Good practices of groundwater management in a scarcity context

Project AQUIFER (INTERREG-SUDOE)

Innovative instruments for the integrated management of groundwater in a context of increasing scarcity of water resources.

Report editors

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1-INTRODUCTION

Groundwater systems are replenished by precipitation and surface water. They discharge into surface waters, the ocean or, in small part, by evapotranspiration back into the atmosphere. Groundwater circulation globally is less than atmospheric and surface waters but what is stored beneath Earth's surface is orders of magnitude larger. Its total volume represents 96% of all Earth's unfrozen fresh water (Vaux, 2011).

Groundwater is often a stable and important drinking water resource, and in many places around the world it is a prerequisite for economic growth; in fact, 50% of the world's population depends on groundwater.

Even though large volumes of fresh groundwater are present below the ground surface and distributed across the entire globe, their abundance and the conditions for their withdrawal are subject to considerable spatial variation. In order to be productive, wells have to extend into geological formations that are characterised by comparatively high porosity and permeability (aquifers) and filled with fresh groundwater. Furthermore, the suitability of a certain location or zone for groundwater withdrawal depends on the rate of replenishment of the tapped aquifer (groundwater recharge) and on water quality. Recharge enables groundwater to be abstracted sustainably; if it is absent or minimal, then groundwater abstraction depletes the stored groundwater volume (UNESCO, 2022).

Most uses of groundwater are consumptive or involve a degradation of water quality when returned to the system of shallow groundwater circulation. The stock of groundwater is generally reduced and the subsequent quality in the all-important shallow aquifers is degraded. There is frequent and increasing over-exploitation of aquifers, notably of the coastal aquifers, a fact that causes marine water intrusion (Aureli et al., 2018). This process will be difficult to reverse, and it has also caused streams to dry up and weakened or destroyed aquatic ecosystems.

In the longer term, prolonged abstraction beyond the rates of recharge will involve fundamental changes to the dynamics of aquifer systems. This interdependency of uses and impacts is fundamental and should be kept in mind throughout subsequent discussions about the key services groundwater provides and the problems facing sustainable management of these resources (Burke et al., 1999). In order to ensure future water security, there is a need for trustworthy, reliable and accurate assessment methods to identify the withdrawal impacts on groundwater resources (Gejl, 2019).

For all the reasons discussed above, groundwater is a critical resource enabling adaptation due to land use change, population growth, environmental degradation and climate change. It can be a driver of change and adaptation, as well as effectively mitigating the impacts of a range of human activities (Lapworth et al., 2022).

Groundwater is also the source of most of the water used for irrigation, supports industries and agriculture, and contributes to rivers, lakes, springs and streams baseflow, moderating the influence of periods of low precipitation. But groundwater is more than a resource. It is an important feature of the natural environment and can provide an important contribution to the water that supports many wetland ecosystems and has a strong influence on the large variety of habitats.

On the other hand, it can also lead to environmental problems but may in many cases offer a medium for environmental solutions. It is part of the hydrologic cycle, and an understanding of its role in this cycle is mandatory if integrated analyses are to be promoted in the consideration of watershed resources and in the regional assessment of environmental contamination. It is a natural resource for the present and future generations (Barreiras, 2020).

The multiple services offered by groundwater

As stated above, groundwater withdrawal for human use is very important but it corresponds to only one category of the services offered by groundwater systems. These services are outlined in Figure 1. Most of the services mentioned are self-explanatory but a few additional comments are set out below.

- Provisioning services allow groundwater to be withdrawn for water use purposes, but in some cases withdrawal is merely for extracting the geothermal energy it carries, after which the abstracted water is returned to the subsurface.
- Regulatory services are in-situ services that reflect the buffer capacity of aquifers, they mainly regulate the groundwater systems' water quantity and water quality regimes.
- Supporting services are in-situ services, too; they are focusing on groundwater-dependent ecosystems (GDEs) and other groundwater-related environmental features.
- Finally, groundwater also provides cultural services; those linked to leisure activities, tradition, religion or spiritual values and are associated with particular sites rather than with an aquifer.

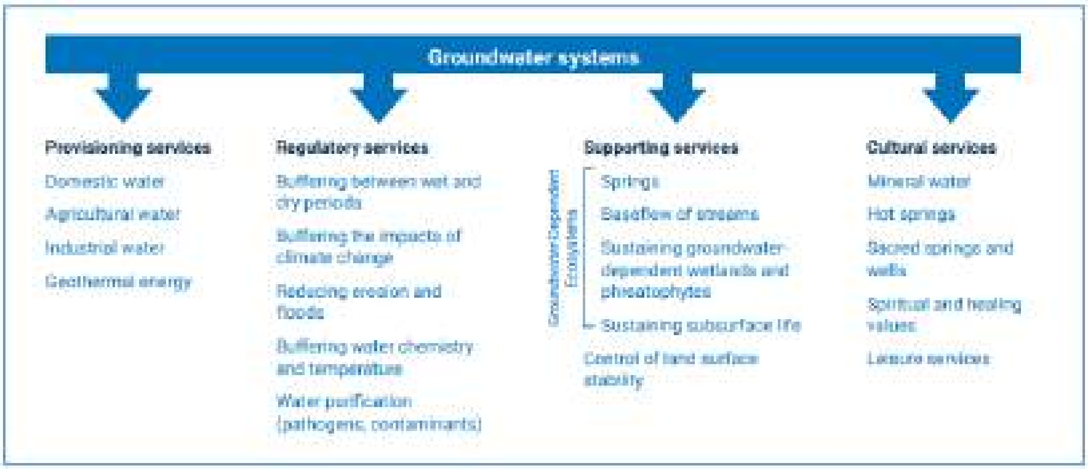

Figure 1. The multiple services offered by groundwater systems. Source: UNESCO, 2022.

Provisioning services are potentially in conflict with supporting services as the latter tend to become stressed under intensive groundwater withdrawal. Groundwater governance and management must pursue an optimal balance between conflicting or competing services.

Groundwater and the Sustainable Development Goals

In addition to the multiple services groundwater systems offer, it is an important resource for achievement of the UN Sustainable Development Agenda for 2030, yet it is poorly recognised and weakly conceptualised in the Sustainable Development Goals (SDGs) (Guppy et al., 2018).

Groundwater could be important in ensuring access to water and sanitation for all (Goal 6) as well as contributing to several other goals: poverty eradication (Goal 1), food security (Goal 2), gender equality (Goal 5), sustainability of cities and human settlement (Goal 11), combating climate change (Goal 13), and protecting terrestrial ecosystems (Goal 15).

Groundwater is explicitly referenced only once – in the targets of Goal 6. Even so, there are potential relationships between groundwater and many other targets, meaning that achievement of the targets would have a positive impact on groundwater. Yet the few conflicting relationships where achievement of a target would have a negative impact on groundwater are important because conflicting relationships are the most critical and difficult ones to manage. The most important potentially conflicting relationship may be that between groundwater and some of the targets for food security (Goal 2), including ending hunger and doubling agricultural productivity (Gleeson et al., 2020).

Finally, global pressure on groundwater resources is increasing sharply and is critically threatening associated ecosystems, particularly in the SUDOE zone. For the inhabitants of the Mediterranean region, the exploitation of groundwater largely contributes to the current water supply, both for drinking and irrigation purposes (Aureli et al., 2018). Increasing demands in the context of growing water scarcity means that groundwater is currently an essential and strategic resource in hydrological and environmental planning.

The scientific community has established that it is necessary to improve knowledge of aquifers, the implementation of reliable monitoring networks, and the involvement of the hydraulic administration and users in the sustainable management of aquifers.

In line with this, one of the main objectives of the present AQUIFER project is to test, disseminate and transfer innovative practices for the preservation, monitoring and integrated management of aquifers that are helpful when making decisions on the management of groundwater resources, improve technology transfer to local agents, create new synergies and develop common tools in the context of scarcity of water resources and environmental threats.

2-THREATS AND CHALLENGES

Groundwater storage depletion occurs when discharge exceeds recharge. Although climate variability and climate change can play a role, most cases of long-term groundwater storage depletion result from intensive abstraction. The rate of global aggregated groundwater storage depletion is considerable: since the beginning of the current century, the estimates are mostly between 100 and 200 km^3/year (accounting for roughly 15 to 25% of total groundwater withdrawals) (UNESCO, 2022).

Historically, groundwater quantity has often been the focus of groundwater resource assessments and there is a real need to now focus more attention on groundwater quality. There is a direct connection between stores of available freshwater provided by groundwater and their status and utility in terms of quality (Gleeson et al., 2020). The excellent quality provided by groundwater in many regions, often reflecting the degree of protection from surface contaminants that groundwater provides, is critical for sustaining agriculture, industry, and drinking water, and is fundamental to reaching the key SDGs.

Even so, the necessary degree of protection is often not achieved. There are many sources of anthropogenic groundwater pollution; most of them are located at or near the land surface, but several other sources inject pollutants into the subsurface at greater depths below the surface. Agricultural pollution is widespread, it is a diffuse source that often includes large quantities of nitrate, pesticides and other agrochemicals. It depends on the type of contamination, but groundwater pollution is a virtually irreversible process; once polluted, aquifer zones tend to remain polluted (UNESCO, 2022).

A major societal challenge is decreasing the gap between research and practice in sustainable water resource management, or at least creating a common ground with fewer barriers to solving real-world problems. It is important to build a balanced dialogue between scientists, engineers, stakeholders, decision makers and end-users to generate reliable design knowledge in the context of nature, socio- and eco-responsibility, governance and ethics. The characterisation, design, planning, monitoring, evaluation and management of water resources must include integrative sustainable methodologies and nature-based solutions (Chaminé et al., 2019).

2.1-Threats and challenges due to the resource decrease

The decline of water resources has been observed as a general trend in many regions of the globe. It is already occurring and is expected to worsen in the SUDOE region. This decline in water resources can be affected by interdependencies between pollution and overexploitation due to increased water abstraction (caused by increased water use and population growth) and decreased infiltration of surface water. If an aquifer is overdrawn, nutrient and chemical concentrations may increase because the contaminants will be less diluted. At the same time, over-abstraction in water-stressed areas can lead to groundwater contamination if saline or contaminated water is introduced into the aquifer (Cantor *et al.*, 2018).

Studies have measured groundwater storage changes over the period 2003–2020 in the Euro-Mediterranean region using the latest data from the Gravity Recovery and Climate Experiment (GRACE/GRACE-FO) satellite mission and the recently re-analysed ERA5-Land climate data from the European Centre for Medium-Range Weather Forecasts. Analysis of annual mean trends over the study period shows significant decreases in groundwater storage in many countries in Europe, North Africa and the entire Arabian Peninsula. Overall, there are significantly negative trends in about 70% of the study region. The average trend across the entire Euro-Mediterranean region is -2.1 mm/year. The results are a clear indicator of groundwater stress in the medium term in the Euro-Mediterranean region, which is expected to increase in the future, and demonstrate the need for adapted strategies for sustainable groundwater management on a trans-regional scale in the context of climate change and population growth (Xanke *et al.*, 2022).

Some of the most important effects of the diminished amount of freshwater in the underground reservoirs are as follows:

- Declining piezometric levels: One of the most important consequences of declining piezometric levels is decreasing water resources. This occurs when water outflows from an aquifer exceed inflows. This is either due to an increase in outflows, such as groundwater abstractions for different uses, or a decrease in inflows, mainly due to a decrease in rainwater infiltration due to the effects of climate change, or both at the same time.

- Decrease in water quality: In proper amounts, waterbodies act as a natural buffer as they are capable of diluting the concentration of pollutants. However, this ecosystem service is reduced in episodes of diminution of water flows or volumes. In these situations, the presence of pollutants tends to increase due to the concentration effect. In the event of water scarcity, the decrease in the water quality exacerbates the situation as it decreases the quality of a water resource that is already scarce in terms of quantity.

- Reduction of the water supply in surficial environments: As many of the surficial water-related ecosystems intersect and are fed by groundwater systems, a decrease in the amount of groundwater in terms both of quality and quantity has a negative effect on related surficial ecosystems. This results in damage to the surficial ecosystems that has negative effects in terms of environmental sustainability, water security for humans, economic activities or ecosystem services.

- Subsidence of the terrain: As the internal pressure of the aquifer decreases due to the decrease in water levels, the newly generated spaces are compacted by the weight of the ground above. As a result, the dynamics that take place when the amount of water within the aquifer gets reduced, produce a downward vertical movement of Earth's surface. Such subsidence episodes can be dangerous when affecting surface infrastructure, such as roads or buildings, and will incur significant costs to the economy.

All these effects take place in combination with other factors. Many of them do not arise by themselves but are due to overall trends and interrelations among them. Thus, the threats and challenges of the decrease in water availability must be assessed in a multidisciplinary manner, taking into consideration not just the effects of each one of them separately, but also considering them from a combined perspective and placing special attention on other side-effects resulting from their intersection.

2.2-Responses to guarantee the availability of groundwater

The availability of groundwater as a water source depends largely upon surface and subsurface geology as well as climate. The porosity and permeability of a geologic formation controls its ability to hold and transmit water. Groundwater in aquifers is one of our most essential natural resources. In relation to actions to ensure the availability of water sources, a number of initiatives are outlined in this eBook.

A first example is the implementation of sedimentation and infiltration ponds in the riverbank of the Llobregat river that have been carried out by the Catalan Water Agency (ACA) and the Community of Users of Llobregat Delta (CUADLL). These ponds enable the infiltration to the Llobregat aquifer of large amounts of reclaimed treated water from wastewater treatment plants (WWTPs). This system is relatively cheap and can be easily replicated in many cases and regions.

Another example of this is the valorisation of stormwater promoted by the Salisbury Water Management Board (SWMB) in the city of Salisbury (Australia) in which urban treated stormwater is stored in aquifers for further non-potable uses in response to urban and irrigation needs.

A successful research example is the one carried out by the Maltese Energy and Water Agency (EWA) for the prevention of saline water infiltration in Malta through the implementation of well injection systems which, through the infiltration of properly treated WWTP effluent, achieved an increase of freshwater pressure in the aquifer, thus preventing saltwater infiltration. Similar actions have been carried out through the collaboration of the Catalan Water Agency (ACA) and the Community of Users of Llobregat Delta (CUADLL) in the Llobregat river area, where the implementation of injection wells to pump WWTP effluents (sometimes in combination with network water) has been useful in setting up a hydraulic barrier to prevent seawater ingress to the Llobregat aquifer.

Pollutants that can be commonly found in groundwater are nitrates that are generated by agricultural and farming practices. Several research and development projects have been conceived to respond to these types of pollutants. An illustrative example carried out in Catalonia has been the project INSITRATE (Life+), led by the research centre Eurecat with the collaboration of Amphos21 and Catalana de Perforacions. The aim of the project was to validate the viability of an innovative bioremediation technology enabling the elimination of nitrates present in the groundwater by enhancing microbial activity by injection of organic compounds into the groundwater flow.

In large cities, groundwater does not always meet the required standards. In such cases, the lack of groundwater may be overcome by using surface water with a filtration step through the riverbank. A paradigmatic example of this practice has been promoted by Berliner Wassebetriebe who have overseen the implementation of an initiative of RiverBank Filtration (RBF) by which water is pumped to the subsurface through the banks of a river. The river sediments act as a natural filter; hence, this system acts as a pre-treatment that can be considered a cost-effective Nature-Based Solution (NBS) that replaces chemical products with the filtering effect produced by sand and gravel near the river.

To achieve proper water quality, a balance must be struck between the water uptake and the abstraction point, along with the physicochemical characteristics of the riverbank and the possibility of clogging. At the same time, this system enables the avoidance of particles and microorganisms and reduces the needs for disinfection.

In regions where the availability of water is compromised due to a semi-arid climate, other initiatives can be carried out, such as the implementation of subsurface dams for groundwater storage. This approach has been successfully implemented in north-eastern regions of Brazil by the Cisterns Program from the Ministry of Citizenship. These subsurface dams allow water to be stored under riverbeds and be retained there for later extraction.

2.3-Threats and challenges arising from the lack of information

Groundwater accounts for 99% of all liquid freshwater on Earth. However, this natural resource is often poorly understood and consequently undervalued and mismanaged. Groundwater receives much less attention from scientific institutions in comparison to surface water, for which the amount of bibliography is much more abundant. This is mainly because groundwater resources are concealed and invisible to the main part of the population in their daily lives. That is why it was honoured on World Water Day 2022 with the slogan “Groundwater: Making the invisible visible”. In addition, taking care of groundwater resources is not a high priority for governments and policymakers, often due to a lack of information about what they really represent. Even so, groundwater resources encompass the main part of available freshwater, being a water resource of incalculable value. Communication and education on the value of groundwater is more than essential since this water resource “makes up to 99% of the liquid fresh water on Earth, not only is groundwater a vital water supply for humanity but it also sustains rivers, lakes, wetlands and ecological systems”.

In addition, groundwater has very slow dynamics and the effects of the decrease of infiltration, the increase of withdrawal and the harmful effects of pollutants are difficult to see and to quantify in the midterm.

For these reasons, anticipating potential problems is a key factor in maintaining groundwater quality and quantity and ensuring its sustainable exploitation in the future. The Water Framework Directive, which requires European Union Member States to achieve good ecological status in all water bodies by 2027, outlines the planning and management procedures of water resources and relies heavily on information collected on those resources. Additionally, in a situation of extreme events and incidents, systems must be put in place for real-time information to be provided to the authorities allowing for an adjusted response.

The Word Water Report 2022 raises the issue of the lack of groundwater data and stresses that groundwater monitoring is often a “neglected area”. It suggests that in order to improve data and information acquisition, which is often the responsibility of national (and local) groundwater agencies, it could be complemented by the private sector. In particular, the oil, gas and mining industries already own a lot of data, information and knowledge on the composition of the deeper subsurface domains, including aquifers. As a matter of corporate social responsibility, private companies are encouraged to share this data and information with public sector professionals.

2.4-Responses to gather reliable and real-time data

To overcome the lack of data on groundwater, great efforts have been made in recent years by scientists and those responsible for the sector to obtain data in real time with the aim of protecting and improving the sustainable management of invisible waters. Due to the growing trend of digitalisation, the need to properly manage the amount of data collected is also rising. An increasing number of groundwater management actors participate in the development of numerical and mathematical models and modelling techniques for complex processes. A number of success stories are outlined in this eBook.

Artificial intelligence and machine learning allow us to re-evaluate existing data, giving a new dimension to data processing and obtaining simulations at low computational cost. A success example in Spain is the Aqualearning project created by Amphos21 (using artificial intelligence in water resources management) that was the winner of the SmartCatalonia Challenge. Also, the Aquadvanced Wellwatch® is a technological solution developed by Suez and Schneider Electric that supports decision making to carry out efficient water extraction avoiding water losses and breakdowns.

In Alicante (eastern Spain), the Provincial Council developed a system capable of monitoring water resources through a system of remote management and telemetry with the help of local enterprises. The methodology applied in case of scarcity is an advanced solution and can serve as a reference to contrast and redefine management in other locations in the SUDOE region in order to improve the management itself.

The use of physicochemical data, such as for monitoring saline intrusion (a success case is the SMD (subsurface monitoring device) tool) has been very successful, but it can go further. In the GOTHAM project (promoted by the technological centre Cetaqua), the GTool tool was created in order to evaluate the integration of social aspects and many other parameters to promote consensus among all agents involved in groundwater management.

Other innovative methods contribute to cross-referencing, facilitating the exchange of data from the various stakeholders, and to disseminating information on the situation and issues. The MétéEau Nappes web platform offers more than just these innovative services; it helps groundwater management in France by providing groundwater level forecasts over a six-month period. The APRONA observatory of the Alsace groundwater in France, which manages a piezometric network of 170 points, contributes to these services with the dual objective of sharing knowledge and assisting decision-making.

Also in France, and with the collaboration eight technical partners, the AQUI-FR platform aims to implement forecasts of groundwater evolution in France, on time scales ranging from days to seasons (>6 months) and from atmospheric forecasts via standardised piezometric indicators.

In Portugal, the National Water Resources Information System (SNIRH) created a public web portal with all the available information on water resources. The system has reporting capabilities and provides technical information for several entities, from academic and public entities to private companies and consultants. The SNIRH also promotes educational content for children. The INOWAS platform, developed in the Dresden Technical University, Germany, consists of a free, web-based modelling platform for planning, assessment and optimisation of Managed Aquifer Recharge (MAR), a nature-based solution that aims at intentionally recharging the aquifers for later use or environmental benefits.

Sustain-COAST, focusing on sustainable coastal groundwater management and pollution reduction through innovative governance in the context of climate change, is a project led by the University of Crete (TUC) and consists of a multidisciplinary team of seven partners from six countries. This project aims to develop a decision support system (DSS) and a geographic information system platform accessible to water stakeholders and policy makers.

Groundwater contamination of anthropogenic origin is the result of activities developed in the land-surface and top-soil. Contaminants are transported through the vadose zone to the groundwater below, imposing severe threats to the quality of all related water resources. To deal with this problem, numerous successful ICT and modelling practices have been implemented and are outlined in this eBook. A project in Israel implemented an innovative system, the Sensoil Vadose-zone Monitoring System™, which enables continuous monitoring and water sample collection. Other specific methodologies were created by the CONDATE-Eau platform of the University of Rennes 1 in France to estimate the residence time of nitrates that move at the same speed as water by dating groundwater using CFC and SF6.

Within the framework of the Horizon 2020 program, the AquaNES project aimed to promote more sustainable water purification techniques to manage situations of water scarcity or excess, and to control the presence of micro-pollutants in the water cycle by monitoring, managing, and modelling water and transfer processes in the soil and subsoil.

In Australia, monitoring groundwater-dependent ecosystems using synthetic aperture radar (SAR) imagery is another innovative aquifer practice that is fundamental to monitoring environmental impacts to achieve effective integrated water resources management. Finally, and continuing with the use of satellites, GEO-AQUIFER is a project that was executed by the Sahara and Sahel Observatory (OSS) with international partners to improve knowledge and concerted management of the Northern Sahara Aquifer System (SASS). The project has contributed to strengthening the capacities (through use of satellite and geographic data) of the services in charge of water management in the countries concerned with the SASS aquifer system. It has also provided tools to those countries to better identify the uses and pressures exerted by both population and climate change on the aquifer system.

2.5-Threats and challenges due to allocation conflicts

Many aquifers are shared by two or more countries. Two countries sharing the same source of groundwater must jointly plan its exploitation as any unilateral, non-concerted action (overexploitation, pollution, salinisation, etc.) may have negative effects on the neighbouring country. As with surface water, countries' sovereignty over groundwater is limited by their interrelationship with and interdependence on other countries. Decision-makers who have sufficient power to resolve issues that may result in economic, social, institutional or environmental conflicts usually deal with conflicts over water allocation within the basin. In addition, in these cases disagreements may arise between different types of end-users, many of whom want to use water on a consumptive basis that will affect the quantity and quality of this water, thus making it unusable for the other partners. We should not generalise, because although water can be a significant cause of conflict, it can also be an important factor in cooperation between countries.

Despite the importance of aquifers and their governance on many occasions, international management, regulation and policies on these water sources have been rather limited. One example is in Chile, which has six transboundary aquifers, two with Peru, three with Bolivia and one with Argentina. However, there are currently no collaborative agreements with any of the three neighbouring countries. Another example that we find in sometimes conflictive territories is the Guaraní aquifer, some 37,000 km3 of water distributed across the territories of Paraguay, Brazil, Uruguay and Argentina.

Such threats and challenges arising from allocation conflicts must be resolved through cooperative governance, taking into consideration the multidisciplinary effects and consequences.

2.6–Responses to improve the governance of groundwater use

It is essential that water users focus attention on this invisible water resource before pollution or depletion of it causes severe economic, environmental and social dislocations. Better governance and management of groundwater are required to move toward sustainable groundwater use (Lapworth et al., 2022).

A successful case of multinational governance is the cooperation agreement between Jordan and Saudi Arabia on the management of the Saq-Ram Aquifer System. In this case, these neighbouring countries agreed to cooperate on monitoring, data exchange, water demand reduction and pollution reduction with the aim of avoiding unsustainable water abstraction.

A success story for improving the governance of groundwater use, as outlined in this eBook, is that of the Northern Sahara aquifer, where the Geo-Aquifer project will create an information and knowledge base to support sustainable transboundary management of the aquifer at national and sub-regional level through the use of satellite data in order to enhance concerted action between Algeria, Libya and Tunisia.

Another good governance example is in the Benalup aquifer (Cádiz, Spain). In order to generate proposals and manage the conflict between the use and the state of the water body, the project investigated the relationship between pressures and impacts on the aquifer, including the existence of unauthorised catchments. Similarly, the Junta Central d'Usuaris d'Aigües del Baix Ter (JCUABT), a public law corporation, was created in 2015 to protect the water of the Ter River (Catalonia) and its aquifers, and to ensure that its availability, both in quantity and quality, is guaranteed for all uses.

Acknowledging the importance of water sustainability is to integrate water stewardship into businesses and to create business value by providing the correct funding and qualified staff to address these problems. This is better achieved by clearly defined shared goals with partners in different business areas through joint manifestos, such as the Portuguese Corporate Manifest for Water Stewardship (PCMWS).

Some projects have had such a good impact that they have been replicated in other areas. This is the case of GICRESAIT, a replication of the Geo-Aquifer project, which focuses on the integrated and concerted management of water resources of the Iullemeden, Taoudéni/Tanezrouft and Niger River aquifer systems.

In another approach, water markets have arisen as promising instruments in water resources management in the Australian state of Victoria. Water licence trading is a market regulated system in which licence holders can decide the amount of water to use seasonally based on their business model, and freely trade the surplus/unused volumes. The sustainable private use of this resource may have additional benefits when compared with surface water, such as lack of evaporation losses, while market dynamics are pushing the increase in environmental benefits.

3-CONCLUSIONS

As outlined in the introduction to this eBook, groundwater plays a key role in climate change adaptation, and provides a critical supply of freshwater, especially in dry regions where surface water availability is limited. This is because, despite being a finite resource, aquifers are able to regenerate and are more resilient to drought than surface water. Moreover, they can be found in places where surface water is not abundant. Groundwater provides an option for achieving the Sustainable Development Goals. However, this requires adequate investment in economic and technical expertise to map groundwater, drill sustainable wells, and find ways to maintain and manage water resources and services.

