 Hm3 from the water injection (25.5 Hm^3) have been used to stop the water intrusion.

The scenario 2 has a minor degree of effectivity in terms of the mass balance rather than scenario 1. Furthermore, this scenario is ineffective from the point of view of areal distribution of the water intrusion.

Table 8: Water budget parameters for scenario 2

CONTRIBUTION	RATES (m3/day)	Rates (Hm3/year)
Storage variation	0.15814	0
Constant head	19504	7.12
Wells	70000	25.55
River	15921	5.81
Recharge	41378	15.10
Seawater	41379	15.10
TOTAL	**188180**	**68.69**
Storage variation	0.42582	0
Constant head	44368	16.19
Wells	140000	51.10
River	2202.7	0.80
Seawater	1611.4	0.59
TOTAL	**188180**	**68.69**

Scenario 3

A scenario where all injection points are working (from I-1 to I-10) and where the total injected volume is the double than in the previous scenarios (50 Hm^3/year) has also been simulated.

As it can be observed in Figure 19 this is the scenario that yields better results in terms of seawater intrusion. But these recharging volumes are unrealistic and, hence, the model should be used to find the better configuration to get the optimum seawater recession with a reasonable water injection volume.

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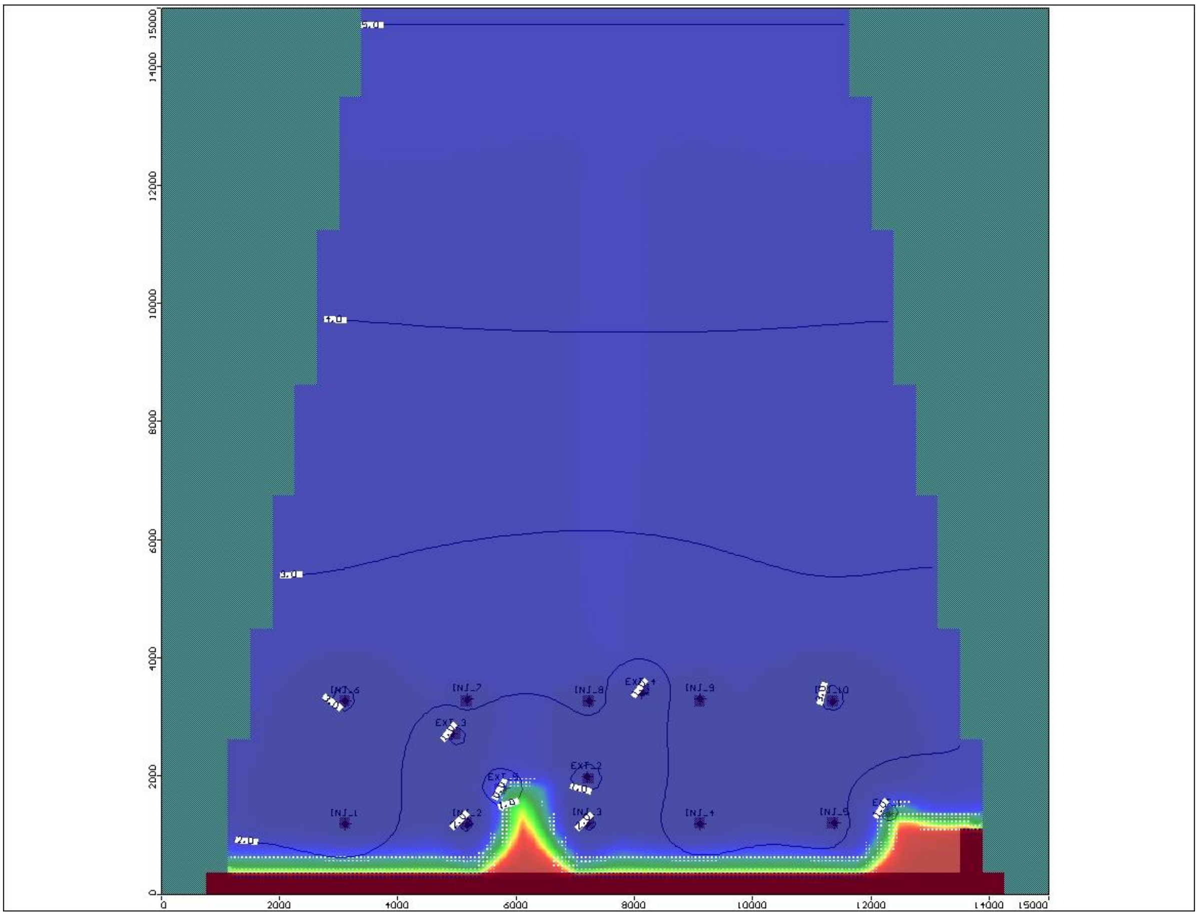

Figure 19: Head and Cl concentration levels simulated in the deep aquifer in the scenario 3 (after 20 years).

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SUMMARY AND CONCLUSIONS

A synthetic numerical model has been built to simulate the positive impacts over groundwater quality and quantity in a typical Mediterranean deltaic aquifer.

The main objective of this numerical model is to bring an easy visualization tool to MAR implementers and to administration to easily evaluate the benefits and impacts of MAR technology in a typical deltaic aquifers. This tool intends to help to overcome one of the barriers of the MAR implementation related to the difficulty to evaluate the feasibility of this technology without site-specific studies and numerical models development. The model, indeed, takes into account the interaction between surface and groundwater.

The model has been developed for a generic aquifer and based on Llobregat delta aquifer. The model intends to reproduce the main hydrogeological characteristics of these aquifer types and the general trends. In a similar way, it reproduces the effects of the technology in a generic way without taking out minor local characteristics. In this way, the change of few parameters allows to assimilate the model to other aquifer type and to evaluate, in general terms, the benefits.

The numerical model has been based on the conceptual model of the Llobregat Delta aquifer and has been developed in Modflow code for flow and solute transport.

The model has shown that the best location for injection wells to mitigate saline intrusion is between extraction points and the sea. The deep injection in Cornellà wells has minor effects over seawater intrusion.

The different model scenarios can be visualized in Amphos 21 web page. It offers an interactive way to choose different parameters of deep MAR (wells location, injection flow, aquifer parameters) and to observe the video with the impacts along time.

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