The latest UN report[1] (UNESCO, 2022) emphasises that it is essential that countries commit to developing an adequate and effective groundwater governance framework. This requires governments to assume their role as stewards of water resources, especially those relevant to groundwater. This must be done to ensure equitable access to and benefit from groundwater, as well as actions to ensure that this resource remains available for future generations. Preventing overexploitation of aquifers often involves setting limits on abstractions.

For a long time, the mismanagement of this valuable resource has not only created groundwater pollution problems but has also created present and future water supply problems. In the case of the European Union, approximately 75% of the EU's population depends on groundwater for its water supply, but it is estimated that 20% of the continent's groundwater bodies are in breach of EU water quality legislation[2] . Part of this is due to population growth, which leads to competition for resources from ever larger populaces.

To face a future of climate change, this eBook has addressed three key areas for the future sustainable management of aquifers and has shown the possibilities for overcoming current and future challenges through research and innovation.

Of the 36 countries sharing transboundary aquifers in the European Union, 24 have declared that operational agreements cover 70% or more of their transboundary aquifer area. Most of the world's major aquifers cross international borders. 468 transboundary aquifers have been identified worldwide, meaning that many countries share groundwater resources. More than 200 agreements have been made concerning transboundary rivers and lakes around the world as their benefits and problems must be shared.

The concept of groundwater governance encompasses the processes, interactions and institutions in which actors (i.e., governments, the private sector, civil society, academia, etc.) participate and decide on groundwater management within and across multiple geographical (national, sub-national, transboundary and global), institutional and sectoral levels. As discussed above, meeting the challenges of the future requires institutions to be proactive and adaptive to regional environmental transformations, political agreements and international legal norms and practices, always working within the limits of nature.

As shown in some of the good practices described in this eBook, the protection of aquifers requires stakeholders to cooperate to avoid overexploitation. Cooperation inevitably requires that the interactions of multiple

[1] https://unesdoc.unesco.org/ark:/48223/pf0000380733_spa

[2] https://www.elagoradiario.com/agua/dia-mundial-aguas-subterraneas-futuro/

actors lead to formal or informal agreements for an equitable and responsible sharing of groundwater as well as for careful conservation and compliance with regulations.

Moreover, groundwater resource development and management has been shown to depend on access to good quality data for planning drilling works and estimating groundwater availability. Capturing data in digital format at source has proven to be key, helping to greatly improve the control of groundwater supplies, which is why digitisation and innovation in water is no longer an option but a reality. We are now in an increasingly better prepared position to understand conservation needs in times of drought, thanks to accurate modelling of groundwater resources and conservation habits.

We find ourselves in a time in which there is an increasing amount of data and models focused on groundwater, and in which different organisations collect a multitude of information related to the different uses and interactions between water and the environment on a daily basis. All this information ends up being stored and managed in a dispersed way, so an integrated data management system is needed to facilitate its conversion into useful information, a system that is modular and scalable, and which facilitates the multiple users of water and the territory to make and coordinate decisions within a framework of greater knowledge. In the context of a serious water crisis in a country, the availability of shared data and models will allow all managers and users to make better decisions.

At the same time, there is a need for greater citizen awareness of groundwater. Groundwater needs to be more visible outside of the professional community, thereby increasing interest, investment and involvement in global groundwater issues, which will ultimately lead to better understanding and management of groundwater resources. Globally, water use is projected to grow by roughly 1% per year over the next 30 years. Our overall dependence on groundwater is expected to rise as surface water availability becomes increasingly limited due to climate change. The AQUIFER Project itself is a means of responding to groundwater management through collaboration between different actors at the international level.

Each partner – the Portuguese Water Partnership (PWP – Parceria Portuguesa para a Água) with the collaboration of the National Laboratory for Civil Engineering (LNEC – Laboratório Nacional de Engenharia Civil), Aqua-Valley (AV), and the Catalan Water Partnership (CWP) – developed ten factsheets drawing on their participation in groundwater-related projects and the well-established research networks of these institutions. The factsheets were categorised into three different themes: Managed Aquifer Recharge and In-situ Treatment; Governance; and Information Technologies and Modelling (attached in the appendix).

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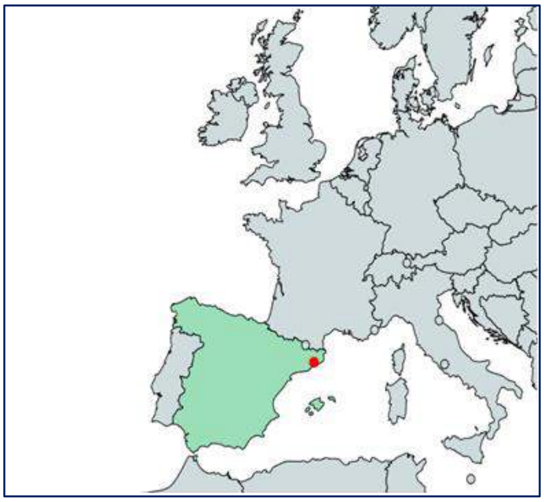
5-APPENDIX

Factsheets of “MAR and in-situ treatment” cases.

MAR and in situ treatment

Ground water resources in the Llobregat delta aquifer (Barcelona)

The continuous exploitation of the hydrogeological resources of the aquifer of the Llobregat delta has reduced piezometric levels and caused saline intrusion. The Catalan Water Agency together with the Community of Users of the Llobregat Delta have promoted and developed multiple actions to improve the quality and quantity of the resources of the delta aquifer.



Recharge rafts are a set of rafts that integrates the sedimentation raft and the infiltration raft, they are works similar to wetlands. With them it is possible to improve the quality of the water before being infiltrated. The water that passes through the rafts comes from a secondary channel diverted from the Llobregat River.

Overexploitation caused the entry of seawater into the aquifer. The proposed solution to the problem was a hydraulic barrier. The project was divided into two phases, the first began by injecting 50% of reclaimed water and 50% water from the network in to four injection wells and quickly went on to inject 100% of reclaimed water from the Baix Llobregat Waste Water Treatment Plant (WWTP). The second phase has not yet been completed but an injection flow of 15,000 m3/day is expected after the expansion of the Baix Llobregat WWTP.

Both actions require specific geographical conditions. While sedimentation ponds can be a more accessible and reproducible action in various environments, the barrier against saline intrusion requires a very specific solution and a greater demand for investment. Both are replicable proposals in the SUDOE region, but it is important to evaluate the suitability of these actions in the context of other initiatives that address the problems of quality and quantity of water resources.

Responsible entity

The “Agència Catalana de l'Aigua” (ACA) collaborates with the Community of Users of the Llobregat Delta (CUADLL) in the management of groundwater flows in a strategic area for the supply of the metropolitan area, including the fluvio-deltaic aquifer of the Llobregat delta.

The ACA is the public body of the Generalitat of Catalonia that is responsible for the planning and management of water in accordance with the basic principles of the Water Framework Directive. It seeks to guarantee the supply, availability, and quality of water at source.

This action plan also promotes the sanitation of wastewater through more than 500 sewage treatment plants and the protection and conservation of water bodies and associated ecosystems.

The CUADLL is a public law corporation attached to the ACA and subject to the provisions of water regulations and its own regulatory instruments (statutes and regulations).

Members of the CUADLL include users with the right to the use of groundwater whose catchments are located within the delta area, and consist mainly, of users for supply, industry and agriculture.

The objectives of CUADLL are to:

- i) directly manage and police the common interests of water users; ii) inform, on its own initiative or at the request of the Basin Agency or other agencies and entities of the administration, existing and requested new concessions within its territorial scope; iii) propose to the Hydraulic Administration, at its request or on its own initiative, measures it deems appropriate in relation to its field of competence; and iv) manage the services delegated to it by the ACA.

Institutional setting

The ACA, attached to the Department of Climate Action, Food and Rural Agenda of the Generalitat of Catalonia, emerged from the merger of the Sanitation Board, the Water Board and the General Directorate of Hydraulic Works.

To alleviate the water deficit and recover the quality of the body of groundwater, and in accordance with the mandates derived from the Water Framework Directive, the ACA carries out actions agreed with the CUADLL, the metropolitan authority and the General Water Society of Barcelona (F. Ortuño et al. 2009).

Geographical setting

The lower valley of the Llobregat River and the delta are located southwest of the Metropolitan Area of Barcelona (AMB). The alluvial valley extends over an area of 30 km^2 and the delta of 80 km^2. The system is composed of aquifers of high transmissivity; the aquifers are fed by the infiltration of rain, although they mainly feed on the infiltration of the river and agricultural infiltration.

The lower valley of the Llobregat is a free alluvial aquifer formed by several fluvial terraces that, when reaching the delta in Cornellà, is divided into two, separated by a wedge of silt, one of shallow depth that covers a large part of the delta, and the other deeper, under the wedge of silt, which is therefore confined, and which is the important aquifer of the delta (Custodio, 2007).

The system is of great importance due to its strategic nature for the population of the AMB (four million inhabitants) (Fouillac, 2009).

The main aquifer of the Llobregat Delta has a generalised piezometric decline below sea level since the early 1970s as a result of overexploitation. This has led to the emergence and advance of marine intrusion into the aquifer, also facilitated by the excavations of the impermeable layer of contact between the aquifer and the sea in the port, which has led to a progressive worsening of the quality of groundwater (Custodio, 1987; Custodio *et al.* 1976; Custodio *et al.* 1989; Iríbar, 1992; Iribar, 1997).

Detailed explanation

Recharging ponds

The recharge action in Sant Vicenç dels Horts is not the only one that takes place in the Llobregat valley. In the towns of Castellbisbal, Santa Coloma de Cervelló recharging rafts were also installed.

The water is derived from the Llobregat River by a secondary channel managed by a manual gate that directs the flow to the sedimentation pond where the materials are deposited. This raft has a wetland-like behaviour reducing turbidity and sedimentable materials. A pipe connects the sedimentation pond to the raft where the infiltration takes place.

The first objective of the facilities was to increase the amount of groundwater. This objective evolved by observing that the improvement in the quality of infiltrated water varied depending on the conditions.

In this context, a reactive layer was built to evaluate the impact of the degradation reactions that occur naturally between the pollutant and the soil in the vadose zone.

The facility does not operate continuously, due to the need to maintain water quality. Pauses also contribute to lessening clogging effects.

Barrier against saline intrusion

To stop the advance of marine intrusion into the aquifer, the ACA built a positive hydraulic barrier through fourteen wells into which treated reclaimed water is injected. The objective of the hydraulic barrier is to prevent the entry of seawater into the aquifer and the deterioration in its quality.

Figure 1 Structural scheme of the recharging system by means of rafts. Source: International Conference: Groundwater, key to the sustainable development goals (2022).

First phase:

The injection water for the hydraulic barrier initially consisted of 50% reclaimed water from the Baix Llobregat WWTP while the remaining 50% was mains water. This model was quickly switched to 100% reclaimed water due to the environmental and economic impact of using mains water for recharging. (F. Ortuño et al. 2009).

Four injection wells were drilled and equipped, which are located about 1,500 m from the coast, arranged parallel to it and separated from each other about 300 m.

The injection is carried out in the wells 24 hours per day. Since its inception, about 1,100,000 m^3 of reclaimed water has been injected into the aquifer. The injected water comes from the Baix Llobregat WWTP where additional advanced treatments of ultrafiltration, reverse osmosis (50% of the water) and UV disinfection are carried out, producing a total of 2,500 m^3/day of reclaimed water.

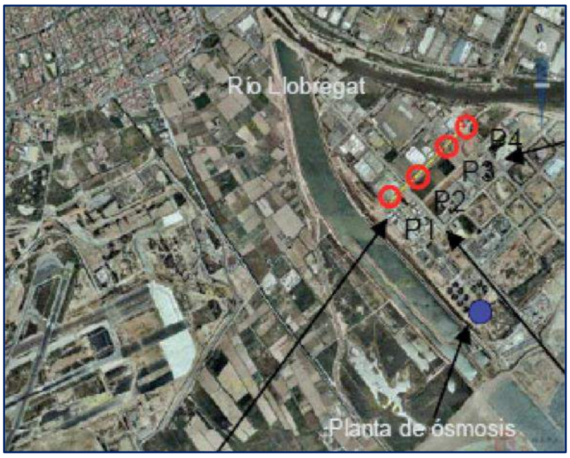


Figure 2: Location of wells and WWTP del Prat. Source: Edited from Google Maps.

<u>*Second phase*</u>:

The second phase of the hydraulic barrier aims to inject into the aquifer 15,000 m^3/day, which is the minimum flow that is estimated necessary, according to numerical models, to completely stop marine intrusion. This phase foresees the expansion of the advanced tertiary effluent water treatment plant of the WWTP, the drilling and equipment of 11 new injection wells and 16 new piezometers, and the execution of all the necessary pipes.

The expansion of the water treatment plant is already in the testing phase, which will allow the obtaining of 15,000 m^3/day of reclaimed water from the tertiary plant for injection in the second phase. The 11 new injection wells have already been drilled and equipped with cleaning pumps.

The 16 new control piezometers are already perforated and have also been equipped with automatic systems.

Historical overview

The first antecedents of aquifer recharge may be traced back to the Arab era, such as the Alpujarran lighthouses (Fernández Escalante et al, 2005) or the system of dikes and *boqueras* (Díaz Marta, 1989). The first modern managed recharge facilities date back to 1969 in the alluvial areas of Besós and Llobregat (Valdés, 1992). Another remarkable experiment was carried out in the Llano de la Palma (Mallorca), using a mixed system based on irrigation with wastewater and injection of surpluses, when they exist, in wells drilled in very permeable calcarenites.

The Geological and Mining Institute of Spain (IGME), in collaboration with other organisations, has been carrying out pilot experiments of artificial recharge since 1984, among which the following should be highlighted: three infiltration ponds in the Oja River (La Rioja); five infiltration ponds in the plain of Guadix (Granada); and a pit-type raft in Carmona (Seville).

In Barcelona, artificial recharge experiments have been carried out for many years to combat saline intrusion, a consequence of the massive extractions of the twentieth century. The first recharging facilities were built in the early 1950s in the alluvial aquifer of the Besòs River and in the 1960s in the alluvial aquifer of the Llobregat River (Custodio & Llamas, 1983; Valdés, 1992; Martín-Alonso, 2003). This last action, managed by the General Water Society of Barcelona, has recharged in some periods up to a maximum of 20 hm^3/year in wells located in the Delta with surplus water from the Water Treatment Plant of Sant Joan Despí. The recharge has been complemented by the scarification of the Llobregat riverbed, crossing the riverbed to favour the infiltration of water (Pérez-Paricio, 1999).

Evidence of benefits from implementation

Recharge ponds have a positive impact on improving the water quality of the aquifer while increasing the amount of resource available. However, these actions require large permeable areas to develop and a precise control of the quality of the water applied.

The low cost of the raft infrastructure and maintenance make the construction a sustainable element. Efficiency is variable, depending on floods throughout the year.

The hydraulic barrier against saline intrusion at the observation points of the aquifer shows a decrease in electrical conductivity (decrease in the concentration of chloride, sodium, potassium, calcium, etc.) demonstrating that it prevents saline intrusion. The barrier is oxidising in a reducing medium; the consequences it can have on the aquifer are being analysed. The injection of water from tertiary treatment has generated an increase in the concentration of nitrates (5.8 mg/l).

Replication potential in the SUDOE region

The replicability of both activities will require geographical conditions similar to the delta area and the Llobregat River.

Sedimentation and infiltration ponds are applicable without great difficulties or investment in areas that have large permeable extensions.

In the case of the hydraulic barrier, the problem must be very concrete and severe to make a technological and operational investment of this calibre. Other options may need to be considered before opting for this type of prevention given the costs mentioned.

Both actions constitute important alternatives to the management of water resources among the various existing options, for example, using reclaimed water to meet uses that do not require quality water, but exploit water from the aquifer. Another alternative, also applied in Barcelona, is the use of desalinated water that generates enough water volume to satisfy the uses, reducing extractions and allowing the recovery of the piezometric level that would simultaneously lead to an improvement in the quality and quantity of groundwater, given, among other factors, the reduction of marine intrusion.

Future outlook

Although recharge ponds (MAR) , involving an effective reuse of reclaimed water, are a viable option in many exploited aquifers, whether in coastal or inland areas, hydraulic barriers are technological developments that require a very well defined problem and whose resolution justifies the investments made. Demand reduction, reuse or desalination options may be more viable options than a hydraulic barrier in the future management of groundwater resources.

Key points of the innovative method

- Meets the challenge of water management in an overexploited area with limited resources.

- The availability of water is sufficient for local activities, avoiding conflicts between users.

- The ACA and the CUADLL lead multiple actions to address the problems of availability and quality, while efficiency and innovation must be valued with historical perspective.

Acknowledgments

This innovative practice was suggested by João Simão Pires of the Portuguese Water Partnership (PWP).

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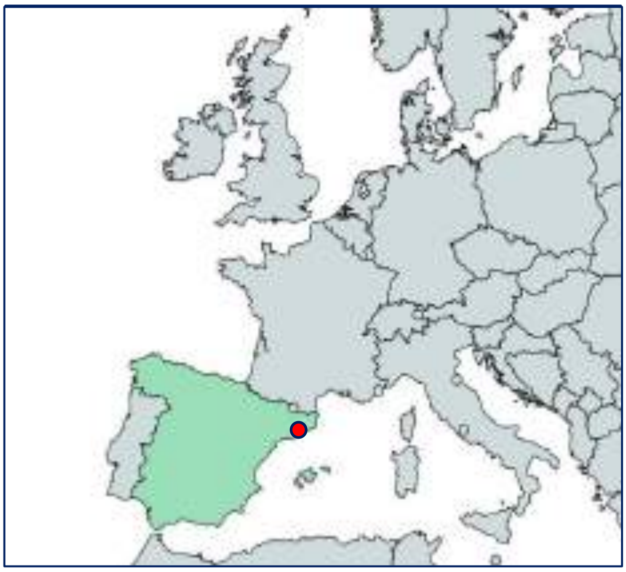
InSiTrate: In situ groundwater nitrate removal technology

Insitrate is a technology developed by Eurecat (formerly CTM Technological Centre) in the context of the Life+ programme, in collaboration with the companies Amphos21 and Catalana de Perforacions. A large part of the underground water bodies in Catalonia are contaminated by nitrates. For this reason, this consortium has developed an in situ nitrate removal technology based on bioremediation.



The results of the pilot plant are promising, reaching percentages of elimination of nitrate concentration above 80%. The on-site treatment plant is automated and does not generate waste that needs to be treated or disposed of later.

The InSiTrate project is not a management action but a technological application that requires certain hydrogeological conditions of the aquifer for its correct performance. However, its local approach, low cost and high efficiency make it an interesting development in the treatment of groundwater.

Responsible entity

Eurecat, Technology Centre of Catalonia promotes the competitiveness of businesses and the well-being of society through applied research and innovation.

https://eurecat.org/es/

Eurecat is the main technology centre in Catalonia and the second private organisation in Spain for raising funds from Horizon 2020. It is an entity specialised in offering applied R&D, technological services, highly specialised training, technological consulting and professional events for businesses from all sectors. It has participated in more than 200 large national and international R&D&I consortium projects of high strategic value and has 88 patents and 7 spin-offs.

Eurecat develops and optimises technologies and processes to improve water, soil and air management, as well as associated resources. It carries out research, development and innovation projects with businesses from all sectors to improve economic, environmental and social sustainability.

Eurecat uses advanced modelling and experimentation tools at different scales (laboratory, pilot plant and real scale) to develop and validate new technologies and their applications. It works with a wide range of pollutant treatment technologies to limit their presence in the natural environment, as well as to recover water resources and support the transition to a circular economy.

The experience of the Water, Air and Soil Unit, combined with the capabilities of the different technological units of Eurecat, allows it to provide solutions to complex and specific problems in a wide range of sectors: water treatment, chemical, agri-food, pharmaceutical, basic industries and capital goods, among others.

In the water sector, the main objectives are:

- Development and optimisation of water management and associated resources; processes for the elimination of trace and/or recalcitrant compounds; effluent treatment; and in situ and ex situ treatment technologies.
- Advanced separation processes, biological treatment, advanced oxidation, electrochemical and disinfection for liquid treatment.
- Identification and evaluation of opportunities to improve efficiency and implement a circular economy.
- Identification and development of processes for cascade recirculation and reuse in industrial processes.
- Recovery of water resources and liquid effluents (nutrients, energy and raw materials).
- Tools for monitoring, prediction and quality assurance in distribution networks.
- Studies, modelling and simulation of the behaviour and mobility of pollutants in soils and groundwater.
- Bioremediation processes with nanoparticles, monitored natural attenuation, reactive permeable barriers, chemical oxidation, stripping, etc.
- Recovery of waste/by-products for the improvement of the physicochemical properties of the soil.

Institutional setting

Eurecat technology development centre InSiTrate is framed in the LIFE+ programme of the European Union, the framework of the joint participation with the companies Amphos21 and Catalana de Perforacions. The Catalan Water Agency (ACA) and the City Council of Llavaneres also collaborate in the project.

Geographical setting

Nitrate pollution comes from anthropogenic activities such as the application of fertilisers associated with malpractice in livestock waste management, being one of the causes of non-compliance with the Water Framework Directive in terms of the quality of hydrogeological resources. In Catalonia, specifically, there is a high level of groundwater pollution associated with this compound, affecting 33% of the area (ACA, n.d.) (Figure 1).

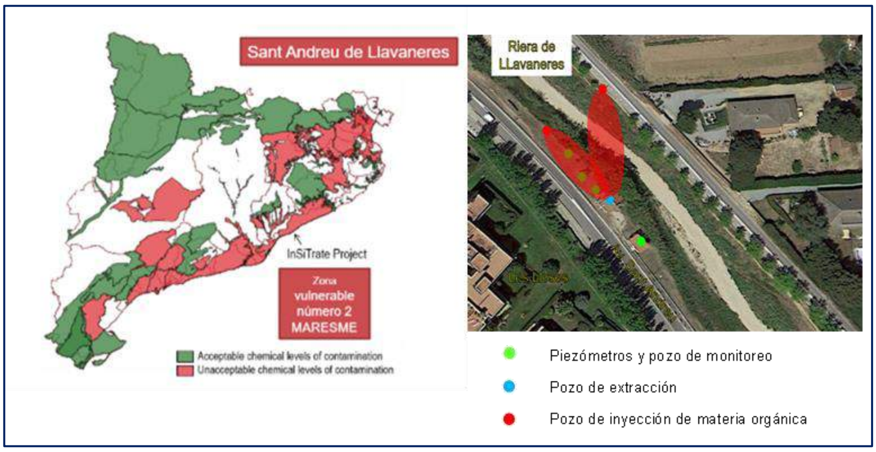


Figure 1: Vulnerable areas of Catalonia and location of the pilot plant. Source: ACA y Layman's Report

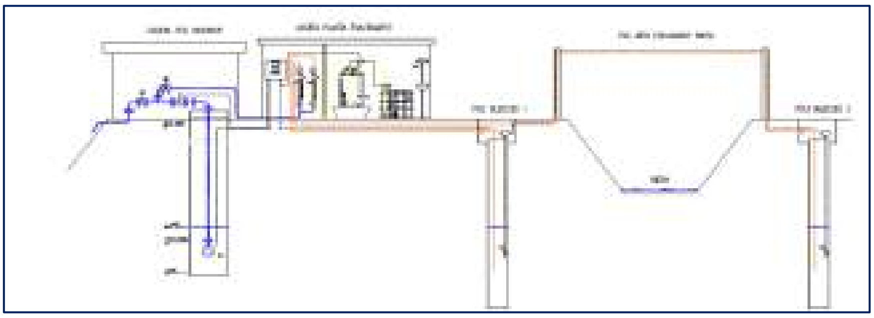


Figure 2: Scheme of pilot plant at Sant Andreu de Llavaneres. Source: Layman's Report

The pilot plant for the treatment of nitrate pollution in the alluvial aquifer of the Llavaneres stream was built 10 m from the Sant Andreu de Llavaneres stream (Maresme region). The alluvial aquifer is formed by sediments of coarse sands and silts of the Quaternary that cover a granite formation (InSiTrate, 2017).

Detailed explanation

The most commonly used conventional technologies for nitrate removal first require the extraction of water for further treatment. Ex situ technologies are expensive and can generate unwanted by-products (waste). The Life+ InSiTrate project shows the feasibility of in situ technology based on the process of induced bioremediation.

The objectives of Life+ InSiTrate were:

- Demonstrate on a pilot scale the feasibility of in situ bioremediation technology for nitrate-contaminated groundwater for the production of drinking water.

- The development of an innovative design and prediction tool based on a mathematical model that describes the process of in situ bioremediation in any aquifer and helps the design of optimal remediation strategies for other sites.

- The study of the feasibility of the technology in situ from the technical, environmental and economic point of view, and the comparison of this technology with other existing ones using the same indicators.

- To promote community acceptance of this technology and encourage the participation of stakeholders and working groups in the development of the technology.

- The study of the extrapolation of the technology in other specific European sites to demonstrate its potential application.

The process of induced bioremediation consists of the acceleration of the natural process of denitrification by microorganisms present in the affected aquifer. Nitrates are transformed into nitrogen gas by a sequence of microbial reduction reactions. In this case, the injection of organic matter (acetic acid) into the aquifer induces bioremediation.

To carry out the project and build the pilot plant, a hydrogeological and chemical characterisation of the aquifer (InSiTrate, n.d.) was carried out.

The IST-InSiTrate tool is a useful instrument for decision making as it simulates the remediation process under the different injection strategies and hydrogeological characteristics in order to identify the optimal configuration of the denitrification plants (InSiTrate, n.d.) and facilitates the design and remediation strategy of the aquifer, defining the configuration and operating parameters of the plant. (InSiTrate, 2017).

Description of the pilot press

The plant has two injection wells (I1 and I2; Figure 2), an extraction well at a distance of 30 m from I1 and I2, and three piezometers (P1, P2 and P3).

The results of the project demonstrate a reduction in nitrate concentration of between 80–100% in the monitoring wells and about 30% in the extraction wells.

The main problem was bioclogging, which was solved by injecting the organic matter by pulses and performing periodic cleanings.

Community agreement to implement innovative technologies was essential. Open approaches and close collaboration of the research groups and social interest groups involved were required, generating a participatory and integrated approach in the social context. The communication and dissemination plan was structured in a series of tasks aimed at informing citizens of the objectives and development of the project in addition to facilitating the results obtained.

The technology at the commercial level requires that the system be scaled, for this the installation of five injection wells is required to create a reaction zone where the denitrification will be accelerated (I. Jubany et al 2019).

Historical overview

The idea of restoring soils contaminated with oil or its derivatives using microorganisms was first put forward in 1930 by Tausz and Donatli (K. Cota-Ruiz, 2019). Bioremediation is a biotechnology that is several decades old; however, in recent years different bioremediation strategies have been developed and improved (C. Della Rocca et al. 2007).

In situ technologies are based on the direct treatment of groundwater (by chemical or biological processes) in the contaminated aquifer before it is pumped, unlike ex situ techniques that focus on treating contaminated water once extracted to the surface (ACA, 2017).

Nitrate pollution treatment in Catalonia with in situ technologies is still at a very early stage compared to the currently more developed ex situ technologies.

One of the outstanding methodologies is the one used in the InSiTrate project – heterotrophic denitrification in situ.

Evidence of benefits from implementation

The bioremediation technology used in the InSiTrate project has demonstrated the feasibility of nitrate removal in alluvial aquifers with reduction levels above 80% in the pollutant.

The plant works automatically and does not require personnel. It does not generate waste, avoiding problems and management costs.

The application of this technology uses the aquifer as a reactor and at the same time, in comparison to other ex situ biological systems, consumes fewer reagents. These characteristics make it a competitive technology economically when compared to ex situ ones.

Replication potential in the SUDOE region

The InSiTrate project provides an innovative technological application in order to show its efficiency and viability, linking it to community acceptance through a process of public participation.

This technology shows how an efficient point action in a site with certain characteristics can be developed in an unconfined porous aquifer, with an area that allows the installation of wells in a radius of 30 m around the supply well.

Obviously, its replicability will depend on geographical, hydrogeological and economic factors. Its level of efficiency allows it to be compared with other existing technologies when considering its feasibility.

Future outlook

Nitrate concentrations in groundwater are a growing problem linked to land uses and anthropic activities. The development of high-efficiency remediation technologies in the removal or conversion of nitrates, which are economical and easy to use, is expected to be key to solving the quality problems associated with nitrates. The importance of in situ techniques in avoiding large works outside of the aquifer and the extraction of water to be treated outside of it should also be noted.

Key points of the innovative method

-High efficiency technological solution for nitrate removal.

-Automated system controlled remotely facilitating use in remote areas.

- Encourages the involvement of different community sectors.

Acknowledgments

This innovative practice was suggested by Irene Jubany, research coordinator of the Sustainability Area in Eurecat.

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INFORME FINAL DE PROJECTE Desenvolupament d'un prototip de sistema d'ajuda a la decisió i d'una base de dades sobre el territori, per tal de facilitar la presa de decisions sobre les properes inversions per a la instal·lació de tecnologies per al tractament de Nitrats a Catalunya. (2017). ACA

Stormwater harvesting for Aquifer Storage and Recovery in Adelaide, South Australia

Stormwater has been considered as an alternative water source for both potable and non-potable uses, such as gardening and irrigation. The use of this highly variable source has proven to offer some advantages, particularly in reducing demands on the urban potable water supply and ultimately reducing the discharge of untreated urban stormwater to urban streams and marine outfalls. Stormwater may be key in the diversification of water supplies. The City of Salisbury, in South Australia's Adelaide metropolitan area, has developed an integrated approach to managing urban water where wetland treated urban stormwater is stored via aquifer storage and recovery (ASR) and aquifer storage transfer and recovery (ASTR) in confined aquifers to provide a sustainable water supply that is distributed to customers via a dedicated non-potable 'purple pipe' network. This scheme has proven beneficial to the city, both economically and environmentally, and it is being replicated in other regions, not only in Australia but around the world.

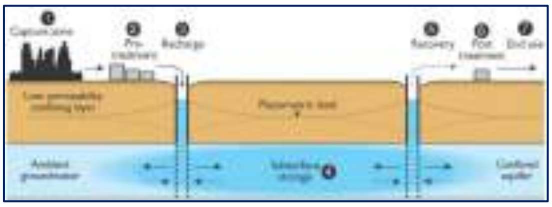

Fig. 1 - Aquifer Storage Transfer and Recovery (ASTR) system (adapted from Page et al., 2010).

Responsible entity

The Salisbury Water MAR Scheme is operated by the Salisbury Water team, a separate business unit of the City of Salisbury (Fig. 2). The unit acts as a water service provider that supports the Council's initiatives to deliver economic, environmental and social benefits to the community.

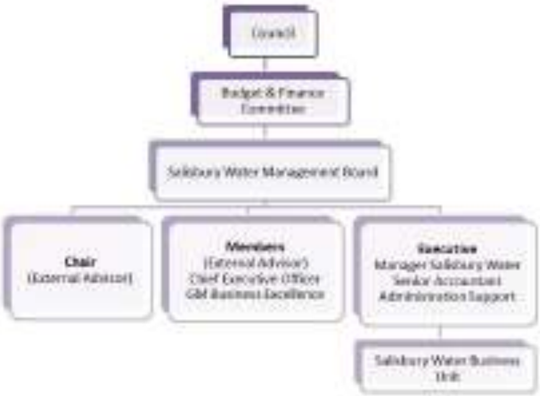

Fig. 2 – Salisbury Water governance structure.

Salisbury Water is governed by the Salisbury Water Management Board (SWMB), which includes external independent water/industry experts and senior Council members. The SWMB is led by an independent external member who advises the City of Salisbury's Chief Executive Officer on strategic direction, legal and regulatory environment and government policy, community issues and risk management. Salisbury Water operates and manages the storing, pumping, treatment and distribution schemes.

Other key partners from the public and private sectors took an important role in the initial stage of the Salisbury MAR scheme feasibility and implementation) (Zheng et al., 2021).

Salisbury Water is also the concept used for the Council's recycled water that is distributed to parks, reserves, schools, industry and residential properties.

Tab. 1 – Key partners (adapted from Zheng et al., 2021).

Organisation	Intervention
South Australian (SA) Department of Mines and Energy	Initial proponent of MAR in SA
SA Department for Environment and Water (DEW)	Resource regulator
SA EPA	Environmental regulator
Heyne Nursery – Commercial plant nursery	First external customer
Michell Wool – large industrial water user	First external funding partner and large-scale alternative water user
Parafield Airport Limited (PAL)	Provided land for the first scale wetland/MAR project in Salisbury
University of South Australia	Early advocate for alternative stormwater management
CSIRO	Research and validation of MAR
Australian Government	Funding partner over several projects

Institutional setting

The first issue to be addressed is the protection of groundwater quality and the standards of the quality of water to be injected. Australia was one of the first nations to develop guidelines for risk-based management of Managed Aquifer Recharge – Australian Guidelines for Water Recycling: Managed Aquifer Recharge ("MAR Guidelines") (NRMMC-EPHC-NHMRC, 2009). These were developed from the experience gathered through decades of research and investigations.

The guidelines were the outcome of a two-year Urban Water Research Association of Australia study that reviewed international practice and guidelines for artificial recharge of waters by injection. South Australia's, Andrews Farm experimental ASR site was used as a case study to demonstrate the viability and sustainability of injecting urban stormwater, which had received only passive treatment in flood detention ponds into a brackish aquifer and recovering it for irrigation (Martin & Dillon, 2002).

These guidelines enforce high performance concerning environmental sustainability and cover licensing, pre-treatment, monitoring, guidance for maximum contaminant concentrations in injectant, residence time prior to recovery and management of ASR operations, and provide a clear path for implementation.

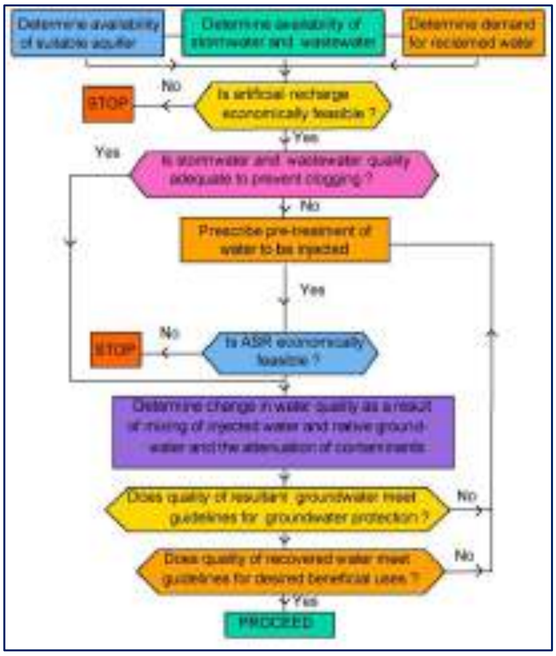

Fig. 3 – Flow chart for AR with stormwater and reclaimed water (adapted from Dillon & Pavelic, 1996 in Martin & Dillon, 2002).

Geographical setting

Southern and Western Australia are two of the most water-challenged areas of Australia (Prommer et al., 2013), experiencing a drying climate over the last 40 years, with severe droughts during the last decade combined with rapid population growth and urban development. In Australia's biggest cities, climate projections for the next several decades show predominantly increased aridity, particularly in the southern winter wet-season, and increased evapotranspiration. The projected increased intensity of extreme daily rainfall events has implications for stormwater runoff. High rainfall intensity can lead to flooding and less recharge to groundwater in some environments where the infiltration capacity of the soils is exceeded. Coastal areas that rely on groundwater sources can also face saltwater intrusion. To cope with this, Australia has invested heavily in the implementation of sustainable urban water management procedures which include managed aquifer recharge (MAR) (Fig.).

Fig. 4 – Location of innovative practice (adapted from Vanderzalm et al., 2020).

Adelaide urban area, composed of several satellite cities, has seen the implementation of several of these schemes given the acceptable geological conditions (Fig.) and in which the study area is included (northern Adelaide).

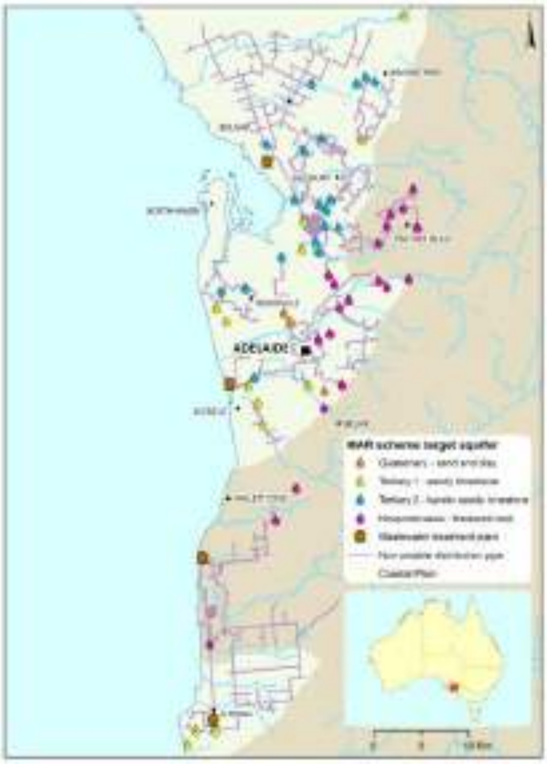

Fig. 5 – Stormwater ASR sites in Adelaide metropolitan area (adapted from Kretschmer, 2017).

Detailed explanation

Salisbury Water MAR Scheme relies on two different methods: aquifer storage and recovery (ASR) and aquifer storage, transfer and recovery (ASTR). The latter involves injecting water into a well for storage, and recovery from a different well, while in ASR water is recovered from the same well (Page et al., 2018) (Fig.). A major attraction of the use of injection wells (bores) and aquifer storage in an urban context is that only a small surface footprint is required for the wellhead works to achieve large storage which can underlie the urban development it serves (Kellogg Brown & Root Pty Ltd, 2004).

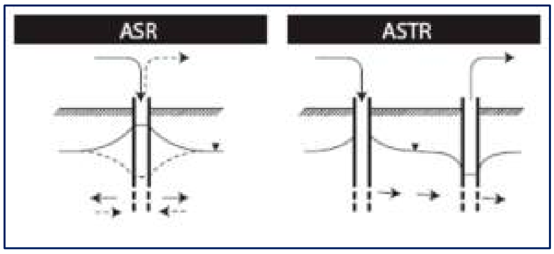

Fig. 6– Schematic of some types of MAR suited to urban water management (adapted from Page et al., 2018).

Depending upon the specific water quality parameters and end-use, ASR implementation may require the combined use of hybrid natural-engineered treatment systems (Page et al., 2017). Due to quality variability, stormwater harvesting systems generally require some level of treatment to minimise operational risks. The use of wetlands and bioretentive systems can assist in reducing loads of organic matter and removing nitrogen and phosphorus through phytoremediation (Ahmed et al., 2019).

In the Salisbury approach, Wetland treated urban stormwater is stored via aquifer storage and recovery (ASR) and aquifer storage transfer and recovery (ASTR) in confined limestone aquifers to provide a sustainable water supply that is distributed to customers via a dedicated non-potable 'purple pipe' network.

The general working practice is as follows: During the high rainfall period in winter, excess stormwater, filtered and cleansed by the wetlands, is pumped into the aquifer which is up to 220 m below the ground. During the summer, the water is recovered as needed.

Monitoring at one of the early constructed wetlands in the early 1990s demonstrated that water quality significantly improved. Driven by the need to cut costs in irrigation of adjacent sports fields, Salisbury Council started the investigation of the use of the wetland water (Zheng et al., 2021). The first ASR trial in 1994, used the Lower Tertiary sandy limestone aquifer (Paddocks ASR scheme, capacity 0.05×10^6 m^3). Recovered water was diverted to an ornamental lake and subsequently used in irrigation. A wool company started to use water from this installation at Salisbury South for scouring trials as the low salinity of recovered water required less detergent in the wool scouring process. The trial resulted in a partnership between Salisbury Council, Michell Wool and Parafield Airport Ltd., with funding support from the Australian Government, to build a stormwater recycling facility on the runways of Parafield Airport, commonly referred to as the 'Water Factory'. This initiative has supplied 1-3 x10^3 m^3/day for the Michell Wool operations. The Paddocks and Parafield schemes (capacity 1.1x10^6 m^3) are now important hubs that supply recycled water to over 1,000 customers and 5,000 homes via third party retailers.

The Parafield system is a constructed wetland and consists of three basins: an in-stream basin, a holding storage basin and a cleansing reed bed basin. The in-stream basin catches the stormwater runoff from the catchment area, slowing flow, removing suspended solids and diverting it to the holding storage basin. The water in the storage basin flows into the reed bed basin by natural gravity. The water that passes through the reed bed is then seasonally (mainly in winter) injected and stored in adjacent aquifers. The treated water is stored in an aquifer storage and recovery system (ASR). The reed bed basin is covered by bird netting, which prevents birds from entering and contaminating the system. Water flowing in the reed bed is regulated to ensure a retention time of ten days and a water level of 30–70 cm (Page et al., 2010).

The total land area of this system is 11.2 ha and the catchment area is 1,600 ha, a mainly residential area with a small number of parkland areas and an industrial area. The catchment area is serviced with a complex stormwater drainage system for the collection of stormwater runoffs, which is mainly street and roof drainage.

Water flowing into and through this highly sophisticated artificial wetland is highly regulated and in times of very high flow the wetland can be isolated from inflowing water. Water recovered from the aquifer storage is supplied to the adjacent suburb of Mawson

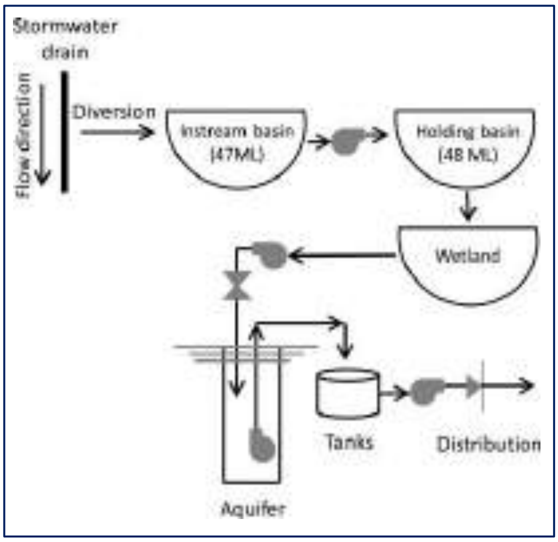

Fig. 7– Parafield's stormwater ASR scheme (adapted from Dandy et al., 2019).

Lakes as a secondary reticulated water service and is also used in a nearby wool washing operation. Users pay a reduced cost compared to fully treated water (Dandy et al., 2019; Kim, 2010).

The project capital cost was AUS$4.5 million, with an initial funding support of AUS$1.4 million through the Commonwealth's Environment Australia Urban Stormwater Initiative, AUS$1 million from GH Michell & Sons Australia (wool company), AUS$140, 000 from the Northern Adelaide Plains Barossa Catchment Water Management Board, an in-kind contribution of AUS$40, 000 from the then SA Department of Water Resources, with the balance being funded by the City of Salisbury (Radcliffe et al., 2017).

Salisbury has today over 150 km of recycled water pipes and the whole system is composed of 31 ASR wells and 32 ASTR wells.

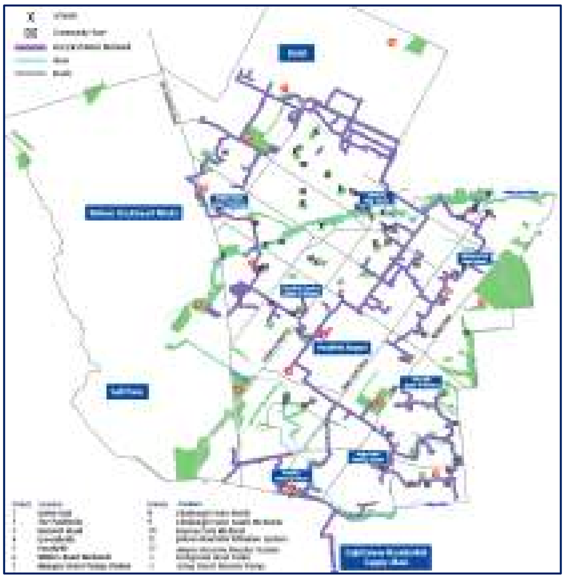

Fig. 8– Salisbury Water network (from Salisbury Water brochure 2021/22).

Historical overview

The use of stormwater as a supplementary water resource in Adelaide was first considered in the early 1950s to enhance brackish aquifers and provide a reserve for times of water shortage. The concept has been deemed more important with the realisation that the Murray River, a major source of Adelaide's water supply, was significantly compromised in quantity and quality through overuse by irrigators and associated saline drainage impacts (Kellogg Brown & Root Pty Ltd, 2004).

In 1977 an Australian study recommended the conserving of water resources in rivers and streams and recharging aquifers, providing those nutrient concentrations were controlled (Radcliffe and Page, 2020).

The millennial drought – a period of reduced rainfall at the beginning of the twenty-first century – forced the Australian water industry to adapt. The National Water Initiative (NWI) was passed and laid the basis for water markets, trading and pricing but also led to the development of regulatory guidelines on the use of stormwater and recycled water (Vanderzalm et al., 2020).

In 1994, Salisbury's first ASR trial commenced and in 1999 Parafield Stormwater Harvesting Facility was developed to supply a wool processing company (Kim, 2010). Other hubs were connected by a reticulation network from 2001, with significant upgrades completed between 2012 and 2016, while the officially regulated sale of water supply commenced in 2004.

Evidence of benefits from implementation

Salisbury Water reported multiple benefits to both the local community and the wider region. The most relevant are:

- Reduced demand on existing water resources such as the Murray River and the Adelaide Hills Water Catchments.
- Increased local biodiversity through the establishment of over 50 wetlands which provide a habitat for bird species.
- Reducing the volume of stormwater run-off and helping to protect the sensitive marine environment of the Barker Inlet in the St. Vincent Gulf.
- Increased opportunities for environmental education and research and public awareness with community volunteer engagement.
- Salisbury Water used to irrigate is helping to keep the city's green infrastructure, which also provides recreational activities.
- Increased water availability allows for irrigation even during drought periods.
- Increased flood protection for property.

- Natural treatment of stormwater enabled a low-cost treatment option for community use and an alternative water supply for industry (savings of over AUS$3 million each year) (Zheng et al., 2021).

The social acceptance of stormwater use was assessed using surveys on "Would you support case A, B or C for stormwater use?" and "Would you trust authorities to ensure the quality of water of these cases?" The results showed that the support for stormwater schemes is high for all three options (Dandy et al., 2019).

(A) Treatment through a wetland and aquifer storage and recovery and then delivery to their house via a separate third pipe network where it could be used for garden watering, toilet flushing and in the washing machine.

(B) Treatment through a wetland, aquifer storage and recovery and delivery to a water supply reservoir for blending with other source water before being further treated through a water treatment plant. The water would then be distributed through the water supply mains for drinking and other purposes.

(C) Treatment through a wetland and aquifer storage and recovery and then direct injection into the water supply mains for drinking and other purposes.

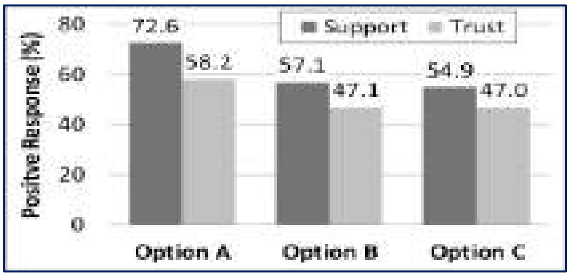

Fig. 9 - Percentage of respondents with a positive response concerning the various measures for each stormwater option (adapted from Dandy et al., 2019).

Replication potential in the SUDOE region

The Salisbury Water example is already being adopted nationally and abroad, such as in Western Australia Perth's GWRS strategy to improve long-term water security for the city using water banking via ASTR (Vanderzalm et al., 2020).

The main issues of ASR relate to source water quality and the technical feasibility at the selected location (hydrogeological and technical systems designed to achieve benefits that exceed costs, system compliance with existing regulations, and establishment of consultative mechanisms to allow stakeholder negotiations). In urban settings, issues usually revolve around constraints on available storage or, if the water is of low quality, the need for additional infrastructure to deliver enough water to comply with demand (Martin & Dillon, 2002).

The Mediterranean region is expected to face similar problems with extreme events related to climate change and MAR/ASR may provide a suitable solution in urban and peri-urban areas. Although not directly related to MAR and ASR, Portugal's Lisbon municipality, in collaboration with a local water services company, is currently establishing the construction of a system of ducts in the city, which will make it possible to create a network of recycled and safe water for reuse in irrigation and washing from the Water Factories (previously WWTP). The overall reduction in drinking water consumption has been one of the municipality's major strategic objectives, and the reused water network is a decisive step in this direction, having been one of the measures most valued by the European Commission in awarding Lisbon the distinction of European Green Capital 2020.

Future outlook

Stormwater abundance may be a problem in the near future. In Australia, impacts of climate change are emerging with the nationally-averaged rainfall 40% below average for the year at 277.6 mm, compared to 465.2 mm for 1961–1990 (Radcliffe and Page, 2020). On the other hand, from an economic perspective, nature-based technologies may have a wider role in the future with smaller investments required in the long term. The Salisbury Water wetland-ASR provided an additional drinking water supply with notable savings and low complexity systems if compared with WWTP tertiary treatment schemes (Radcliffe and Page, 2020).

Key points of the innovative method

-- Non-drinking water in the City of Salisbury is referred to as Salisbury Water and is a mix of treated stormwater and native groundwater which is used to irrigate parks, reserves, schools and industry.

- Collection, storage and distribution uses constructed wetlands, managed aquifer recharge (MAR) and a 'purple pipe' distribution network across the city.

- Use of alternative water for non-drinking water purposes allows for reduced treatment costs and supply throughout the year.

- Wetlands also provide flood protection and increase local biodiversity with recreational opportunities.

- Capture, treat and reuse stormwater to help protect sensitive downstream marine environments.

Acknowledgements

This innovative practice was suggested by Sergi Compte of the Catalan Water Partnership.

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Participating members:

Salisbury Water (https://www.salisbury.sa.gov.au/services/salisbury-water/what-is-salisbury-water)

Using Managed Aquifer Recharge to mitigate saltwater intrusion in a Southern Malta Coastal aquifer

Water is a scarce resource in the Mediterranean region. The Maltese archipelago is a relevant regional case study in which the available water sources do not provide sufficient volumes to meet demand, and sustainable water resource management measures are necessary to face climatic variability and supply security. A national policy framework for the use of non-conventional water sources paved the way for the implementation of alternative methods such as Managed Aquifer Recharge (MAR).

Photo of Som Thapa Magar. Source Pexels

The Maltese Energy and Water Agency, through European Union Research Funding, implemented a series of well injection experiments using highly polished treated wastewater to curb the advance of saltwater intrusion into Malta's main source of freshwater, the karstic limestone lower aquifer. Groundwater overexploitation and the expected changes in rainfall patterns due to climate change drives the protection prioritisation of this source, the most important in the region. The MAR scheme developed showed that, although no considerable results were achieved, together with other methods associated with agriculture and industrial water use reduction and treated wastewater reuse, MAR is a sound complementary methodology to help cope with near-future challenges.

Responsible entity

The implementation of Managed Aquifer Recharge to mitigate the advance of saltwater in the Maltese aquifers was first suggested by Energy and Water Agency (EWA), a governmental agency of the Maltese Ministry of Energy, Enterprise and Sustainable Development. It aims to implement national water and energy sectors policies to ensure security, sustainability and affordability of energy and water in Malta.

EWA partnered with Malta's Water Services Corporation (WSC), a public entity responsible for the production and distribution of drinking water and collecting and treating wastewater on the islands. It also designs, builds and sells dedicated desalination and water processing equipment; and provides accredited laboratory services to industry, hotels and private individuals.

Fig. 1 – Responsible entities for project implementation.

In recent years, the Water Services Corporation, through the New Water programme has invested in the development of facilities for polishing treated wastewater to enable its utilisation in the agricultural and commercial sectors in substitution of groundwater resources (Sapiano, 2020).

Institutional setting

Malta National Climate Change Adaptation Strategy, the main driver for water management, is enforced through the basis of the Water Catchment Management Plans (WCMP). According to the Maltese Resources Authority, these plans, similar to other catchment plans implemented throughout the EU, represent a holistic approach to address water issues, considering impacts on health, biodiversity, landscape, soil and climate. The objectives related to groundwater include the following:

- Preventing deterioration in the status of groundwater bodies.
- Protecting, enhancing and restoring all groundwater bodies.
- Prevention of and limitation of the ingress of pollutants into groundwater.
- Reversing any significant upward trend of pollutants in groundwater.
- Achievement of good groundwater qualitative and quantitative status by 2015, or in specific circumstances by 2021 and 2027.

The second WCMP (2015–2021) (EWA, 2015) envisaged a reduction of groundwater use by increasing efficient use; recycling/reuse of water resources; and supply substitution through the use of alternative resources such as water re-use, grey-water recycling, water efficiency measures, managed aquifer recharge and the optimisation of water use by the commercial and agricultural sector.

Geographical setting

The Maltese archipelago consists of three inhabited islands – Malta, Gozo and Comino.

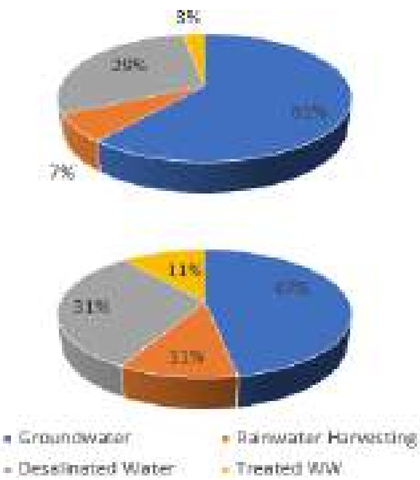

Fig. 2– Current (2014) and expected (2021) water resources supply base (adapted from EWA, 2015).

The Aqueduct Water Risk Atlas characterises Malta as an extremely high Water Stress Index area – the ratio of total water withdrawals to the available surface and groundwater resources – with medium drought risk and medium-high seasonal water variability (Hofste et al., 2019) with a semi-arid Mediterranean Climate (Sapiano, 2020). Freshwater is a scarce resource in the Maltese archipelago as its geological conditions do not allow for efficient surface water storage. The islands comprise a succession of Tertiary limestones and marls with scarce quaternary deposits (Barbagli et al., 2021). The geological characteristics result in two main aquifer types: small, perched, groundwater bodies and the lower main sea-level groundwater bodies which sustain groundwater floating lenses in direct contact with saltwater (Lotti et al., 2021). The second is commonly referred to as the Malta Mean Sea Level aquifer (MSL).

Together with one of the highest population densities in the world and tourism pressure, with peak seasonal increase in the driest months of around 550 mm/y, mainly in September and April (Sapiano, 2020), there are increased challenges in water resources management. In 2014, around 60% of natural freshwater produced was extracted from groundwater sources to cope with national demand (EWA, 2015).

Climate change impacts are expected to decrease the mean annual rainfall, with extreme high run-off generating rainfall events and resulting in the decrease in aquifer recharge (EWA, 2015; Sapiano, 2020).

Desalination of seawater has become one of the most important sources of freshwater in Malta, today accounting for more than 60% of the public drinking water supply (Sapiano, 2020). Groundwater abstracted from the southern region of the MSL aquifer system exhibits characteristically high chloride contents. This deterioration in quality has resulted from the saltwater intrusion in response to the historically high groundwater abstraction rates registered in the area, particularly from the dense and widely distributed private abstraction for agricultural purposes. This situation has resulted in the discontinuation of groundwater abstraction for public supply in this region since the early 1990s.

Detailed explanation

The Lower Coralline Limestone formation represents the most important aquifer formation of the Maltese islands and supports the MSL aquifer. The primary porosity of the formation is highly variable and suggests that a large part of the primary pore-space is not interconnected, and the effective porosity of the formation is mainly connected with fracture permeability. The fractures range from micro-fissures to karst cavities (Barbagli et al., 2021; Sapiano, 2020).

The Malta demonstration site is located in the southeastern coastal area, Ta Barkat, 130 m from the coastline, near a wastewater treatment plant (WWTP) which provides a highly polished treated effluent for injection. Geologically, the area shows karstic cavities, which are influenced by the tidal effects and with freshwater-saltwater interface depth at around 25–30 m (Sapiano, 2015).

Injection water was transported through a 75 mm diameter HDPE pipe from the polishing plant to the recharge wells through a 300 m network connecting all the recharge wells and which was developed by the project partner, the Water Services Corporation. Monitoring of the MAR scheme was conducted through four boreholes located further inland. Experimental injection procedures were initiated in October 2016 and maintained over the subsequent six-month period, up to the end of March 2017, using six recharge wells (Sapiano, 2017).

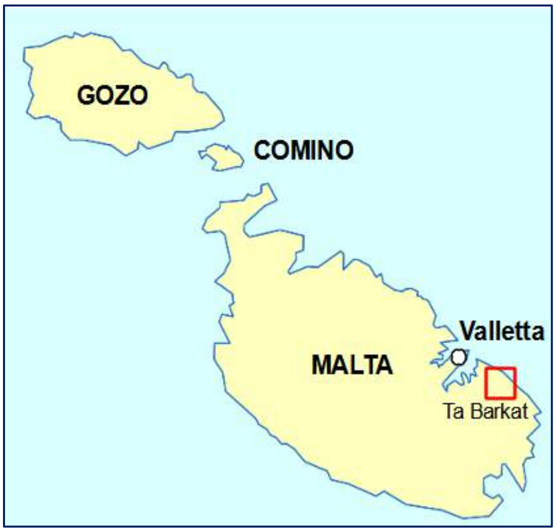

Fig. 3– Location of Ta Barkat MAR scheme and WWTP.

Fig. 4 – Ta Barkat MAR scheme (adapted from Sapiano).

Electrical conductivity and temperature readings did not show relevant impacts from the experiment and a local increase in the hydraulic head was observed around the injection wells. A long-term flush of the interface towards the coastline is expected with the continuity of the injection. Third-party abstraction activities in the area possibly made changes in water level due to the artificial recharge event more difficult to identify.

Technically, MAR implementation in Ta Barkat was intended as a test site to assess the practical impact of MAR in a coastal groundwater system and help guide the development of an upscaled MAR system further inland in a region where the aquifer system shows better characteristics, namely, where an increase in the hydraulic head would change hydraulic gradients and limit the outflow of groundwater from the central regions.

Historical overview

Alternative methods for managing water are historically common in Malta. Harvesting of rainwater is an ancient practice with the first structures being traced back to the Neolithic. At a national level, runoff is collected and managed through small dams constructed along the main valley systems, which structures also permit a certain level of MAR to the underlying sea-level aquifer systems (Sapiano, 2020).

Treated sewage effluent offers a potential alternative to freshwater in irrigation if correct salinity treatment is applied (Mangion et al., 2005) but also a source to other alternative uses such as MAR.

The MAR pilot was initiated during the First Catchment Management Cycle (EWA, 2015), financed by EU MARSOL Project (Framework Programme 7) and aimed to develop a regulatory framework for MAR authorisation under EU Groundwater and Environmental Impact Directives.

Other experimental MAR schemes were tested through numerical modelling parallel to the experimental Ta Barkat site. A large-scale 3D groundwater model of the southern sector of MSL Aquifer was developed to study two scenarios: business as usual, where no injection of water occurs; and injection in a hypothetical well-field with a uniform injection rate of 2 hm^3/year for ten years (Monteiro et al., 2016). Those volumes correspond to the surplus in polished wastewater (New Water). The results were promising as the groundwater level increased and a decrease in the seawater-freshwater ratio was observed, although effects were geographically limited to the areas around the injection wells

Particle tracking modelling showed that the injected wastewater flows towards the sea, as opposed to the direction of the existing public supply wells, not affecting the quality of the water abstracted for supply.

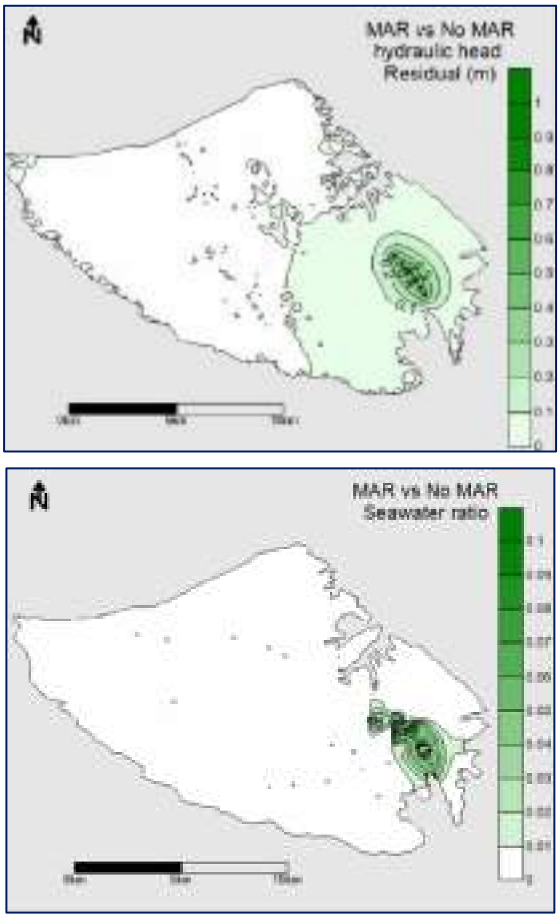

Fig. 5– Groundwater numerical model results (adapted from Monteiro et al., 2016).

Evidence of benefits from implementation

From a technical perspective, the expected benefits of a MAR scheme in such an aquifer system are of two types (Sapiano, 2017). Firstly, the MAR system will lead to an increase in water levels in the coastal zone resulting in a global lowering of the freshwater-saltwater interface. A thicker freshwater floating lens will limit the advance of intrusion beneath the abstraction stations protecting or improving the quality of the extracted groundwater.

Secondly, injection creates a mound that limits the outward flow of freshwater from the central regions of the aquifer system. Higher hydraulic heads around the MAR site would modify groundwater flow conditions by inducing an inward groundwater flow component blocking the naturally infiltrated groundwater (better quality) in inland regions of the aquifer system, preferentially discharging the recharge waters. This can also flush out contaminants from the coastal aquifer system, having also a beneficial 'cleaning' effect downstream of the MAR site.

Replication potential in the SUDOE region

The use of MAR as a tool to curb saltwater intrusion has been extensively investigated in numerical modelling in case studies around the world with favourable results (Allow, 2012; Masciopinto, 2013; Lu et al., 2017; Armanuos et al., 2019; Armanuos et al., 2020; El Alfy et al., 2020).

Real-scale implementation of such schemes, usually referred to as saltwater barriers, is common in the USA, particularly in California, with some degree of success. In Los Angeles, injection wells have been used since the early 1950s to hinder the advance of saltwater intrusion (Herndon and Markus, 2014). In 1975 the Orange County Water District established a "water factory" in which treated wastewater is also used to counter saltwater intrusion (Kiparsky et al., 2021). In Europe, a seawater injection barrier recharge scheme using reclaimed water was tested in the Llobregat delta aquifer (Barcelona, Spain) with a significant groundwater quality improvement (Ortuño et al., 2012).

The main obstacle associated with MAR is primarily one of an economic nature instead of the urge to immediately solve an environmental or scarcity problem. MAR schemes in coastal regions are expected to lose a

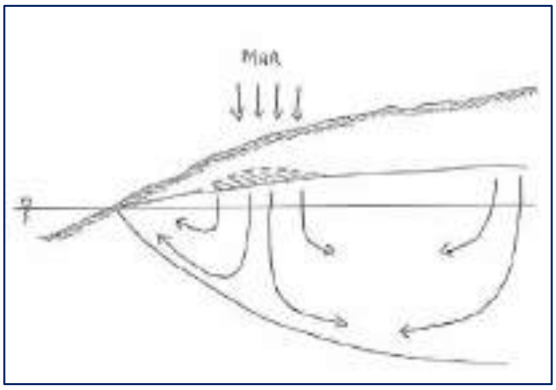

Fig. 6– Scheme of expected effects from MAR injection (adapted from Sapiano, 2016).

significant fraction of the injected volume by aquifer discharge the sea. From a policy and planning perspective, the energy spent in generating polished water as a replacement to groundwater that ultimately will not be recovered may be seen as a poor investment and other methods can be applied, such as adopting water-saving policies, prior to the undertaking of any MAR scheme. Visible benefits will only be achieved after a long period of MAR implementation due to the common groundwater dynamics (i.e., very low velocities compared with surface water). Considering Malta's hydrogeological conditions, current water demand patterns and the quality of water being produced by the Ta Barkat polishing plant, MAR is to be considered as a 'last' solution to maximise the resource benefits, or as a complementary solution to very specific management challenges (Sapiano, 2017).

Future outlook

MAR to prevent saltwater intrusion in Malta is a near-future reality. An EU LIFE Integrated Project is ongoing, aiming to drive the implementation of Malta's Second River Basin Management Plan (RBMP), and to achieve the environmental objectives of the Water Framework Directive. The project revisits the challenges of water scarcity, high population density and saltwater intrusion vulnerability challenges and has, as one of the sixteen actions, developed a MAR pilot scheme in the Pwales groundwater body, in the northern part of Malta island. The MAR scheme will inject polished wastewater, initially used for irrigation, from a nearby WWTP during periods when the water demand is low during rainier months. The plant, owned and operated by the WSC, receives water from the northern part of Malta and following biological treatment is submitted to ultrafiltration, reverse osmosis, and an advanced oxidation process to produce reclaimed water which is suitable for unrestricted irrigation and will not compromise either soils or aquifers.

This action will at first be based on numerical modelling, similar to MARSOL, which will evaluate the feasibility of the method. Field investigations and modelling of this pilot MAR scheme will be conducted by an early-stage researcher as part of the Managed Aquifer Recharge Solutions Training Network (MARSoluT), a four-year Marie Skłodowska-Curie Actions (MSCA) Innovative Training Network (ITN) funded by the European Commission.

Key points of the innovative method

- The pilot scheme is expected to curb saltwater intrusion caused by overex-ploitation of groundwater and declining natural recharge.

- Makes use of high-quality treated wastewater that does not compromise the groundwater quality if injected.

Acknowledgements

This innovative practice was suggested by João Simão Pires of the Portuguese Water Partnership (PWP).

- Monitoring showed residual impacts in terms of groundwater level improvements.

- The methodology is most effective as a complimentary water resources tool, together with water-saving policies.

- This implementation paved the way for further MAR experiments that are expected to be conducted in another site in the northern region of Malta using reclaimed water (polished treated wastewater).

- Similar saltwater intrusion "barriers" have been successfully used in Europe and the United States of America.

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Project participating members:

Energy and Water Agency (https://www.energywater-agency.gov.mt/)

Water Services Corporation (https://www.wsc.com.mt/)

Riverbank filtration for water quality improvement in a Managed Aquifer Recharge scheme in Berlin, Germany

In Germany, groundwater is used for drinking water production wherever possible since, when compared with surface water, groundwater is well protected against most types of pollution, has a relatively regular quality and temperature, and its abstraction can be easily adjusted to short-term fluctuations in consumption (Schmidt et al., 2003). However, natural groundwater is seldom available in the amounts necessary to cover the water demands of large cities. Thus, the option chosen was to increase the natural supply of groundwater with induced infiltration of surface water, which explains the development of groundwater waterworks in Germany located near rivers. In the beginning natural groundwater was extracted, then mixed groundwater, and later it was almost pure Riverbank Filtration (RBF).

Riverbank Filtration is a water withdrawal method in which water is pumped from the ground via the banks of a river (or other surface water body, in that case called Bank Filtration). The water abstracted is thus surface water that has received a preliminary treatment by passing a short distance through sediments and soil to where it is abstracted (https://www.emergency-wash.org/water/en/technologies/technology/riverbank-filtration).

Responsible entity

Berlinwasser Group (Fig. 1) is the entity responsible for the Berlin water supply “in the most efficient and sustainable way, ensuring its quality by acting with a sense of responsibility, showing commitment and using state-of-the-art technology”.

Fig. 1 – Responsible entity for the project implementation.

The Berlinwasser Group is also a preferred industrial service provider to the water and wastewater industry in regions outside of Berlin. This is due to their specialist know-how from their predecessor companies, which were active both in East and West Berlin.

Institutional setting

RBF was first applied in Germany’s capital, Berlin, more than 100 years ago. For the past 70 years, bank filtration has produced approximately 60% of the city’s drinking water (Gillefalk et al., 2018). Methodologies have kept improving since the beginning.

Water abstraction occurs in around 650 wells and is part of a semi-closed water cycle, where effluents from wastewater treatment plants reach surface water bodies subject to water extraction via RBF for water provisioning (Fig. 2). In total, nine lakes and many reaches of the rivers Spree, Dahme and Havel are affected by RBF (Gillefalk et al., 2018).

Water suppliers in Berlin produce approximately 75% of the drinking water by bank filtration and artificial groundwater recharge (Fig. 3).

Because of pollution, direct supply of river water has dropped to 1%.

In order to be able to extract the required quantities, the groundwater is replenished with treated surface water by storing water in shallow earth basins or in natural ponds and ditches. The upper layers of soil act like a giant filter. The natural cleaning power of the soil improves the quality of the water physically, chemically and biologically, so that it is comparable to that

Fig. 2 – Riverbank filtration as part of a semi-closed water cycle (Gillefalk et al., 2018).

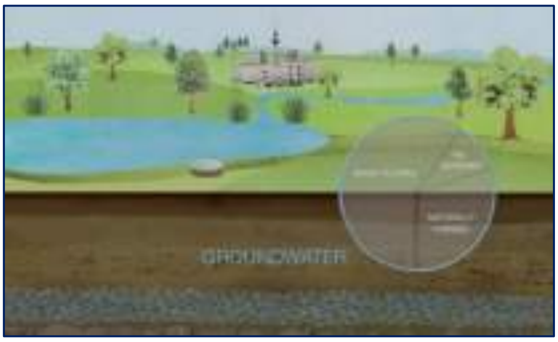

Fig. 3 – Groundwater supply origin (https://www.youtube.com/watch?v=Oy3mmckWz1k)

of natural groundwater. On the way to the wells, percolated water also reaches the same temperature as groundwater.

Geographical setting

The Berlin water supply region has an area of 892 km2 and a population of 3.6 million. It extends 45 km at its widest point from east to west, and 38 kilometres from north to south. The River Spree flows through the city's districts from east to west, forming a seven kilometres wide valley, bounded by high areas in the north and south. It then flows into the valley of the River Havel near Spandau. These valleys are part of the Warsaw-Berlin Glacial Valley formed by the water masses which melted after the Ice Age. They are filled with sand and gravel at a depth starting at 30 metres. These gravel layers contain the groundwater resources which serve as the basis for Berlin's drinking water supply (https://www.bwb.de/en/2164.php (Fig. 4).

Fig. 4 – Berliner Wasserbetrieb (http://my.page2flip.de/8563996/9953154/9955547/html5.html#/1).

Detailed explanation

Riverbank Filtration is a technology that operates by pumping water from wells drilled along the banks of a river. During the pumping process, river water infiltrates into the riverbed sediments and is purified along the way (Fig. 5).

RBF is a natural pre-treatment technology (nature-based solution or NBS) that uses sand and gravel aquifers as a natural filter – instead of chemicals – to pre-treat surface water and groundwater supplies, in a cost-effective approach.

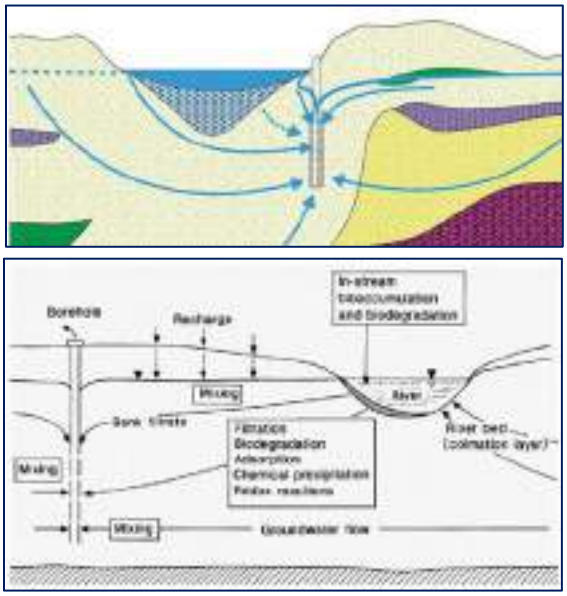

Fig. 5 – Riverbank Filtration scheme. (https://www.youtube.com/watch?v=Oy3mmckWz1k and Hiscock & Grischek, 2002).

The type of sediments between the surface water source and the groundwater intake, as well as the distance between the water source and abstraction point, determine both water quantity and quality. A balance of the two is required: the intake needs to produce sufficient quantity of an acceptable quality.

Fig. 6 shows the typical flow conditions associated with different types of riverbank filtration schemes.

Riverbed clogging can have a significant impact on water quantity. To overcome this, the construction of artificial ditches and side channels for further infiltration zones has been created. Additionally, RBF intakes can also be increased through managed aquifer recharge methods, such as infiltration basins, gully plugs, check dams, leaky dams and groundwater dams in seasonal rivers.

To improve water quality and to achieve better infiltration zones, a specific sand layer has more recently been incorporated in percolation ditches, channels and ponds. A further stage of development has been the construction of recharge basins.

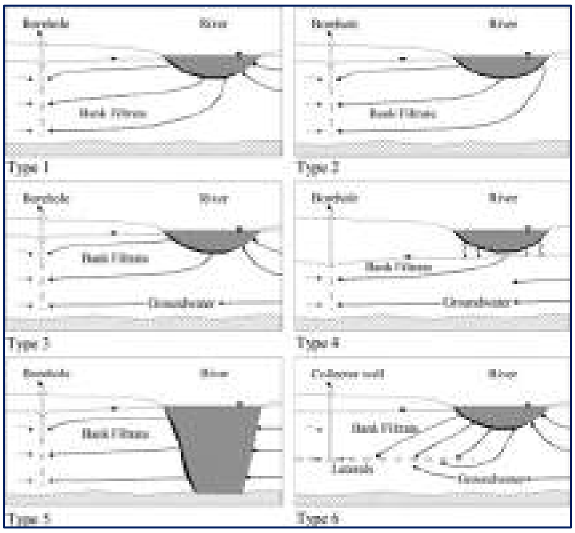

Fig. 6 – Schematic representation of types of flow conditions at riverbank filtration sites (Hiscock & Grischek, 2002) [1]

[1] The majority of riverbank filtration schemes are of Type 1. Groundwater flow beneath the river (Types 3, 4 and 6) is typically neglected at most sites. The formation of unsaturated conditions beneath the river occurs if groundwater abstraction rates are not adapted to the hydraulic conductivity of the riverbed or if the hydraulic conductivity of the riverbed material becomes clogged due to surface water pollution inputs (Type 4). At some sites, the riverbed cuts into the confining layer (Type 5). Collector wells are used with laterals at different depths, of different lengths and directions. Type 6 gives only one example with a lateral towards the river.

The water well intakes are located at a short distance away from a surface water source (usually less than 50 meters), which means that the percolation and retention time may vary from five to one hundred days. The microbiological, chemical and physical water quality of surface water is much improved through RBF due to the combination of natural treatment processes, though a final treatment is usually still needed. Indeed, increasing chemical pollution, which can result in high concentrations of nutrients, heavy metals, organic compounds and micropollutants in the river water, led to the introduction of supplementary pre- and post-treatment steps to build up a multiple-barrier system.

A variety of technologies may be applied to treat bank filtrate, depending on the river water quality (Fig. 7).

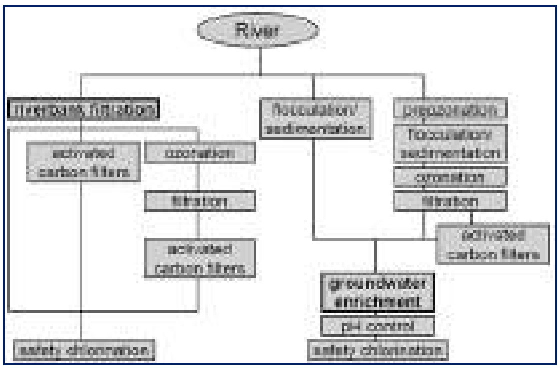

Fig. 7 – Process scheme development of river water treatment in Germany (Schmidt et al., 2003).

Typically, aeration or ozone may be used to oxidise iron and manganese from anaerobic aquifers, and activated carbon can be used for adsorption and protection against more persistent contaminants. Granular activated carbon filters, often combined with ozonation and filtration are also used.

Fig. 7 also presents the usual treatment scheme when artificial groundwater recharge is added in infiltration basins to increase the water volume available.

RBF water treatment provides particle removal, pathogen removal, organic and inorganic chemical removal, peak smoothing in spills, temperature equalisation, reduction in DBP formation, and production of more biologically stable water.

Historical overview

The effectiveness of bank filtration and artificial groundwater recharge has long been recognised in Germany. In the late nineteenth century, after various bacterial diseases caused by direct intake of drinking water from rivers (e.g. an outbreak of epidemic cholera in Hamburg in 1892/93), direct extraction of surface water for public-water supply was discredited and was replaced or supplemented by artificial or natural subsoil passage of river water due to its efficiency in removing microorganisms from the infiltrating surface water (Schmidt et al., 2003).

Today, approximately 16% of the drinking water in Germany is produced from bank filtrate and more than 300 water works use bank filtration, with roughly 50 plants based on artificial groundwater recharge (Fig. 8).

Berlin water supply is an emblematic example of RBF and is providing knowledge as a living lab for understanding and learning about the improvement of physical, chemical and biological water quality.

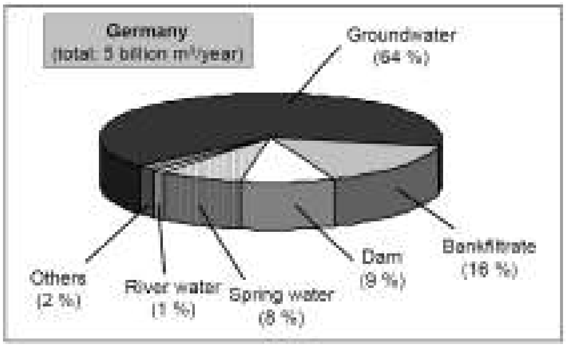

Fig. 8 – Sources used for drinking water treatment in Germany (Schmidt et al., 2003).

Evidence of benefits from implementation

Some of the benefits of RBF are:

- Reduces turbidity in a cost-efficient manner.
- Removes particles, biological contaminants and biodegradable compounds.
- Improves microbiological, physical and chemical water quality compared to surface water.
- Brings a more consistent water quality and temperature.
- Reduces the need/cost for disinfection.
- Decreases construction and operation costs, offering the lowest costs among water supply options (e.g., when compared with pumping from deeper aquifers).
- Generates less sludge.
- Has easy maintenance.
- Is not susceptible to invasive plant infestation and has no impact on fisheries.

Replication potential in the SUDOE region

The use of Riverbank Filtration in the SUDOE region has strong replication potential since these are well established techniques tested in many hydrogeological settings with similar characteristics to the SUDOE region. Furthermore, the specific conditions of this region (e.g., high temperatures with high evaporation; algae blooms in surface reservoirs) are naturally attenuated when using water from RBF.

The passage of water underground with a natural multiple barrier sand filter system provides several benefits for drinking water treatment. The results obtained in Berlin show that during infiltration and underground transport, processes such as filtration, sorption and biodegradation produce significant improvements in raw water quality, therefore reducing subsequent treatment needs.

Future outlook

The majority of the Berlin drinking water supply comes from bank filtration and artificial groundwater recharge. This is a process where river water infiltrates into the riverbed sediments, being purified along the way, and is pumped in wells located along the river.

This natural pre-treatment technology, which uses the aquifer's sedimentary material as a natural filter to pre-treat surface water and groundwater supplies, is a cost-effective approach. Though bank filtration diminishes the loads of contaminants present in source water, there is still a need for future research on some aspects, such as.:

- The influence of scale factors and local environmental conditions on soil-water interactions and biodegradation processes.
- The production of undesirable transformation products in the aquifer and eventually in drinking water wells.
- The seasonal dynamics of temperature and redox conditions temporally establishing separate zones where certain compounds can modify their reactivity, their capacity to produce metabolites, and/or their redox behaviour.

Globally, there are also future challenges derived from climate change, such as higher temperatures and less summer precipitation, which may also impact in higher concentrations of nutrients and persistent trace organics that can lead to a shift to more anoxic (anaerobic) conditions retarding the contaminants degradation.

Management of bank filtration schemes should be incorporated into wider catchment planning in order to limit potentially polluting activities in the groundwater recharge area and also to balance river infiltration losses with the ecological needs of the river.

Key points of the innovative method

In Berlin, and Germany as a whole, bank filtration and artificial groundwater recharge have been used for the drinking water supply at several sites making use of different subsoil characteristics for water quality improvement, and no loss of purification capacity could be noticed (Schmidt et al., 2003).

Riverbank Filtration is an innovative method which is being continuously subject to improvements, its main characteristics being to:

- Bring a more consistent water quality (microbiological, physical and chemical) and temperature in a natural and cost-efficient manner.

- Reduce the need/cost for disinfection.

- Decrease construction and operation costs (less sludge, easy maintenance), offering the lowest costs among water supply options

Acknowledgments

This innovative practice was selected from the initial broader thematic "Recharge, treatment and storage of alternative water sources in aquifers (Managed Aquifer Recharge)" after discussion between the PPA and LNEC.

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MAR and in situ treatment

Subsurface dams for groundwater storage in semi-arid regions of Northeast Brazil

Water is a scarce resource in the semi-arid region of Northeast Brazil. As stated by Shubo et al. (2020), in the Brazilian countryside, especially in the semi-arid region, there was a lack of rainfall during the time period 1981–2019. Climate models show a trend towards increased frequency and intensity of droughts and lengthening of dry periods in the northeast, as has already occurred in some Brazilian regions (Denys et al., 2016, in Shubo et al., op. cit.). From 2012 to 2017 another major drought affected the semi-arid region with 2015 considered the most critical year of that period (Shubo et al., op. cit.).

The drought of the 1990s led to the development of subsurface (or underground) dams, with the aim of storing and providing water to supply small villages, communities and agricultural activities, while being able to retain people in these arid regions and avoiding their migration into the main cities. Such dams have the advantages of being able to store larger volumes of water than the natural alluvium aquifers underlain by crystalline basement rocks, and of being less susceptible to evaporative losses as the water is stored underground.

Responsible entity

Since 2003 the implementation of subsurface dams in northeast Brazil is supported by the Cisterns Programme – water for drinking and for agriculture (*Programa Cisternas – água para beber e para agricultura*) of the Ministry of Citizenship of Brazil (Fig. 1) subsidises the construction of subsurface dams for people living in rural areas without a water supply or having limited access to water of good quality.

Fig. 1 – Cisterns Program.

However, much earlier during the development boom of the 1990s, several state governments of the semi-arid region launched programmes for the development of the subsurface dams.

Institutional setting

Several entities have developed programmes, acted and researched in the area of the subsurface dams:

ASA – *Articulação Semiárido Brasileiro* (Articulation of Brazilian Semi-Arid) a network of more than 3,000 civil society organisations dedicated to putting into action the political project of semi-arid coexistence.

EMBRAPA - *Empresa Brasileira de Pesquisa Agropecuária* (Brazilian Agricultural Research Corporation) of the Ministry of Agriculture, Livestock and Food Supply has been carrying out research since the 1980s, and has contributed to sharing the experiences of farmers, development agents and researchers through the exchange of popular and technical-scientific knowledge.

CAATINGA – An NGO that developed a type of subsurface dam and has been supporting local communities and constructing several dams.

IPT - *Instituto de Pesquisas Tecnológicas de São Paulo* (Institute for Technological Research), a public research institute linked to the Secretariat for Economic Development of the State of São Paulo, it has developed studies and built subsurface dams in the Ceará and Rio Grande do Norte states.

SECTMA - *Secretaria de Ciência, Tecnologia e Meio Ambiente* (Secretary of Science, Technology and Environment) of Penambuco State, launched a programme that promoted the construction of around 500 subsurface dams.

UFPE – *Universidad de Federal de Pernambuco* (Federal University of Pernambuco) developed the methodology and technology to build the subsurface dams in Pernambuco state.

Geographical setting

The northeast Brazilian semi-arid region covers an area of 1,108,435 km2 and includes 1,348 municipalities distributed through nine states (Fig. 2). Precipitation is lower than 800 mm/year, the aridity index is lower than 0.50, evaporation is high, and the short rainfall season presents irregular distribution (Fig. 2).

Fig. 2 – Semiarid region in NE Brazil (Source: Agência Nacional de Águas).

This region is considered one of the most vulnerable to climatic variations due to irregular rainfall, water deficiency, low capacity for adaptation and the poverty of the population (Silva et al., 2021).

Fig. 3 represents some of the subsurface dams included in the IGRAC website.

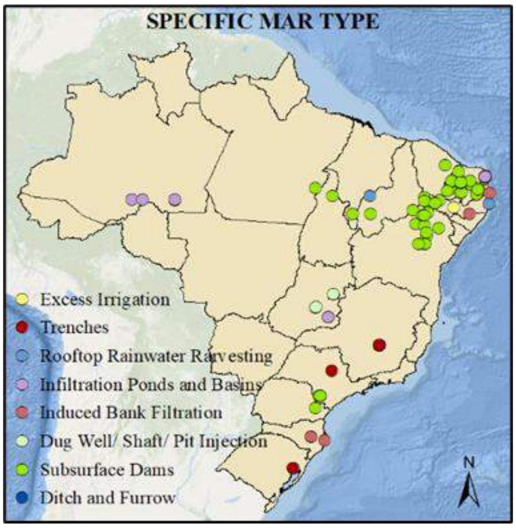

Fig. 3 – Representation of the subsurface dams (green dots) located mainly in NE Brazil (Source: Shubo et al. (2020), as reported on IGRAC website.).

Detailed explanation

General description

This description is adapted from Shubo et al. (2020) with inputs from Costa (2004).

An underground dam allows rainwater to be stored under riverbeds during the rainy season, making it available during the dry season. Although simple, its construction must comply with some technical requirements regarding its location: the alluvium must be predominantly sandy; the slope must be as flat as possible; the depth of the impermeable layer must be greater than 1.5 m below the riverbed; the construction site must be at the narrowest part of the riverbed; the river basin head, where there is less water, should be avoided; and the recharge area upstream of the dam should be of at least 1 km of alluvium material. Regarding water quality, low salinity rates are essential to make its implementation feasible and this should be addressed before building the dam.

The core idea of its operation is to restrict the flow of the alluvial aquifer by building an impermeable transverse barrier, thus raising the level of the upstream water table. In Brazil, there are two types of underground dams suited to local features: the submerged type, also known as the Costa & Melo type, and the submersible type. Both of them make use of a buried impermeable barrier to restrict the underground flow and are equipped with an Amazon type well to allow the use of the accumulated water in the saturated zone. To build the barrier, a trench is dug down to the impervious layer. Then a plastic layer is placed over the barrier and covered with the excavated material to block the groundwater flow. Other kinds of impermeabilising options exist, as described in Costa (2004).

The first type, known as a Costa & Melo-type underground dam (submerged dam), is suitable for the bed river of temporary creeks where the thickness of the sedimentary layer is greater than 1.5 m. This style of construction uses an impermeable barrier that is completely buried, retaining only the groundwater flow, making the water table in the alluvium rise upstream of the barrier. There is no physical constraint to the runoff.

In the Brazilian semi-arid region, mainly in the states of Pernambuco, Ceará, and Rio Grande do Norte, this is one of the most commonly applied techniques to deal with water shortages. Fig. 4 shows a schematic of a Costa & Melo type underground dam.

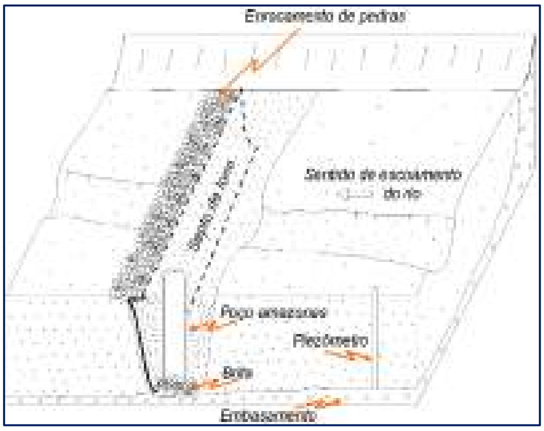

Fig. 4 – Schematic of a Costa & Melo subsurface dam (Source: Cirilo, Costa, 1999).

In the second type of underground dam, the submersible underground dam, apart from the buried barrier, there is another one made of rocks, bricks or clay over the riverbed. This barrier makes the superficial flow spread over the surrounding land, creating a water pond that lasts for up to two to three months after the end of the wet season. The process of lake formation generates a gradual accumulation of sediments, increasing the thickness of the soil upstream of the dam, thus providing an increase of the storage capacity over time, as happens in sand dams. This technique is suitable for small rivers and water pathways. This dam over the riverbed is equipped with a spillway made of concrete to allow excess water spill over and preserve the barrage, limiting the water level. Upstream, close to the dam, a large diameter well is built to recover water for irrigation and for other uses, such as livestock water supply when the water level falls below ground level. Fig. 5 shows a schematic of the submersible underground dam.

Next a more detailed, yet synthesised, description of the building steps of a Costa & Melo type underground dam is presented.

Detailed description of a Costa & Melo subsurface dam

This section describes the basic concepts for the construction of the Costa & Melo dam, based on the work of Costa (2004).

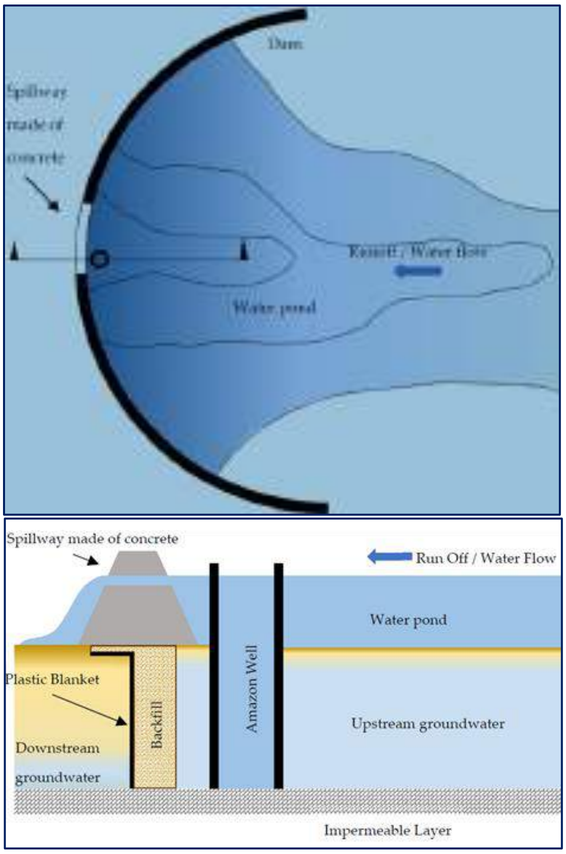

Fig. 5 – Schematic of a submersible underground dam (top: plant view, bottom; cross section) (Source: Shubo et al. 2020).

This dam model was developed by researchers of the UFPE, Waldir D. Costa and Pedro G. de Melo, at the beginning of the 1980s and further adapted to local conditions by the former researcher.

It consists of: (1) the excavation of a straight trench perpendicular to the stream's direction; (2) the location of an impermeable barrier inside the trench; (3) the building of one or more large diameter wells, one of them located besides the impermeable barrier and containing drains along the trench; (4) a surface rock filling, on the surface of the impermeable barrier downstream side; and (5) implementing one or more piezometers upstream in the alluvium area influenced by the dam.

The main advantages are: (1) execution is fast (one to two days if machinery is used); (2) low construction costs; (3) may be built using local labour; (4) allows monitoring of the salinity and the water level; and (5) may be used for multiple water usages.

The main disadvantage is that it requires specific local physical conditions as set out in the previous section.

Two of the main issues in implementing a subsurface dam are the social aspects and the water demand. It is crucial that the opportunities provided by constructing the dam are acknowledged by the local community and that its owner is committed to preserving and exploiting the maximum water availability, mainly by growing the adequate crops.

Prior to the construction of the dam, and to find sites with the adequate conditions, some research must be done:

(1) Data survey: research suitable local communities situated in conditions suitable for irrigated agriculture; climate data; hydrogeological reports; topographical and geological maps; and areal-photo maps.

(2) Analysis of the data survey searching for the adequate physical conditions.

(3) Field survey, including of water quality.

(4) Geological survey with or without geophysics profiling, in order to define the geometry of the alluvium bed and its granulometry.

(5) If possible and justifiable, well drilling and pumping tests to define the hydraulic properties of the alluvium; and collecting of water samples for chemical analysis.

(6) Designing the subsurface dam, considering: (a) length of the dam, (b) average depth of the trench, (c) trench width, (d) recommended barrier type, (e) type of large diameter well, (f) number of needed wells, depending on the alluvium extension, and (g) number and location of the piezometers.

(7) Prepare the final conclusive report.

Costa (2004) goes through a thorough description of all the construction details of the underground dam. To get further information the reader it is encouraged to read this work (in Portuguese).

Using a large diameter well, located in the deepest part of the alluvium upstream of the dam, allows for complete use of the groundwater and depletes the aquifer during the period of the first annual rainfalls. This renews stored water, thus avoiding salinisation processes due to progressive evaporation.

Historical overview

The present overview is based on Netto et al. (2007). The first historical records of subsurface dams go back to the Roman period in Sardinia (Italy) and North Africa. Since the beginning of the eighteenth century, dams have been used mainly in north and southeast Africa, India, Israel and Iran. They were also used in the Sahara and, at the end of the nineteenth century, in California.

The first subsurface dams in Brazil date back to 1919 in Paraíba and 1920 in *Rio Grande do Norte*, both semi-arid regions, for agricultural development. Other dams were put in place after 1935 in several semi-arid Brazilian states, mainly during the 1980s and 1990s, to combat water scarcity and develop agriculture in local communities. This was accomplished with the help of NGOs, public institutes and universities.

For example, in 1997, SECTMA constructed six experimental units in Caruaru municipality (Pernambuco state). Due to the promising results, Pernambuco state launched a programme that promoted the construction of around 500 subsurface dams. UFPE, with the help of their students, followed-up with hydrology, hydrochemistry and socio-economic studies of some of these dams, namely those constructed on the Mutuca river in the Pernambuco state (Costa, 2004).

Since 2007, the ASA has been installing subsurface dams, and, through the programme One Land Two

Waters (P1+2), which is part of the Cisterns Programme, has built more than , units, which benefited more than 5,415 inhabitants. Fig. 6 shows the distribution per state according to the ASA (2018, in Silva et al., 2019).

Studies continue today and EMBRAPA and partners are developing an edaphoclimatic zoning project for potential areas for the construction of underground dams in the Alagoas semi-arid region (ZonBarragem project). Based on the map generated as a result of the project, the Government of the State of Alagoas launched the State Programme for Underground Dams (Silva et al., 2021).

Fig. 6 – Number of subsurface dams built between 2007 and 2018 under the programme One Land Two Waters (P1+2) (Source: ASA 2018, in Silva et al., 2019).

Evidence of benefits from implementation

Advantages of underground dams

Some of the major advantages of these dams are, from a technical point of view:

- The technology used behind these dams is very simple. In fact, other than community wells, these dams are the simplest and the most effective system for serving the water needs of the poorer communities of Brazil.
- These dams are highly economical as they are built using locally available resources and technology.
- These dams are also easy to install, requiring no external expertise for operation and maintenance.
- In comparison to surface water reservoirs, these dams have very low evaporation rates.
- Being based on simple technology, they can easily be implemented along with other technologies like soil and water conser-vation techniques, and dug wells upstream.

From a social and agricultural point of view the advantages are (Silva et al., 2021):

- Contribution to families' food sovereignty and nutritional security.
- Increased access to and multiple uses of water.
- Diversification and integration, providing greater resilience and sustainability to family-based agroecosystems.
- Strengthening social inclusion and the productive organisation of women and young people.
- Surplus is sold at local markets.
- Creates a solidarity space that is self-managed and farmer-led.
- Is aligned with five of the 17 Sustainable Development Goals (SDGs).

Disadvantages of underground dams

At times, installed dams leak or fail to provide good quality water, which shows how many vital issues need to be addressed before construction of these dams are carried out on a large scale within a given alluvial valley.

This may be overcome by the operating and adequate monitoring practices of the exploitation of the alluviums and their crops.

A general disadvantage of the construction of subsurface dams may be baseflow reduction affecting some groundwater dependent ecosystems.

Replication potential in the SUDOE region

Low precipitation and high evaporation areas in the SUDOE region geologically composed of crystalline bedrock where alluviums develop are acceptable areas where small scale agriculture could be developed if underground dams were constructed. Particular attention should be paid to the general location conditions outlined previously. The Alentejo region in southern Portugal could be a candidate region for the introduction of these technologies.

Future outlook

For small rural communities and, in Europe, communities willing to downshift their way of life, crop production in water enhanced small regions could become a desirable practice. Before implementing this kind of project, a general study concerning the water deficits that could be supplied using this infrastructure should be performed, including of the crop types and the crop water demands.

In the Alentejo region the underground dam solution may be boosted by the fact that under most climate change scenarios this region is expected to become more arid.

Key points of the innovative method

- This technology has been used with high success in several semi-arid regions of the world.

- It allows local community development and their retention in the rural areas.

- The technology is low cost and easy to implement using local manpower.

- Nonetheless, it requires geological and socio-economic studies to define adequate areas for it to be implemented.

- The operation of these areas requires cooperation of the owners for the best management of the farm areas (water exploitation, crop growing, monitoring water quality and groundwater level).

- The existence of a network of organisations facilitates the implementation of these programmes to combat droughts and desertification.

Acknowledgements

This innovative practice was suggested by Prof. José Saldanha Matos of Technical University of Lisbon (IST-CERIS).

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Factsheets of “ICT and modelling” cases.

Aquadvanced: Improving a water distribution network's efficiency

Aquadvanced Wellwatch® is a technological solution developed by Suez and Schneider Electric and implemented by Aigua de Rigat.

Given the difficulty of having an efficient extraction system, avoiding water losses and breakdowns, knowing the levels of the wells, and carrying out a sustainable management of the water resource, this technology allows real-time monitoring and continuous optimisation of the efficiency and performance of both the well and the pumps by controlling the parameters in real time.

Aquadvanced Wellwatch® is able to integrate into an interface all the parameters related to the proper functioning of the collection and distribution system. This decision support tool allows a new management model based on real-time control. It allows you to make decisions in advance, advancing maintenance actions in the distribution system.

The application of this method contributes to the reduction of costs and improves efficiency in the management of water resources. The replication capacity will depend on both the type of system and the economic capacity to acquire this technology. The trend towards real-time data analysis makes it a promising technology in a context of water scarcity and climate change.

Responsible entity

Aigua de Rigat was established in the early 1920s to meet the water demand of Igualada, Vilanova del Camí and La Pobla de Claramunt. For almost 100 years it has offered a quality water supply service to more than 29,000 service points (homes, industries and shops) in the region of l'Anoia.

Aigua de Rigat specialises in all processes related to the integral water cycle and has a team of professionals committed to meeting the specific needs of each municipality and its users.

https://www.aiguaderigat.cat/inicio

Currently, the management model of Aigua de Rigat is based on experience and constant innovation, and proximity to homes and companies, which allows it to adapt to their needs, offering the services of the integrated water cycle.

In Aigua de Rigat the drinking water service of six municipalities is managed, involving the distribution of 5,830,000 m3 per year to a population of 61,708 people using the most advanced technology.

Institutional setting

Aigua de Rigat is a company controlled by Agbar, a subsidiary of the French multinational Suez, and the City of Igualada (La Veu, 2018).

Suez and Schneider Electric created a joint venture with the aim of making it a leader in the water digitalisation sector (Independent, 2021).

Aquadvanced is part of the launch of “Advanced Solutions”, a new range of tailor-made solutions offered by Suez Environment and Schneider Electric to respond to the challenges of local administrations and industry (Schneider Electric, 2021).

Geographical setting

The Carme-Capellades aquifer (CC) is a body of water whose intense exploitation has caused a significant decrease in levels in recent decades, worsening its quantitative state and affecting the natural discharge in different points such as the Capellades raft.

In area P1, covering the municipalities of La Llacuna, Mediona, Santa Maria dels Miralls and a small part of Bellapart and Querol, is the recharge zone. In area P2 the upwellings of the aquifer are located and includes the municipalities of Orpí, Carme, the Torre de Claramunt, the Pobla de Claramunt, Capellades, Sant Joan de Mediona, Cabrera d'Anoia and Sant Quintí de Mediona (Martí. P. O, 2020).

Detailed explanation

Aigua de Rigat is committed to the preservation of all water sources, including underground ones. In this area, it is committed to advanced and sustainable management based on the optimisation of resource extraction. In addition, it monitors the risk of overexploitation and promotes the artificial recharge of aquifers, which alleviates pressure on water ecosystems.

Figure 1 Location of the CC aquifer, the recharge zone (P1) and the aquifer upwellings (P2). Source: https://www.revistaigualada.cat/wp-content/uploads/2020/12/revista-igualada-66-24.pdf

The dependence on rain, and more specifically the scarcity of this in recent periods of drought, as well as the pressure to which these underground catchments are subjected, means that the wells require continuous monitoring to ensure their maintenance, control their performance and optimise the capture of groundwater resources. To carry out a sustainable management of water resources, Aigua de Rigat has implemented an innovative advanced management system, called *AQUADVANCED® Well Watch*, which allows for control of water availability in the wells in real time (Aigua de Rigat, 2021).

AQUADVANCED® Well Watch is the pioneering global solution for continuously monitoring and optimising the performance of wells and their pumps.

Suez Agriculture's proposals incorporate complete monitoring of the survey (levels, flow, pressure, electrical voltage, power, etc.), communication through a 4G modem to send data to SCADA or computer systems for data hosting, alarm SMS and e-mail reports, and efficiency ratios to assist in efficient management

Figure 2: Hydraulic and electrical signals, and calculations viewable in the interface.
Source: https://www.construccionyvivienda.com/2021/03/03/suez-monitoreo-y-optimizacion-de-pozos-y-bombas-con-tecnologias-well-services-y-aquadvanced-well-watch/

and create a database.

The Aquadvanced Wellwatch® platform integrates all hydraulic and electrical signals into a single local interface and calculates yields and efficiency ratios that are used daily in sounding control work (Suez, 2021).

Advantages:

- Increased service life of wells and pumps.
- Reduced operating and investment costs.
- Well-managed water resources and sustainable availability of groundwater resources.
- Controlled water resources and secure access to groundwater resources.
- Optimisation of maintenance plans.

With the monitoring of groundwater catchments through data that is displayed in real time to visualise the aquifer resources, the efficiency of the water collection and extraction can be controlled. The objective is to avoid water loss and equipment breakdowns, reduce the impact on citizens in the event of incidents or changing weather conditions, to improve energy efficiency, and to guarantee efficient performance of the water supply. This system allows control of the wells of Les Comes, one of the main sources of water supply in the area of Igualada which has its origin in the Carme-Capellades aquifer (Aigua de Rigat, n.d.).

For example, one of the sensors that monitor the performance indicators has been installed in the well of Les Comes 5 and records water level depth, pumping flows, impulsion pressure and electrical parameters. Using this data, the performance of the equipment is optimised and can be adapted to the meteorological conditions (times of drought or rain). As a result, Aigua de Rigat can plan maintenance operations and reduce the impact on citizens and farms. Likewise, this control tool helps to preserve farms, prolong the useful life of the equipment, and optimise energy consumption. The innovation capacity of Aigua de Rigat allows it to implement solutions that improve the lives of citizens and the health of the planet, with the aim of contributing to the achievement of the UN Sustainable Development Goals.

Aquadvanced Wellwatch® is a decision support tool that enables advanced management through continuous control.

Historical overview

The combination of blockchain and the Internet of Things (IoT) will define a new technological paradigm in the coming years. The combination of both technologies in the monitoring and management of energy and water resources has much potential. While IoT tools collect a large accumulation of data in real time, blockchain technology is able to evaluate, simulate and even make predictions.

IoT is a very useful technology to model and monitor environmental phenomena. It facilitates wireless network connection, allowing distant devices to be connected to each other more easily. This is applicable in multiple relevant fields, from treatment plants (wastewater or water treatment plants) to the modelling of aquifers, or the control of the quality and quantity of water resources.

Artificial intelligence (which can assess, understand, recognise and decide) combined with blockchain (to verify, execute and record) can generate models that allow monitoring and prediction. In this sense, machine learning stands out, a technology based on statistical learning methods (Mustafa, H.M et al., 2021).

This combination has been applied in numerous recent projects, for example, Open Water Web (an Open Data Platform), Waspmote Smart Water (a platform for quality monitoring), and WaterWatch (a tool to produce multiple flow maps), among others (Salam, A., 2020).

Evidence of benefits from implementation

With this tool you can integrate and analyse all the data on the status and operation of the network and facilities, and transform the data into information and simple criteria for decision making.

The Aquadvanced Wellwatch® software allows for the optimisation of the extraction operations, guarantees the commitment of supply to the supplied populations, and reduces losses in the distribution network (that can exceed 30% of the volume) for better use of the resource.

Through Aquadvanced Wellwatch®, leaks in the network can be identified and resolved through maintenance or repair of the network in real time.

Replication potential in the SUDOE region

Real-time measurement systems contribute to data collection, reducing problems, and minimising costs. The difficulty of replication lies in access to the software, and the treatment and extraction of the data that provides valuable information.

There is the possibility to acquire the software developed by Suez and Schneider Electric and deploy it in the desired region. There is also the possibility of developing specific software adapted to the particular case, adapting the technological and business approach represented by this initiative in the management of hydrogeological resources, which is applicable to any groundwater exploitation system.

Future outlook

The future management of water resources will be based on the control, analysis and interpretation of data to achieve sustainable and optimised management, an approach that management bodies call "intelligent management". The judicious use of data contributes to guaranteeing the quality and quantity of supply, controlling efficiency and opening lines of improvement based on the information collected, which will be necessary in a context of scarcity of water resources.

Key points of the innovative method

- The management of a water exploitation system based on the collection of data and its interpretation using machine learning methods.

- The implementation of these technologies, together with the evaluation of their performance, should support new strategies in aquifer exploitation systems and distribution of resources to users. This technology has been used with high success in several semi-arid regions of the world.

Acknowledgments

This innovative practice was suggested by Miquel Corredor of Junta Central d'Usuaris de l'Aqüifer Carme-Capellades.

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ICT and modelling

Aqualearning: Using Artificial Intelligence in water resources management

Aqualearning is a project created by Amphos21 and was the winner of the SmartCatalonia Challenge.

This environmental consultancy has developed a software based on artificial intelligence and machine learning that values existing data, giving a new dimension to the processing of data and obtaining simulations at low computational cost. The application helps establish relationships-cause effects within resources and natural systems applicable to the field of prediction of minority contaminants and control of well levels. With the development of sensors, and the increase in the volume and generation of data, these tools facilitate data processing, efficient management and decision making, avoiding the misuse of resources, and reducing costs and time.

Responsible entity

Amphos 21 is a scientific, technical and strategic consulting company at the service of the environment in five main markets (nuclear, mining, water, sustainability and CCS and climate change) and of economic and social development. Amphos 21 began its activities in Barcelona in 1994. Currently the company includes more than 200 professionals, and its 25 years of experience as an international consultant have allowed it to develop projects in more than 20 countries. (CWP, 2022).

Source: https://www.amphos21.com/

The focus of Amphos21 is to propose efficient, innovative, integrated and transversal solutions applying a quantitative method to any solution. The consultancy has acquired extensive experience in the evaluation, analysis and modelling of a wide range of processes in geological fields, including hydrogeology, geochemistry, geomechanics and coupled reactive transport. In this context they visualise hydrological resources in an integrated solution, which synthesises all relevant aspects of the hydrological cycle for a given project.

Institutional setting

Aqualearning is an independently financed project lead by Amphos21. It was the winning project of the SmartCatalonia Challenge organised by the Generalitat de Catalunya (ACA, 2022).

Geographical setting

The project does not have a defined location, activities have been carried out locally (Catalonia), in Europe (Sweden), and in Latin America (Chile and Peru).

Detailed explanation

Aqualearning is a solution based on artificial intelligence (AI) supported by IML's own Amphos21's software. Its main function is to transform data into valuable information. The process used can be broken down as follows:

It begins with the analysis and preparation of the data, evaluating the variables, finding correlations, and separating the data that provide information from those that do not.

A part of the data is used to 'train' the algorithm. In this sense, once the algorithm is trained, its predictions are validated. Validation uses unused data to see if it has the ability and robustness to generate predictions as accurately as possible. When the predictions are already reliable, the algorithm is prepared to generate future alerts or decision making. Aqualearning contains different algorithms developed using open source (TensorFlow technology).

Aqualearning benefits from the cause-effect relationship inherent in natural resource-related processes to manage them using AI.

The software was applied at different sites.

It was applied for the prediction of minority elements in the aquifer of Forsmark (Sweden) where it is planned to build a deep store for nuclear waste. It was able to correlate the appearance of minority elements with the presence of some majority elements using physicochemical data and majority elements (collected since 1994), by means of a decision tree (algorithm typology). The hypothesis was proved correct, with a high coefficient of determination that allowed the prediction of concentrations of barium (97% average accuracy) and uranium and molybdenum (>85% average accuracy).

It was also applied to a water resource affected by mining in Chile and Peru. In these countries, some mining waste generates effluents of strong acidifiers. Currently the experimental process to evaluate the effect of the pH of the waters of each new exploitation or expansion on the environment is slow (30 weeks). Using the data from the first weeks and the concentrations of some elements (copper), the Aqualearning software was able to predict the effect of the pH of the waters at the end of the experiment. The result was achieved with more than 90% accuracy (using 4,230 data), while predictions of copper concentrations achieved 85% accuracy. This contribution makes it possible to accelerate the sizing of mine treatment plants in Peru in advance. Although it does not replace the experimental process, the results of Aqualearning have been a great help in the planning of actions and investments in the cases tested.

Finally, another application of this predictive methodology was made in a groundwater pumping field with 14 active wells. It was known that some of them interfere, but due to the geology and the arrangement of the fractures, which ones had not been identified. Using Aqualearning it was possible to predict the levels of the wells by means of the flow data extracted during the previous days, obtaining a satisfactory adjustment (ICRA, 2022), (IDAEA, 2022).

Historical overview

In the mid-twentieth century, the technologies for control of water resources exploitations were manual, requiring a minimum knowledge and the transfer of this knowledge. Subsequently, alert systems enabled entities in the sector to reduce personnel costs and increase their efficiency.

With the advent of telecommunications, it has been possible to remotely monitor the collection facilities through sensors to collect the necessary data for management and decision making. (R. Lopez, 2020)

More recently, advanced software analyses data in order to acquire valuable information in real time. The current challenge is to use the data in the prediction of the system's responses to a given situation based on the information previously collected (big data).

Evidence of benefits from implementation

The application of the Aqualearning software uses series of historical data, extracting from them relevant information for the management of any monitored system. These tools streamline, reduce costs, and allow prediction and early warning with criteria, for example, in the sustainable management of aquifers and the optimisation of the exploitation of wells. Historical data is used to characterise aquifer response and catchment performance, control contaminant concentration, or reduce energy costs.

It has a relevant application in the optimisation of the water supply service, currently consisting of a completely innovative approach for which Aqualearning supports a technical and methodological positioning of reference.

Replication potential in the SUDOE region

This application is replicable in any system of exploitation of the hydrogeological resources in the SUDOE region that has a data acquisition system, and for which predicting a cause-effect relationship using AI can provide an improvement in the management of the activities developed.

Future outlook

There is no defined limit to the technology and it is applicable in many fields, including water resources management. Constant data collection is already part of the management action. Parallel to the use of sensors, the different decision-making technologies based on the data collected are constantly evolving. The use of AI is postulated as a methodology of wide possibilities.

However, it will be necessary to improve the data processing processes, the homogenisation of these and to develop analysis capabilities for the use of AI in the optimisation of tasks and decision making.

Key points of the innovative method

- It is a pioneering tool for the application of AI in the management and exploitation of water resources.

- It is an efficient tool with proven application.

Acknowledgments

This innovative practice was suggested by Ester Vilanova Muset from AMPHOS 21.

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Intelligent control of the water distribution system in Alicante (Eastern Spain)

Alicante is a province with a water deficit due to its low rainfall, persistent periods of drought and a complex hydrogeological configuration. In 1993, the Provincial Council developed a system capable of monitoring water resources, through a system of remote management and telemetry, with the help of local businesses.

The telemetry system allows the monitoring and managing of the infrastructure and network in in real time. It also contains a tool (ModopENE) useful for improving and optimising the efficiency of drive pumps. Finally, it contains a module that allows the supply network to be sectorised and managed. The remote management and telemetry system generates alerts and warnings in real time that the operators or person in charge receive.

The replicability of these actions lies in the sensorisation of the area. It is a technically advanced solution that can facilitate efficient management systems in other areas with similar contexts of water scarcity and arid conditions.

Responsible entity

The Provincial Council of Alicante, through its Ciclo Hídrico de Alicante, is responsible for the provincial water resources and providing technical advice to local administrations, as well as building hydraulic infrastructures that provide service to municipalities, in the role of the Provincial Institution as the "City Council of City Councils".

DIPUTACIÓN DE ALICANTE CICLO HÍDRICO

https://ciclohidrico.com/

The Ciclo Hídrico de Alicante is a part of the Provincial Administration made up of officials specialising in the management and administration of the water cycle and its infrastructures.

Its objective is to support all the City Councils of the Province of Alicante and other local entities, including enterprises, associations, and communities with municipal representation through the provision of services to ensure the effective development of the municipal water supply service in sufficient quantity and quality to improve the well-being of citizens and the municipal sanitation service, and advising on the optimal management of the resource and hydraulic infrastructures.

Specifically, the remote control and management system of the Diputación de Alicante monitors in real time the hydraulic infrastructures of the province. The data is stored in the Provincial Water Database, which can be accessed from anywhere over the internet. Operating expenses are covered by the Provincial Council's own budget.

Water policy at the provincial level is established around two fundamental objectives:

- The use of own water resources.
- The optimal management of the resources, both own and external, at the municipal and provincial level.

Institutional setting

The Ciclo Hídrico de Alicante has carried out several actions with the purpose of advising local entities on the optimal management of water resources and hydraulic infrastructures.

In the last 20 years, the Ciclo Hídrico de Alicante has invested about € 31 million in studies related to services and facilities. During that time, 128 agreements were signed with Universities, Hydrographic Confederations, consortia, associations, IGME, City Councils and sanitation entities (Diputación de Alicante, 2016).

The 2014 management report includes the companies contracted to develop the remote management system; Sistemas Avanzados Telecom-Levante, S.L, Hard Byte, S.L, Silicon Media, S.L.U. Danysoft Internacional, S.L. (Diputación de Alicante, 2014).

Geographical setting

A good part of the 5,800 km2 of the province of Alicante is permeable terrain, constituting geological formations with aquifer characteristics. The vast majority of Alicante aquifers are found in formations of carbonate nature – limestones and dolomites of the Cretaceous and, to a lesser extent, calcarenites, sandstones and Jurassic or tertiary limestones. Detrital aquifers are less abundant, and their location is limited to the depressions that make up the carbonate reliefs (alluvial formations) and the coastal strip.

Detailed explanation

In 1993, the Telemetry and Control System of Water Resources and Hydraulic Infrastructures was initiated in order to obtain real-time information on the different parameters involved in the water cycle and its municipal management. The high-water cycle is managed by the SISCON IB software and a set of hardware that together make up the SISCON system.

SISCON is a data collection system with a presence in 107 municipalities. SISCON consists of three modules: the SICON IB module focuses on infrastructures and the high network, while the ModopENE module is applied in energy optimisation. Both modules are useful tools for diagnosing, controlling and optimising water flows and energy control. The third module, MapConta, allows the sectorisation of the supply network.

The operation of SISCON can be divided into four:

- Automatic data capture in remote installations, with more than 4,000 sensors, and storage in their internal memory.
- Transmission of data to the central computer by means of a communication medium via radio, on the mesh of repeater stations of the communications system trunking[a] of automatic sharing of resources and channels.
- Information processing in the flexible and simple environment of SISCON IB software.
- Updating and storage of data in the computers of the remote control room in the facilities of the Water Cycle Department (P. Alfaro, 2004).

[a] Radio Trunking Systems are mobile radio communication systems for private applications, forming groups and subgroups of users.

The system is designed to provide real-time and quality information on the following variables (R. Hernández et al. 2017):

- Hydrological: piezometry, hydrometry and exploitations.
- Hydraulic supply infrastructures: catchments, tanks and water treatment plants.

The system is flexible, it can transmit via analogue, digital or telephone radio allowing connection with a multitude of commercial automata.

These characteristics allow SISCON to join other systems and/or applications of the Provincial Council, such as the provincial hydrological information system, exporting data and information collected in the remote management system (Aguas de Alicante, s/f).

Warnings and alarms

Those responsible for hydrological management receive the different warnings and alarms via email or SMS so that they can consult or perform actions on a mobile device. This interface also displays warnings regarding:

- Maximum and minimum flow rates.
- Evolution of the flow rate.
- High night flow.
- Fugue.
- Reagent dosing.
- Faults.
- Electrical parameters.
- Extraction: Depending on the continuity of the extraction, the state of the pump can be estimated.
- Minimum maximum pressure.
- Complex notices: for example, low flow rates and low pressures are indicative of pump failures or drive leaks.

Remote reading

Remote reading is a technology that allows the periodic remote reading of meters, avoiding the need for qualified personnel to visit the meter (Ciclo hídrico, 2017).

There are two basic models of remote reading, the walk-by and the fixed network. The walk-by model requires a meter that emits radio waves at each location. An operator collects the measurements with a receiving device that downloads them to the database. The fixed network model dispenses with the operator by sending the data directly. This system has the advantage of being able to monitor the meter's activity in real time. Currently (2017), the province of Alicante is transforming its walk-by model to the fixed network model (Diputación de Alicante, n/d).

Historical overview

The digitalisation applied to the water cycle is linked to the Alicante Smart Province Strategic Plan which aims to provide the framework for the province, its public services and organisations to be converted into an interconnected smart system to better serve and benefit the community (Diputación de Alicante, n.d.).

The first definitions of a Smart City appeared at the beginning of the 2000s; "A smart city is a city performing well in a forward-looking way in these six characteristics – smart economy, smart people, smart government, smart mobility, smart environment and smart living – built on the 'smart' combination of endowments and activities of self-decisive, independent and aware citizens" (Giffinger et al., 2010, p.13).

Previously, the concept of a Sustainable City, which began to develop in the 1980s, served as a response to the challenges faced by cities by adopting sustainable development, understood as development that manages to face the present needs without compromising those of future generations (WCED, 1987). The intent is that the development of intelligent solutions, with advanced technological elements incorporated into the infrastructure, would improve the lives of citizens, the management of resources and the commitment to the environment (Muñoz, 2011).

In 2012, the European Commission selected certain priority action areas, including energy, transport and ICT. The purpose of integrating technology in all these areas was to achieve positive and real efficiency, as well as a decrease in energy consumption and greenhouse gas emissions (Pulido, 2013). In the field of water resources, an improvement in the efficiency of management using these technologies would result in the optimal use of resources (European Commission, 2014).

These policy initiatives at EU level have affected the digital transformation of the water sector and, among them, the innovations for hydrological management implemented in the province of Alicante.

Evidence of benefits from implementation

The provincial remote management system integrates elements of the entire water cycle and allows communication by analogue and digital means. It is a system that is related to the Hydrogeological Information System and management and optimisation applications present in the Water Cycle.

The system supports and improves the management of hydraulic infrastructures and water resources, reducing costs and improving communication with the users.

Replication potential in the SUDOE region

In the SUDOE region, all entities have control networks and hydraulic infrastructures that can be remotely managed.

The methodology applied in Alicante in the face of a scarcity scenario is an advanced solution and can serve as a reference to contrast and redefine management in other locations in the SUDOE region in order to improve the management itself.

Future outlook

The implementation of remote control and telemetry technologies are a step towards Smart Cities. In this sense, Alicante is a pioneer in Spain, basing its water management on real time knowledge of water resources.

Key points of the innovative method

- The commitment of the Provincial Council of Alicante around the management of water resources has allowed the implementation of the remote management and remote reading system.

- It requires investment and continuous work to improve knowledge and decision making.

- Innovation lies in the vision of the future of those responsible for managing the resource in an arid location and scarcity situation where the resource is a strategic element.

Acknowledgments

This innovative practice was suggested by José Luis García Aróstegui of the Instituto Geológico y Minero de España.

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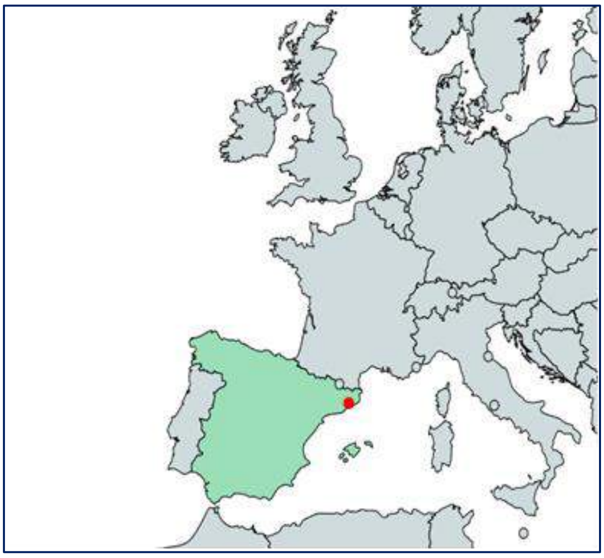
Integrated hydrogeological models for sustainable aquifer exploitation and management in a climate change scenario.



The GIRBESÒS project was born from the water needs of the metropolitan area of Barcelona (AMB) and the possibility of exploiting the Besòs aquifer in order to supply the AMB. The project was developed by the Underground Hydrology Group (GHS) of the Universitat Politècnica de Catalunya GiRBESÒS and addresses the problem of quantity and quality of the aquifer.

It was necessary to develop tools that allow evaluating different management strategies and that in turn minimise the impact on the river, water ecosystems and third parties. These tools had to integrate all the conditions to which the aquifer is subjected, including climate change. Thus, GHS has developed an integrated management model of the water resources of the Besòs which reproduces the different hydrogeological sections.

At the same time, the 3D model developed takes into account the different contouring conditions that include flows, natural recharge, extractions, etc. It is remarkable how the model makes explicit the river as an active part in the model and not as a contour parameter.

Responsible entity

The Underground Hydrology Group (GHS) of the Universitat Politècnica de Catalunya (UPC) is a research group under the auspices of the Generalitat de Catalunya. It is one of the world's leading research groups in the field of hydrogeology, working on the characterisation and modelling of aquifers for over 30 years. Its mission is to promote research, teach and transfer knowledge to society.

The GHS is made up of eight senior professors/researchers, three post-doctoral researchers and around twenty-five PhD and Master's students. The main lines of research addressed by the GHS are:

- Hydrogeological modelling.
- Hydrogeochemical modelling.
- Transport processes in the porous medium.
- CO_2 storage.
- Artificial recharge of aquifers.
- Coastal aquifers and groundwater discharge into the sea.

It is worth emphasising the role of the GHS in the knowledge, monitoring and modelling of local hydrogeological resources, in particular, of the aquifers of the Llobregat and Besòs delta. The models developed by the GHS in these basins integrate in great detail the geological structures of the environment and are able to faithfully reproduce the interactions of groundwater with the different elements that condition its flow (e.g., underground infrastructures, river courses, rainfall dynamics, aquifer exploitations, etc.).

The GHS collaborates with different organisations, in both the public sector (administrations, universities) and private sector, carrying out research and development projects.

Institutional environment

The Catalan Water Agency (ACA), a public company of the Generalitat de Catalunya, is the entity that plans and manages the integral water cycle in Catalonia, always with regard to the principles of the Water Framework Directive. The ACA, through its action plans and measures that are renewed every six years, sets the guidelines to guarantee the current and future supply and the quality of the resource at source. In addition, the ACA, through these action plans, ensures wastewater sanitation and the protection of water bodies and dependent ecosystems.

The current hydrological planning and its program of measures for the period 2022–2026 are particularly focused on favouring mitigation and adaptation to climate change, ensuring the guarantee of supply while favouring the state of water ecosystems.

Part of the measures of this planning cycle aim to finance projects in the Besòs river basin, with a particular focus on managing its underground water resources.

Although the ACA has the ultimate responsibility for the fulfilment of the measures, various organisations participate locally or transversally so that they are optimally developed. In the case of the Besòs basin, bodies such as the Consorci del Besòs, the Consorci Besòs-Tordera, the water supply concessionaires, Barcelona Cicle de l'Aigua SA, the Diputació de Barcelona, the Metropolitan Area of Barcelona, etc., are involved in different parts of the management of the water cycle and in the preservation of the basin.

Geographical environment

The basin of the river Besòs has an area of just over 1,000 km^2. It extends from the northern slope of the Cordillera Littoral to the southern limit of the Plana de

Vic, occupying part of the Vallès-Penedès tectonic trench, to the Mediterranean Sea, where it forms a small delta at the end of the alluvial plain.

The Besòs basin is formed mostly by alluvial and fluvio-deltaic sediments of the ancient Quaternary and recent river terraces of the Holocene period. These quaternary materials are deposited on top of a plinth of slates or Palaeozoic granites in the river section, while in the deltaic zone they rest on a substrate of marls and Pliocene clays.

The study area, in a regional context, is framed in the lower section of the alluvial basin of the Besòs River, from its confluence with the Ripoll River, through the Montcada Strait, to the delta and the mouth of the river (Figure 1).

The different sedimentary assemblages in the basin can be grouped into four hydrogeological units. From the Ripoll River to Sant Adrià de Besòs, there is a free aquifer, directly connected to the river with a mostly influential character. The materials are made up of clean gravels, sands and small silt-clay intercalations.

In the delta area one can distinguish two more permeable levels, formed by sands and gravels, separated by a confining layer of lower permeability of prodelta deposits.

The transmissivities in the basin reach maximum values in the opening zone of the Strait of Montcada, with values close to 14,000 ^{2}/d.

The minimum values of this parameter would correspond to the sediments of the prodelta, being of the order of 10-2-10-3 m^{2}/d.

Detailed explanation

Although the aquifers associated with the Besòs River were intensively exploited during the first half of the nineteenth century and part of the second, their use was never planned or carried out in a sustainable manner. The poor quality of the water bodies, resulting from indiscriminate exploitation and a lack of control, forced the abandonment of a large part of the underground uses in the basin.

With the creation of the ACA and its plans of actions and measures, the quality and quantity of groundwater resources has been progressively recovering. The improvement of water quality in the Besòs basin and the restoration of piezometric levels compared to the 1970s has once again put the Besòs as a reference point in the future planning of the ACA.

In order to guarantee the supply for the population, the ACA plans to increase extractions in the Besòs aquifer in order to produce drinking water to supply Barcelona and its metropolitan area.

For this reason, it was necessary to develop tools for evaluating different management strategies and that in turn minimized the impact on the river, water ecosystems and the effects on third parties. These tools had to integrate the effects on the hydrological cycle that climate change is already evidencing, and that will worsen in the future (e.g., increase in evapotranspiration and decrease in effective recharge, greater occurrence of extreme climatic phenomena, reduction of flows in rivers and consequent increase in the concentration of pollutants, sea level rise and advancing marine intrusion). Knowing these effects and finding the tools to alleviate or adapt to them is fundamental for the survival of natural and human systems.

To this end, the GHS has developed a model of integrated management of the water resources of the Besòs. Integrated hydrogeological models are those that reproduce the behaviour of underground flow and solute transport taking into account the interaction of the river with the aquifer and the presence of underground infrastructures that may cause an impact on the aquifer.

This integrated model is based on a 3D geological model, which reproduces the different hydrogeological units in the field of study, based on the review and interpretation of approximately 800 soundings. The 3D geological model includes the different underground infrastructures that intercept the aquifer, such as the different metro tunnels and the tunnel of the high-speed train line as it passes through Montcada i Reixac.

The hydrogeological model has been developed with the free code MODFLOW 6 that solves the flow equation by a method of integrated finite differences. This approach is ideal for generating unstructured meshes, which allow a better adaptation to the contours, a greater discretisation of singular objects in the terrain, and the definition of different layers with different hydrogeological properties.

The different layers of the model are zoned based on different transmissivity values, according to the bibliographic values and according to the established geological model.

At the same time, the model takes into account the different boundary conditions (lateral flows, pumped extractions, drainage in tunnels, natural recharge) and makes explicit the river as an active part in the model rather than a mere contour condition.

The model settings across the scope are considered very good, since the average square error at most control points is between 0.2 and 2 meters. This fact becomes even more relevant if one takes into account that the hydrogeological system of the Besòs delta has a very large sedimentological complexity.

The good adjustments of the model make it a very powerful tool to be able to simulate future scenarios and plan the different management strategies in a context of climate change. The simulations may include predictions made by the Intergovernmental Panel on Climate Change (IPCC), i.e., sea level rise, or reduced flows in surface courses or rising temperatures, which have a direct effect on evapotranspiration and natural recharge of the aquifer.

Historical overview

The use of water from the Besòs basin does not in itself imply a novel strategy since this aquifer has been exploited since the early twentieth century. In fact, thanks to the extraction of groundwater from both the Llobregat and the Besòs and Llano de Barcelona, the industry of Barcelona underwent great development throughout the last century. It is estimated that extractions for industrial uses and to supply the population reached their maximum value in the 1960s, with values close to 60 hm^3 / year. However, with the migration of industry and due to the poor quality of groundwater caused by pollution, underground resources in the Besòs Basin and Llano area of Barcelona were no longer exploited as intensely. The levels of the aquifer began recovering with the cessation of overexploitation and have returned to close to their natural level.

However, changes in land use, and specifically the phenomenon of urbanisation in the second half of the twentieth century, have caused a progressive increase in levels and recurrent problems of filtration in underground infrastructures (garages, basements of buildings, tunnels, etc.). These drains reached maximum values during the 1990s, with annual volumes of up to 10 hm3. Currently the case of Besòs is paradoxical; while on the one hand it is necessary to carry out permanent pumping, drainage and exhaustion to avoid negative effects, on the other, this water is generally not used and ends up pouring into the sewerage system.

Evidence of benefits from implementation

Knowing the impact that climate change will have on the availability of water resources is essential to anticipate its effects and to be able to prepare coherent plans for this framework. In turn, the model allows simulation of scenarios in which mitigating measures are included, such as a possible increase in extractions or a possible decrease in the availability of water resources due to climate change. These mitigating measures have to do with the artificial recharge of aquifers, which allows for recharging water from different sources (for example, river water or reclaimed water) thus increasing the available reserves.

Future outlook

In recent years, administrations and local entities are making great efforts to achieve the ecological restoration of the Besòs River. More recently, the ACA has specified, in its recent Action Plan for the period 2022–2027 its intention to make a more intensive use of the water resources of the Besòs. The integrated management model developed by the GHS is presented as a planning tool capable of providing administrations with objective arguments for decision-making, guaranteeing the good management of water resources, adapting it to the challenges posed by climate change.

Key points of the innovative method

- Model developed with free code and worldwide reference, which allows the imple-mentation of unstructured mesh.

- Very useful tool for hydrological planning and decision making.

- Climate change adaptation tool.

Acknowledgments

The innovative practice was suggested by the GHS group of the UPC. The development of this tool has been possible thanks to the participation and financing of the Barcelona City Council through the GiR-Besòs Project. The collaboration of Barcelona Cicle de l'Aigua, SA is also appreciated.

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ICT and modelling

Data science in water resources management

IDAEA is an environmental science institute dedicated to future challenges linked to climate change and water scarcity.

The Department of Geosciences investigates the hydraulic, chemical, thermal and mechanical processes associated with hydrogeology. It participates in the development of numerical and mathematical models and modelling techniques for complex processes. In this way, it has developed multiple innovative applications for efficient data management.

These include an application to create geological cuts from sounding data; the use of artificial intelligence to predict the levels of rivers, aquifers and similar physical environments; a program for the calculation of hydraulic parameters from hydrogeological data combined with the integration of neural networks; in addition to other geospatial applications based on the use of artificial intelligence, big data and the advanced processing of big data.

These methodologies arise from the need to properly manage the amount of data intake implied by the current digitalisation of the sector, a growing trend in recent years. To this problem must be added the need for an efficient and immediate management that can be achieved with these open-access applications.

Responsible entity

The Institute for Environmental Assessment and Water Research (IDAEA) is an institute of environmental sciences of the Spanish National Research Council (CSIC) founded in 2008 in Barcelona and dedicated to the study of the human footprint in the biosphere.

https://www.idaea.csic.es

IDAEA-CSIC's work focuses on two of the environmental challenges of our time: the preservation of water quality and availability, and air quality. The work is guided by the principle that our scientific understanding of current threats to global ecosystems is best addressed from a holistic perspective.

The Institute stands out in the analysis of organic and inorganic pollutants and their impact on ecosystems; the study, modelling and management of water resources; the development of algorithms in different scientific fields; and the study of inhalable particles and toxic gases.

Institutional setting

IDAEA was conceived as a new multidisciplinary research institute within the CSIC that brings together a wide range of knowledge in environmental sciences and is organised into two broad Departments – Geosciences, responsible for the contributions reflected in this document, and Environmental Chemistry.

Geographical setting

The methodologies provided by IDAEA are not linked to a location. The projects and publications are available on the IDAEA website.

Detailed explanation

A responsible and efficient management of water resources requires knowledge to face possible conditions and problems related to water.

It is important to integrate conceptual knowledge of water bodies. For this it is required to: (i) know the system (conceptual model), usually with fieldwork and georeferencing using geographic information systems (GIS); and (ii) a monitoring network that provides information on the status of the resource and validates the conceptual model.

Large volumes of data must be collected and stored efficiently in order to be consulted.

In order to relate the conceptual models with the treatment of the data generated by the monitoring, a series of platforms and applications appear to transfer data, integrate them into database systems in order to perform a correct analysis and interpretation, and allow for more efficient management.

Creation of geological sections: Geopropy Tool

This tool allows the creation of three-dimensional geological cuts using an open source in Python. Profiles are generated from polling data.

Water Level Prediction Tool

This tool using machine learning to show the relationships between variables in a certain time series within a hydrological model. In some hydrological models it uses real-time monitoring after an upstream event (rainfall episodes, excess extractions, etc.) to predict the short-term behaviour downstream.

Hydraulic parameter calculation tools

With granulometry, the permeability of the terrain can be determined from a series of analytical formulas. Through artificial intelligence (neural networks) it is possible to identify which formula describes the reality in each case in a more detailed way. Hydraulic parameters are predicted from “cheap” data efficiently by use of complementary empirical formulas and neural networks.

Hydrochemical indicators

Machine learning is used to find the chemical components that indicate a certain group of very specific compounds or high analytical cost.

Geospatial models

Geospatial maps are generated without needing physical processes. An example is its application in the Andes in a complex management situation, a continuous determination of the isotopic composition of rainwater throughout the territory concisely evaluated the recharge of the aquifer without directly measuring it.

Meteorological data provides data on volumes and rainfall. The isotopic data are collected from different analytics and campaigns carried out in the territory that are usually not obtained systematically and/or continuously. Two models are generated that are integrated into one. The first represents the meteorological distribution that overlaps the timing and value of the analytics. The integrated model allows calculations of the isotopy of the waters that are recharging the aquifers.

Managing large volumes of data

To deal with a large volume of data, special database management platforms and data calculation and processing hardware are needed.

IDAEA has applied this methodology in radar interferometry to measure ground deformations. The images that are generated contain millions of pixels, generating hundreds of images. To deal with this volume of data, the data is filtered and then quantified and interpreted. To be able to perform this task requires a more capable system than Excel or a database and hardware with greater computing capacity.

Historical overview

Water management has evolved at different stages depending on the needs and concerns of each time.

Water 1.0: The objective was to increase the supply by dominating the resource, making large dams and transfers. It was necessary to bring water to cities and crops. The cost was less important and the environmental repercussions of the implementations were not evaluated.

Water 2.0: During this period users and managers became aware of the importance of the resource. The economy generated by water and its cost was valued, hydraulic works required greater permits and end users were asked to assume the costs. Importance was given to the uses, differentiating the quantity and quality of water they required. Policies that involved users appeared and social impacts were valued. At this stage of water management, appreciation of the ecological value of water and the environmental impact of its exploitation begins.

Water 3.0: The term sustainable management was introduced, based on respect for the environment, citizen participation and nature-based technologies. Works and actions that increased resilience, the restoration of ecosystems and the preservation of environmental values were financed.

Water 4.0 or Smart Water: This is the digital transformation of water with the aim of making the sector more efficient. It seeks to modernise conventional systems that act on water resources through infrastructures and management systems, taking advantage of the many opportunities presented by Information and Communications Technology that have appeared in the twenty-first century (Bufler et al. 2017; BCX, 2016).

The methodologies developed by IDAEA will facilitate the advance of the management of the resource from stage 3.0 to 4.0 and are among the tools that will allow an intelligent use of water based on intensive monitoring and massive data processing.

Evidence of benefits from implementation

These tools are useful for professionals in the sector and research teams, improve efficiency in the interpretation of data, and allow us to better adapt to new forms of information and decision making. With their application, a more efficient exploration of existing data is possible. They also allow conceptual knowledge to be integrated with the aim of acting more quickly, effectively and adaptably in an area characterised by the complexity and high variability of its different components.

Replication potential in the SUDOE region

The use of these methodologies is not associated with a specific action or location. They are advanced computer tools that allow users to approach current and future problems, based on the management and interpretation of big data and informed decision making.

Future outlook

A growing volume of data requires software and hardware with the ability to integrate various types of data in order to acquire valuable information.

Key points of the innovative method

- IDAEA develops computer tools framed in the generation of complex software suitable for the treatment of large volumes of data.

- The treatment of data provides valuable knowledge about water systems that, with traditional systems, would not be possible.

- These diverse software libraries are aimed at the interpretation of massive data such as those generated by digitalisation in the water sector.

Acknowledgments

This innovative practice was suggested by Enric Vázquez-Suñé, researcher at IDAEA (CSIC).

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Gotham: A new tool for integrated groundwater management

GOTHAM is a project developed by the consortium formed by entities from five countries (Spain, France, Italy, Lebanon and Jordan) led by Cetaqua-Andalusia that is framed in the context of water scarcity and climate change based around three case studies. The first in Dalías, Spain; the second in Lebanon and the third in Jordan.

The project proposes a new framework of water management focused on users, given that current models generate information at each level but without exchange between the different agents involved in the management of the resource (public bodies, private enterprises, users, etc.).

The GTool tool was created in order to evaluate the integration of social aspects; the availability of water resources; their uses and consumption variations; their quality and quantity; environmental impacts and the impact of economic measures. It is an innovative tool designed to promote consensus among all agents involved in groundwater management. It also facilitates evaluation of the viability and main benefits of the managed recharge of an aquifer.

This new approach can be replicated in any area, especially in arid regions.

Responsible entity

Cetaqua, Water Technology Centre, is a model of public-private collaboration created to ensure the sustainability and efficiency of the water cycle considering local needs. This model has established itself as a benchmark in the application of academic knowledge to water and environmental management, generating products and services that benefit society.

Cetaqua integrates, manages and executes research, technological development and innovation projects in the integrated water cycle in order to provide innovative solutions to private companies, public administrations and wider society. It is composed of four independent centres with a common action strategy. The Centre of Andalusia focuses on two main areas of activity: (i) Water 4.0, solutions for digital transformation, and (ii) Water resources, production and regeneration, which has as a priority the conservation of groundwater protection and aquifer research through SAM (Software Asset Management) and the characterisation of the state of aquifers.

The Cetaqua centres have a list of more than 60 publicly funded collaborative projects.

Institutional setting

The GOTHAM Project (https://www.gotham-prima.eu) is framed within the European PRIMA (Mediterranean Research and Innovation Partnership), focused on the development and implementation of solutions for water resources in the Mediterranean basin. This will be developed in the Campo de Dalías (Almería, Spain), and will be replicated at two additional sites, in Laat Baalbeck-Hermel (Lebanon) and in the Azraq-Zarqa Basin (Jordan).

The project has a duration of three years and Cetaqua-Andalucía leads a consortium formed by entities from five different countries: Spain (Cetaqua Andalucía and Universidad de Córdoda – WEARE), France (GAC Group), Italy (Istituto per la Cooperazione Universitaria (ICU) and Engineering Ingegneria Informatica (ENG)), Lebanon (Ministry of Agriculture), and Jordan (National Agriculture Research Centre – NARC).

The GOTHAM project has several participating entities. Hidralia will collaborate in the development of this innovation project together with the municipalities of Roquetas, La Mojonera and Adra, as responsible for the management of the urban water cycle in these localities.

To achieve an effective tool, Cetaqua also has in Andalusia the participation of local collaborators, users, managers and administrators involved in the water cycle, such as the General Directorate of Planning and Water Resources of the Junta de Andalucía, which will allow access to its control network for the installation of sensors and the monitoring of the state of the Campo de Dalías-Sierra de Gádor water body, and the Consorcio del Ciclo Integral del Agua del Poniente (CIAP).

Also participating as stakeholders in the project is the Central Board of Users of the Aquifer of the West of Almeria.

Geographical setting

The Mediterranean basin is at high risk due to climate changes and human factors. Today, the most affected areas are the eastern and southern coasts, which face great water stress and/or water scarcity (GOTHAM, 2022).

The study area in Spain is located in the Hydrological Subsystem III-4, within the Hydrographic Demarcation of the Andalusian Mediterranean Basins (DHCMA). The Campo de Dalías-Gador, with an extension of 330 km2, constitutes a coastal plain between the mountain range of the Sierra de Gádor, with heights of 200 to 300 m, and the Mediterranean Sea. On the pilot site there are ten municipalities (Adra, Berja, Balanegra, Dalías, El Ejido, La Mojonera, Vícar, Eníx, Roquetas de Mar y Félix), with a total population of 261,115 inhabitants in 2019 (GOTHAM, 2022).

The case study includes the aquifers present in the coastal plain and the south flank of the Sierra de Gádor. This system constitutes the main body of water in the province of Almeria due to the volume of underground contributions. Five main aquifers within this subsystem III-4 of the DHCMA are described (GOTHAM, 2022).

Detailed explanation

The GOTHAM project engages with the challenge of water depletion due to controversial uses. To overcome water stress, GOTHAM addresses the decision process of current groundwater governance models, within which questions are raised and knowledge is generated at each level of decision-making but yet there is no exchange of information between the different actors.

GOTHAM aims to develop a user-oriented groundwater management framework that can be applied in all Mediterranean countries to carry out water balance diagnoses to understand the requirements of users and the main issues that affect the quantity and quality of water supply (GOTHAM, 2022). Within this paradigm, studies are carried out to determine the best alternatives to improve the state of underground water bodies. These alternatives are optimised allocation systems integrating all sources of water resources with uses; variations in consumption; and environmental, economic and social impacts. To this end, the GTool tool has been created – an agro-economic module that simulates the effect of different economic measures (incentives for water savings, water pricing, plans in the water market, etc.) and evaluates the economic use values and compensations between users in alternative scenarios of allocation of water resources.

In addition, it attempts to predict future water demand and drought episodes in the area of influence of the groundwater body. In turn, quantitative (overextraction and depletion) and qualitative impacts (such as degradation of chemical status by seawater intrusion and transport of pollutants, including nitrates and organic pollutants) are assessed in order to establish the need to modify water management decisions in advance. This tool also assesses the feasibility and potential benefits of managed aquifer recharge (MAR) and aquifer recovery as an additional groundwater management option, including socio-economic, technical and environmental constraints, as well as the effect on the aquifer in terms of quantity and quality (GOTHAM, 2022).

Historical overview

According to the MITECO (2020), an adequate water governance system needs to generate and maintain up-to-date and relevant information for management objectives, adapted to the needs of the competent administrations, easily accessible and verifiable by stakeholders, and transformed into knowledge useful for decision-making.

The objective of the project is to advance the digitalisation of water management. However, given the current situation in the sector in which there is still no advanced use of ICT, together with the rapid evolution of these technologies, their adoption presents benefits for almost all situations.

Through the implementation or improvement of ICT systems, the following objectives can be achieved:

- Capture of the appropriate information to make management decisions accurately at different levels: national, by basin, by infrastructure element or vertical according to the different parameters of water, volume, availability, quality, health, etc.
- Reduce the costs of inefficiencies in management.
- Enable accountability of water management.

- Allow the planning and modelling of the sector for management decision-making.
- Allow the participation of the agents of the sector and of the community in the management of the water.

Being an indispensable element in the modern management of almost any economic sector, ICT does not determine the priorities of water management in any of its aspects. However, they provide relevant information to agents and decision-makers and help to make its management better known to society. They also allow, through the opening of management and the creation of appropriate internal procedures, the participation of the multiple actors in the sector, including local communities.

It should be noted that the structural changes in the water sector that have to come about as a result of demographic changes, climate change, increased demand and, in general, respect for the principles of water governance, can be adequately addressed by information technologies and these will help to better manage resources. However, the answers to these many challenges cannot be found solely by the implementation of this type of technology. The objectives achievable by ICT can be summarised in the following points:

- Management in real time for which data must be captured with the necessary frequency and resolution.
- Availability of data from a multitude of sources at decision points by using new technologies.
- Common mechanisms for access to common and known data based on open international benchmarks that allow public and private development.
- Opening of the data to make it available to communities and actors in the sector, possibly in real time, enabling active participation.
- Creation of an infrastructure that allows the modelling of water management prior to decision-making.
- Complete digitalisation, eliminating the manual processes associated with paper management.

Evidence of benefits from implementation

GTool is an innovative groundwater management tool specifically designed with the consensus of all water actors (regulators, end users, water producers and suppliers), which will enable a new user-based groundwater management framework – a bottom-up approach rather than the current top-down model in which the regulator sets enforcement rules on an almost exclusive basis. This is considered to be the only way to achieve long-term sustainable management of aquifers due to their complexity in terms of uncertainty (in relation to resources, reservoirs or internal geometry) and monitoring and control by management (usually large areas and a hidden resource) (GOTHAM, 2022).

Replication potential in the SUDOE region

It is a tool applicable in all areas with water need, with large agricultural exploitation, or arid areas, such as the areas where the project has developed: Almeria, Lebanon and Jordan.

Future outlook

This tool allows the possibility of questioning the current management model and proposing a new management model based on users to achieve sustainable aquifer management.

Key points of the innovative method

- A new management model based on knowledge sharing and user involvement.

- Promotes the participation of users from all relevant sectors.

- Uses ICT to support economic, social and environmental decision-making.

Acknowledgments

The innovative practice was suggested by Sergi Compte of the Catalan Water Partnership (CWP).

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Groundwater dating by CFC and SF6 (France)

Figure 1 : Groundwater dating methodology.

Groundwater dating by chlorofluorocarbons (CFC) and sulphur hexafluoride (SF6) dating is a geochemical analysis methodology for estimating the mean turnover time of groundwater. This methodology is developed by the CONDATE-Eau platform of the University of Rennes 1 in France. This expertise is carried by only 8 laboratories in the world, and allows a fine analysis (in picograms per litre), where conventional analyses are generally in micrograms per litre. The use of these tracers allows for understanding of the functioning of aquifer systems via circulation models. CFCs are gases known for their impact on the ozone layer; today there are no more CFC-emitting countries. There are three main sources of CFC emissions: polystyrene foams (CFC-11), refrigerators (CFC-12), and solvents (CFC-113). SF6 is used as an electrical insulator. This methodology was developed in groundwater following the intensification of agricultural practices in the 1970–1980s and a significant increase in nitrate releases. The objective of this methodology was to estimate the residence time of nitrates that move at the same speed as water. The tool is now used by communities, engineering companies and university laboratories as a management tool for aquifer systems to reveal the time needed before observing the effects of action programs aimed at limiting nitrate inputs on a territory. It is also a communication tool for farmers and field actors to show them the time frame in which the results of their efforts will be visible.

Responsible entity

The CONDATE-Eau Platform is the entity responsible for this innovative management practice. It is a platform of the University of Rennes 1 that offers services in hydrogeology and residence time estimation to communities, engineering agencies and other academic partners.

Institutional setting

Since 2000, the Water Framework Directive (WFD) has set ambitious objectives in terms of restoring the quality of water resources (whether they are intended for drinking water supply or not). Within the framework of this Directive, the member states of the European Union must act in particular to protect their drinking water catchments in order to reduce the treatments applied to the water extracted and to fight against the deterioration of the quality of the resource. The water bodies used for water catchments for human consumption (or which may be used in the future) are listed as protected areas. In France, the law on water and aquatic environments (LEMA, n°2006-1772, article 21) and the decree of 14 May 2007 (n°2007-888) have reinforced the existing regulatory tools. These texts have made it possible to use the “Environmentally Restricted Areas” (ERA) system on catchments. This practice can be used on the scale of the catchment area (AAC is the French term) presenting a particular challenge for the current or future supply of drinking water (quantitative and qualitative protection of drinking water catchments). Subsequently, the Grenelle Environment Forum confirmed the importance of the protection of water catchments intended for drinking water supply. The implementation of the Grenelle conclusions (article 27 of the law n°2009-967 of August 3, 2009) thus provides for the protection of a little more than 500 catchments among those most threatened by diffuse pollution as of 2012.

Geographical setting

The practice is carried out on all types of aquifers on an international scale. Several examples of the use of this practice have been carried out in France, Brazil, India, Quebec, etc. There are about 30 projects per year on average of groundwater dating by CFC and SF6, of which 15% are carried out on an international scale.

Figure 2 : Location of CFC and SF6 dating studies conducted by CONDATE-Eau.

Detailed explanation

The estimation of the mean turnover time of groundwater is a geochemical analysis methodology that allows the dating of groundwater from CFC and SF6 gases. The principle is that these tracers tell us the time it took for the water to travel between its point of infiltration and its point of withdrawal. Once the gases are dissolved in the water table, they isolate themselves and keep their atmospheric signature.

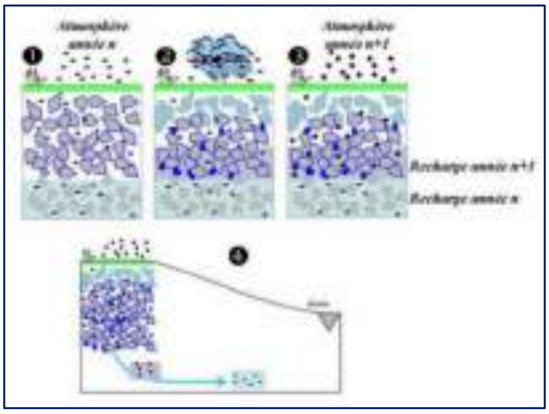
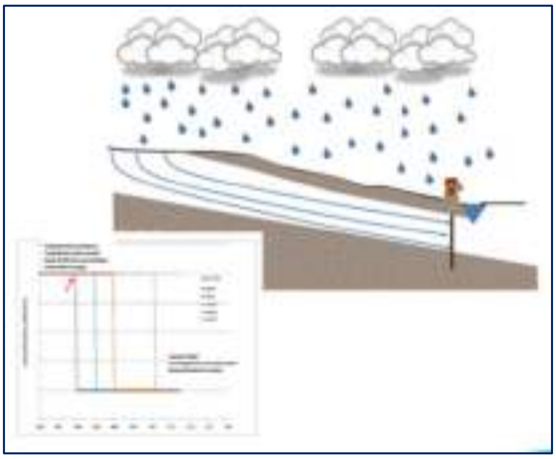


Figure 3 : Schematic diagram of CFC and SF6 dating: recording the atmospheric signature.

However, a catchment is fed by a multitude of water drops that have different ages, so we can only estimate the average renewal time of the water table as a whole, we thus speak of average age or apparent age.

The understanding of aquifer functioning is thus achieved via circulation models observed in the environment, which represent either open aquifers, confined aquifers, or a mixture of both. The average age of the water table is then interpreted on the basis of three simple hydrogeological models: (i) piston, (ii) continuous recharge, and (iii) binary mixing.

- For the piston model, all water lines have the same age and therefore all tracers are consistent. The recharge zone is then localised and isolated during the groundwater flow.
- For the exponential or continuous recharge model, the recharge is carried out on the whole catchment area at a given point, i.e., a mixture of water of all ages. The distribution thus corresponds to an exponential distribution. The time obtained is the average age for which two-thirds of the water table has been renewed.



- For the binary mixing model, it is a mixture of two distinct and restricted recharge zone water masses in its simplest form. It can be infinitely complexified.

Historical overview

2005: First work on CFC dissolved gases in the framework of a regional project under the responsibility of Luc Aquilina. This period also corresponds to the end of the thesis of V. Ayraud-Vergnaud (BRGM financed) on the estimation of water residence times in relation to the green tides in Brittany.

2007: Creation of the LADES (Laboratoire de Datation des Eaux Souterraines) consultancy for the estimation of water residence times for communities. Valorisation of the thesis work via a Young University Company.

2010: Closing of the company and beginning of autonomy of the universities.

2011: Opening of the CONDATE-Eau platform within the University of Rennes 1 (OSUR-Observatoire des Sciences de l'Univers de Rennes – CNRS-UR1).

The main key factors of implementation were the Grenelle II law (n°2010-788) of July 12, 2010, and the need to delimit the protection areas of the catchments for drinking water and to set up action programs for these catchment areas.

The main obstacles were the lack of lobbying, as the estimation of the groundwater residence time was not imposed, and financial leverage, as this innovative method requires an expertise with a certain cost that can slow down its use.

Evidence of benefits from implementation

The main advantage of using this methodology is the homogeneity of the gas releases on an international scale. Indeed, we know the evolution curves of the release of these products which are homogeneous on the whole Northern hemisphere. These gases, banned since the Montreal and Kyoto Protocols, are very stable gases that have remained in the atmosphere.

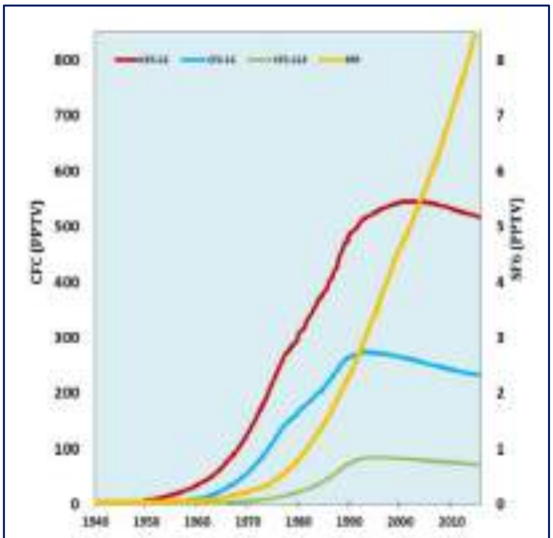
Several references (thesis, platform website, institutional reports) demonstrate the interest in using these groundwater dating methodologies for the management of aquifer systems.

Replication potential in the SUDOE region

The methodology has a strong potential for replication with more than 50 international references. But be aware that this methodology cannot be extrapolated to pesticides which have different transfer times from water.

The implementation of this practice required the purchase of equipment (100 k€), the launch of a thesis, the recruitment of a study engineer (one full-time) for development, and the presence of a research engineer.

Today, the human resources dedicated to the management of the practice are four people (two full-time), with a study engineer on a fixed-term contract for logistics and analyses, and a research engineer on a permanent contract for coordination. Finally, two other research engineers are needed for R&D developments.



Water dating services for local authorities can be subsidised by water agencies, by up to 50–80%. The equipment (investment and renewal) can be subsidised by the State-Region Plan Contracts.

Future outlook

In the short term, the prospects for development are to move on to other types of studies: (i) tracing and measurement by continuous dissolved gas, and (ii) organic geochemistry for the identification of faecal contamination. In the long term, the objective is the monitoring of emerging gases, but technical barriers must be removed because they are not persistent in the atmosphere.

Key points of the innovative method

- Estimation of aquifer turnover time via CFC and SF6 tracers.

- High replication potential: all types of aquifers on an international scale.

- Evaluate the reactivity of the aquifer to recharge modalities.

- Evaluate the time necessary before being able to observe the impacts of action programs.

Acknowledgements

The innovative practice was suggested by Yvan Kedaj (Aqua-Valley). Virginie Vergnaud (University of Rennes 1) participated in the interviews.

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AquaNES : Advanced monitoring and modelling interface for an optimised design and operation of the MAR/SAT system of Agon-Coutainville (France)

AquaNES, a project launched in 2016 developed water and wastewater purification techniques, combining industrial and natural treatment processes. By demonstrating the impact and benefits of the different systems studied, the AquaNES project aimed to promote more sustainable water purification techniques to manage situations of water scarcity or excess, and control the presence of micropollutants in the water cycle. Within the framework of the Horizon 2020 programme, the project has brought together thirty scientific, industrial and academic partners involved in the water sector. Among its thirteen pilot sites, AquaNES launched the monitoring of subsoil water at the Agon-Coutainville (Manche) wastewater treatment site in March 2016, with the installation of observation piezometers to monitor the quality of natural filters. The site is operated by the company SAUR which manages the city's wastewater. The system uses an activated sludge system (biological purification by micro-organisms) coupled with bio-filtration processes by reed beds and sand dunes. This system makes it possible to protect the shellfish production area in the estuary by not discharging the wastewater directly into the sea. Additionally, the purified water allows for the artificial recharging of the coastal groundwater table with fresh water and is used to irrigate a golf course on an occasional basis.

The objective of the studies conducted at this demonstration site is to improve the quality and quantity of purified water by monitoring, managing and modelling water and transfer processes in the soil and subsoil. The works included advanced chemical analysis and online salinity monitoring. The relevance of this combination of industrial and natural processes is studied in the framework of the AquaNES project through risk and life cycle analyses of the system. The valorisation of the acquired data contributes to innovation in the water industry and allows for efficient management of facilities within the water treatment and reuse sector.

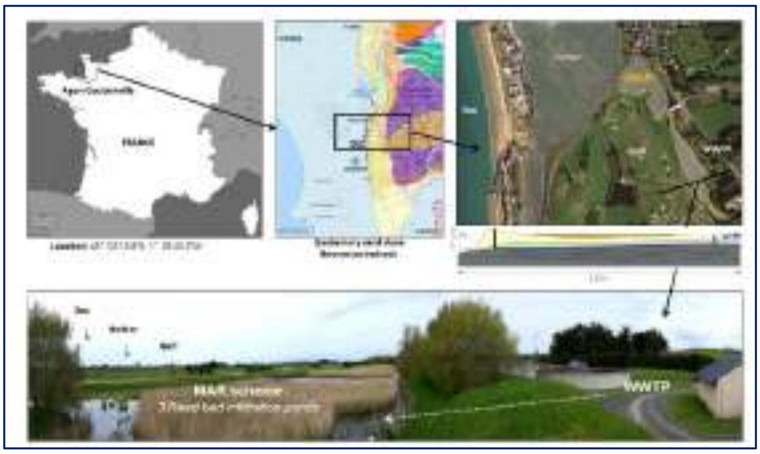

Figure 1: MAR/SAT system of Agon-Coutainville in France.

Responsible entity

The BRGM (French National Geological Survey) is the coordinator of a work package on aquifer management. It is the French public establishment of reference in the applications of earth sciences to manage the resources and risks of the soil and subsoil. The BRGM was created in 1959. It is a public establishment of an industrial and commercial nature (EPIC). Under the supervision of the Ministries of Research, Ecology and Economy, it is based in Orléans, France. The BRGM's work covers several activities: scientific research, expertise, innovation and transfer, analysis and experimentation, mine safety and risk prevention, higher education, continuing professional education, and dissemination of knowledge and open science. It employs more than 1,000 people, including more than 700 engineers and researchers, in its 27 regional offices in metropolitan and overseas France. Its teams operate in some 30 countries. Six major scientific and societal issues structure the BRGM's scientific strategy: geology and knowledge of the subsoil; groundwater management, risks and land use planning; mineral resources and the circular economy; energy transition and the underground space; and data, services and digital infrastructures.

Institutional setting

The project partners are the BRGM, Antea Group, ImaGeau, MicroLan, BioDetection Systems, Cranfield University, Berlin Water Competence Centre, with the help of the municipality of Agon-Coutainville, SAUR and the Coutainville golf course.

Geographical setting

The demonstration site is located in Agon-Coutainville. The commune of Agon-Coutainville is located in France in Normandy, along the western coast of the English Channel, between the Pointe de la Hague and the Bay of Mont Saint Michel. The demonstration site is located near a shellfish farming area and consists of a full-scale operational wastewater treatment plant and a MAR/SAT system. The secondary treated wastewater is discharged into a natural reed bed from which it infiltrates the coastal aquifer. The extracted water is then used for golf course irrigation.

Detailed explanation

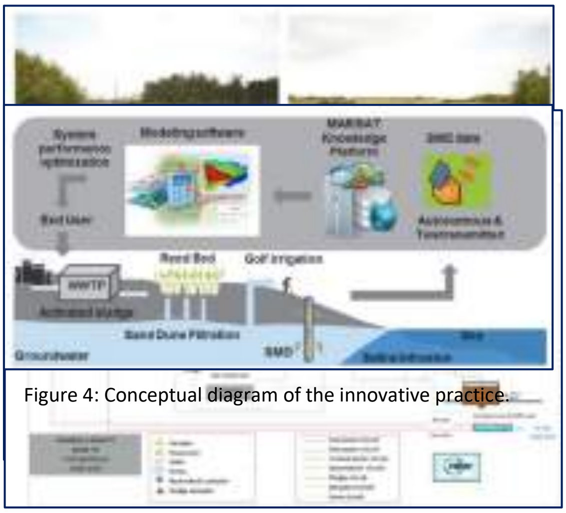

Figure 4: Conceptual diagram of the innovative practice.

Figure 3: Treatment process on the Agon-Coutainville site.

The integrated system is based on the technical treatment by an activated sludge process in the wastewater treatment plant (WWTP) consisting of a pre-screening, a pumping station, a buffer tank, a rotary screen, oil and sand separators with sand classifiers (separator basins), two aeration basins (4,000 m^3), a 470 m^2 clarifier, and a metering channel for the treated water. The WWTP treats and infiltrates via the SAT system ~2,000 m^3/day varying from 500 to 5,000 m^3/day depending on the season and vacations. In winter, the flow is significantly higher because the WWTP also receives rainwater. On the basis of an estimated capacity of 35,300 equivalent inhabitants, the Agon-Coutainville WWTP has a maximum DBO5 treatment capacity of 2,120 kg/day. The treated urban wastewater flows by gravity to one of the three infiltration basins located outside the plant. Once in the infiltration basins, the treated wastewater infiltrates through the reed beds to recharge the coastal aquifers composed of a 2–10 m layer of Quaternary sand. The three infiltration basins are flooded alternately throughout the year.

The objective of this demonstration site is to improve monitoring strategies and process modelling to evaluate the effectiveness of combining natural and engineered treatment systems in a coastal area and for reuse by:

- Demonstrating the effectiveness of secondary wastewater treatment combined with reed bed filtration with MAR/SAT on groundwater quality and quantity.
- Introducing new monitoring, data management and subsurface modelling methods, including advanced chemical and isotopic analyses, to understand the ability of SAT to improve water quality.
- Observe the fate of viruses/pathogens and other contaminants in treatment systems.
- Evaluate the utility of the system in limiting saline intrusion in this sensitive coastal area using a hydrogeological/reactive transport model representing the state of the system.
- Represent all of these interrelationships in a customised technology and communication tool.

Historical overview

2016: European funding under the Horizon Europe programme, approval number 689450.

One of the key factors that allowed the implementation of this practice is the site of Agon-Coutainville, which is a fragile environmental area since the 1990's and in which it was essential to avoid any discharge. At this site, there was a natural reed bed (2,000 m^2) through which it was decided to infiltrate wastewater treated by an activated sludge treatment.

The obstacles to the implementation of this solution were mainly financial. Indeed, the financing levers were not well adapted for a reproduction of the approach at the time. On the other hand, the AquaNes project was developed on a pilot scale over a period of three years.

Evidence of benefits from implementation

There are advantages to using this innovative practice including a financial benefit. The data collected confirm that the SAT system results in an additional reduction in salinity (P50 Cl: 550 mg/L for the WWTP outlet, 125 mg/L in the observation wells), in Escherichia Coli (E.Coli) concentrations up to 2.5 orders of magnitude and in regulated nutrient concentrations (e.g., NO_3, Ptot) up to one order of magnitude. Micropollutants, primarily discharged from the WWTP, generally had higher (median) concentrations in the treated wastewater (WWTP outlet), exceeding the recommended environmental quality standards (EQS) for carbamazepine (CBZ) and diclofenac (DIC). The SAT system, in combination with natural recharge, significantly reduces concentrations of contaminants of concern such as benzotriazole, CBZ and DIC concentrations, which overall fall below the recommended

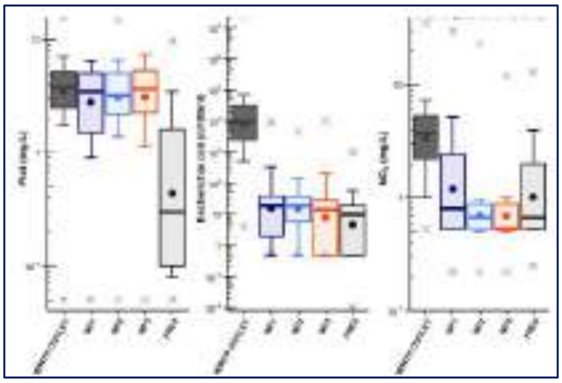

Figure 5: Concentration of regulated nutrients in WWTP outlet effluent and groundwater for observation wells.

threshold values defined by the EQS. The decrease in concentrations is likely due to the combined effect of dilution of treated wastewater in the aquifer and biogeochemical reactions (sorption and/or degradation).

Replication potential in the SUDOE region

The project has a reproducible character, mainly at a large scale (e.g., for big cities). The human resources implemented require different levels of complementary expertise: researchers, research engineers, technicians, computer scientists, geochemists, and hydrogeologists.

Future outlook

The short-term outlooks are to develop tools oriented towards governance, notably the implementation of tertiary treatment solutions on a part of the watershed, and to weight the criteria by communicating with the ARS, the Water Agencies, and the communities.

In the near future, recharge and reuse sites using non-conventional water will have to be the subject of a "site-specific" analysis in order to estimate the possibility of storage, reuse, and the associated environmental costs/benefits and co-benefits.

Key points of the innovative method

- Combination of natural processing and engineered systems.

- Monitoring and modelling interface.

- Controlled recharge of an aquifer.

Acknowledgements

The innovative practice was suggested by Marie PETTENATI (BRGM) who also participated in the interview.

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MétéEAU Nappes, a tool for monitoring and forecasting groundwater (France)

MétéEau Nappes is an innovative web platform to help with groundwater management in France. It is developed, administered and hosted by the French Geological Survey (BRGM). Its development was initiated in a context of climate change and conflicts of uses, leading to an increase in pressure on and, therefore, the need to optimise the management of water resources in France. The objective of this management practice is to inform/alert in near real time on the level of water tables, to anticipate a possible drought situation in low water, and to foresee periods of high water with possible flooding problems.

The platform offers a set of innovative services allowing: (i) the collection and dissemination of water cycle data, (ii) the display of the situation of the water tables in real time and the monitoring of past or future behaviour of aquifers in France, (iii) a decision support service with forecasts for the management of water resources in sensitive territories, and (iv) an API associated with the website.

Meteorological, hydrological and piezometric data are put online in real time in an interoperable format from several representative sites in metropolitan France. It is thus possible, for the monitoring points currently proposed and associated with a global hydrological model, to view the most recent measurements from the national piezometric network and, in particular, forecasts of groundwater levels. These data are made available in the form of maps and dynamic curves based on modelling and forecasting of low and high-water levels. Associated with the global models used (Gardénia, EROS and Tempo ©BRGM), these data allow forecasting of the water table level. These forecasts, up to 6 months in the future, are compared to piezometric thresholds of drought from the prefectural orders of restriction of use in progress. The forecasts can also be self-refreshing (currently monthly).

The year 2021 marked the opening of the web platform to the general public. The main users are: (i) groundwater experts (French Ministries (MTE/ DGALN and DGPR)), Institutions (DREAL, DDT(M), Flood Forecasting Services, Water Agencies, etc.), (ii) private partners, (iii) local authorities, EPCIs, EPTBs, the Mixed Syndicates of the basin, (iv) farmers, (v) consultancies, (vi) universities and (vii) the press.

The potential perspectives of evolution of this groundwater management practice are: the extension of the number of monitored sites, the deployment on a European or even international scale, and the integration of new modelling tools (artificial intelligence methods, mesh models, semi-distributed models) to obtain other predictions.

Responsible entity

The BRGM (Bureau de Recherches Géologiques et Minières) is responsible for MétéEAU Nappes. The BRGM is the French national geological survey. It is the French public establishment of reference in the applications of earth sciences to manage the resources and risks of the soil and subsoil. The BRGM was created in 1959. It is a public establishment of an industrial and commercial nature (EPIC). Under the supervision of the Ministries of Research, Ecology and Economy, it is based in Orléans, France. The BRGM's activities cover several areas: scientific research, expertise, innovation and transfer, analysis and experimentation, mine safety and risk prevention, higher education, continuing professional education, and dissemination of knowledge and open science. It employs more than 1,000 people, including more than 700 engineers and researchers, in its 27 regional offices in metropolitan and overseas France. Its teams operate in some thirty countries. Six major scientific and societal issues structure the BRGM's scientific strategy: geology and knowledge of the subsoil; groundwater management, risks and land use planning; mineral resources and the circular economy; energy transition and the underground space; and data, services and digital infrastructures.

Institutional setting

The platform is edited, managed and subsidised by the BRGM. The stakeholders of this practice are the BRGM and its institutional partners (Météo-France). Within the framework of the implementation of the GEMAPI and in a climate change context, knowing in real time the availability of water resources and being able to forecast the level of the water tables are essential information for the actors in the water sector. Indeed, they allow for: (i) characterising the particularities of a site, (ii) optimising resource management by adapting groundwater withdrawals and managing conflicts of use, (iii) making decisions in the face of a water shortage or overflow, and (iv) testing scenarios to anticipate the effects of climate change.

Geographical setting

The practice takes place at several sites representative of metropolitan France. The geographical framework of this practice is intended to extend to the European and international scale, in particular in England via the INTERREG Water for Tomorrow project, in Spain and Portugal via the INTERREG SUDOE AQUIFER project, and in South Africa (in Cape Town).

Detailed explanation

The services and functionalities offered by MétéEAU Nappes are: (i) a web interface; (ii) a historical and real time display of meteorological data, groundwater and surface water data provided by the SCHAPI, Météo-France and the BRGM; (iii) maps of the groundwater situation on the current date or forecast outputs according to various climatic scenarios; (iv) curves superimposing piezometric levels (historical, real time data, forecast levels; drought/flood piezometric thresholds), river flows and rainfall in real time; (v) automatic monthly refreshment with Gardénia of the forecasted groundwater level data with recent meteorological data; (vi) provision of metadata associated with forecasts, including: model used, time step, calibration period, correlation coefficient, taking into account or not of withdrawals, cost of the natural ground at the right of the piezometer, bibliographical sources of the piezometric thresholds; and (vii) a dynamic private application programming interface (API).

This web platform contributes, in particular, to the national hydrological situation bulletin for the groundwater component, but also to the forecasting of the evolution of surface water by grouping together the regional hydrogeological models on a national platform (AQUI-FR project).

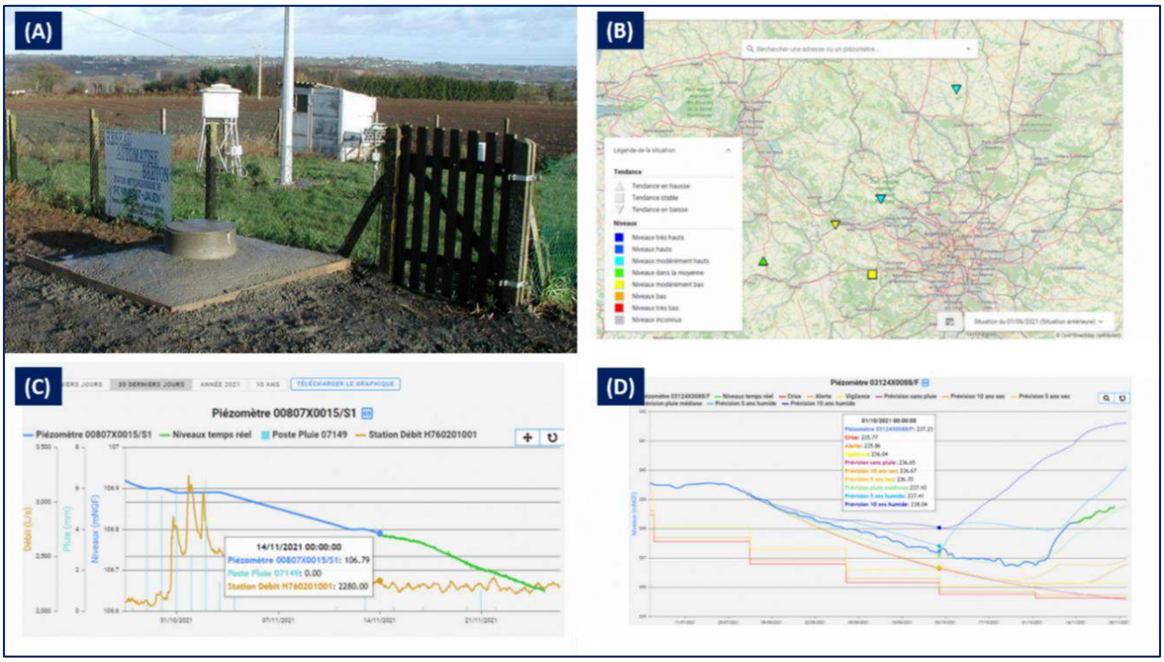

Figure 1 : (A) Piezometer equipped with measurement and remote transmission tools, (B) display of the water table situation, (C) display of real time measurements, (D) forecast of water table levels (© BRGM).

The technological means used to achieve these services are: GPRS technology (currently deployed on nearly 1,500 stations of the national piezometric network) allowing the provision of daily measured data, as well as a dedicated technical architecture based on international standards and on recent technologies allowing the cross-referencing of real time data from different sources and the valorisation of existing modelling.

MétéEAU Nappes is a real decision-making tool for water resource management in high-stake territories which offers a set of varied services useful for the management of low water levels and risks of flooding by rising water tables through: (i) display of the situation of the water tables at the current date and in the future by the use of the web service of calculation of the SPI (Standardised Piezometric Indicator) for the piezometric data in real time but also for the forecasting data; (ii) collection and diffusion in real time of the groundwater data (about 1500 works of the 1600 managed by the BRGM allow an automatic daily provision of the data); (iii) provision of the most recent data on the surface water and the pluviometry; (iv) decision support service for water management in the territories (integration of piezometric thresholds of restriction of the drought decrees); (v) maps and curves refreshed at each connection date (dynamic information); (vi) possible automatic monthly refreshment of the predictive data of groundwater levels; (vii) reserved access allowing to access to specific models for a particular geographical sector; and (viii) API (Application Programming Interface) allowing direct data exchange with MétéEAU Nappes.

Historical overview

The main steps in implementing this practice were:

- 2015: launch of the BRGM internal research project.
- 2017: deployment of a prototype.
- 2019: website went into production (dedicated URL accessible only to the BRGM).

- 2020: restricted opening of the website.
- 2021: opening of the website.

The multidisciplinary expertise of the BRGM to realise a proof of concept, and strong support by the BRGM innovation, valorisation and transfer unit (value proposition, business model).

The obstacles encountered were the need to prove the viability of the project, and the interoperability of the data, which was sometimes limited.

Evidence of benefits from implementation

There is no evidence of the benefits of this practice as there is no real feedback yet. However, there is evidence that the practice is evolving and that there are benefits to using it. Notable developments are: (i) an agreement with Veolia for the creation of a new value proposition to their customers; (ii) the addition of around twelve points modelled for the MTE/DEB Department (contribution to the national map of drought risk on water bodies for the summer); and (iii) the agreement within the framework of the AQUIFER Sudoe project which will allow for the addition of 6 more points.

Replication potential in the SUDOE region

The management practice is not intended to be replicated, but the number of points is bound to increase. The implementation of MétéEau Nappes has required a multidisciplinary team of five part-time staff (hydrogeologists, modelers, computer developers, sensor specialists, etc.). The project did not benefit from subsidies but was self-financed by the BRGM. It should be noted that since 2021, several projects of support to public policies, research projects and international projects have been signed.

Future outlook

The short term evolution perspectives are: (i) the agreement with partners to add points in MétéEAU Nappes; (ii) the addition of several points thanks to programs (INTERREG SUDOE AQUIFER, Val de Saône, Water For main triggers of this implementation were: the desire of the media, the public and state services to have information on the probability of floods or droughts in relation to the current level of the water table, support from the BRGM in terms of funding, the

Tomorrow, etc.); (iii) forecasts in relation to meteorological factors but also in relation to abstraction scenarios (VEOLIA and Water For Tomorrow); (iv) the use of the ERA5 climate database for climate data (20x20 km grid) which will allow each model to associate the forecast data at D-5 i; (v) the integration of forecasts coming from other software (e.g.mesh, global, reservoir, or semi-distributed models); and (vi) deployment on a European scale.

The long-term perspectives are: (i) moving towards new AI-based modelling tools to obtain predictions; (ii) adding a batch process with recovery of results from other models; (iii) displaying information associated with climate change (climate scenarios, hydrological balances, water level forecasts); and (iv) international deployment.

Key points of the innovative method

- Monitoring of the situation in real time and forecasting of groundwater.

- Collection and dissemination of data on a web platform open to the public and thus to experts.

- Decision support service for sustainable water management in the territories.

Acknowledgements

The innovative practice was suggested by Sandra BERANGER (BRGM). Bruno MOUGIN (BRGM) participated in the interviews.

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ICT and modelling

APRONA: an observatory of the Alsace Groundwater (France)

AProna is an observatory of the Alsace groundwater in France. This partnership project brings together all the water stakeholders and has the dual objectives of sharing knowledge and assisting decision-making. The approach is also open to the German and Swiss transboundary territories of the Rhine plain, subject to the data and information available on certain bordering sectors. APRONA is in charge of organisation, coordination, and development.

Surface water and groundwater are monitored by several organisations in the territory. The waters of these two systems are in almost permanent interaction. Through a mutualisation of existing tools, a GIS portal offers an access to water data in Alsace and allows for the display of indicators and dashboards providing a synthetic vision of the desired information.

The observatory contributes to: (i) cross-referencing, facilitating the exchange of data from the various stakeholders and valorising them in different forms; (ii) improving knowledge of groundwater and surface water and their interactions to promote a better understanding of the water cycle and aquatic environments; (iii) disseminating information on the situation and issues related to water in Alsace for water professionals, the general public and decision-makers; and (iv) providing unbiased content on the quantity and quality of water in Alsace.

The users of the platform are mainly engineering companies, local authorities who can benefit from a dedicated access, the general public, farmers, and private enterprises such as gravel pit managers.

Responsible entity

The association for the protection of the groundwater of the Alsace plain (APRONA) is in charge of managing the regional observation networks related to the quantity and quality of groundwater in Alsace and of making information available to the various water stakeholders. APRONA gathers representatives of the Grand Est Region, the Rhine-Meuse Basin Committee, and local authorities, as well as users, private enterprises, farmers and nature protection associations. Competent personalities are also associated, in particular, a representative of the Ministry of the Environment of Baden-Württemberg, Germany.

Institutional setting

APRONA was created on 28 March 1995. Its founding members were the French State, the Regional Council of Alsace, the General Council of the Lower Rhine, the General Council of the Upper Rhine, and the Rhine-Meuse Water Agency. APRONA is composed of a board of directors, an office, active members, associate members and honorary members. Active members must be approved by the board of directors and have a deliberative vote at the General Assembly. Associate members participate in the work of the association but do not have the right to vote. Finally, honorary members can be appointed by the general assembly on the proposal of the executive committee and the board of directors.

Geographical setting

The Rhine water table (water mass CG001 - Pliocene of Haguenau and Alsace water table) is one of the most important underground water reserves in Europe. It extends, in Alsace, to 3,200 km^2 of which 400 km2 constitute the Pliocene of Haguenau. The quantity of water stored, for this part of Alsace alone, is estimated at 35 billion m^3. The supply of the water table is ensured:

- directly from precipitation on the plain (effective rainfall);
- by infiltration of the Vosges rivers, whose flow is also dependent on precipitation;

Figure 1: Localisation of the Rhenane groundwater.

- by infiltration of water from the Rhine, depending on the section and the development; and
- by lateral contributions at the edge of the Vosges or the Black Forest, and by the water tables of the Doller, Thur, Lauch and Fecht rivers in particular.

The water withdrawals from the aquifer are mainly due to:

- exchanges with the rivers and the Rhine which can drain the water table; and
- withdrawals by pumping for domestic, industrial or agricultural uses.

The fluctuations of the water level are not without consequences for the natural environment and human activities: drying up of wetlands, water rising in individual houses or public buildings, and incidences of pollution (the appearance of new vectors of water pollution from ground or surface water poorly protected by permeable soils and located at a low depth). The water table is subject to degradation due to direct pollution from industrial, agricultural, and domestic sources or pollution of surface water which then infiltrates into the water table.

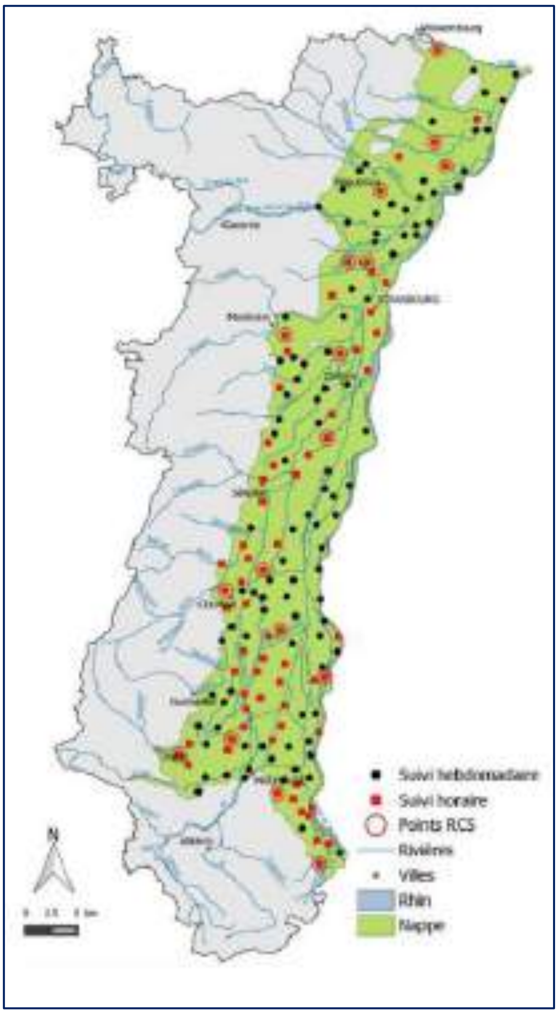

Figure 2: APRONA's measurement network.

The Sundgau is the part of the Haut-Rhin department located south of Mulhouse. From a geographical point of view, it is a landscape of gentle hills continuing towards the west with the hills of Belfortain. The region is bordered to the north by the Doller valley and the Alsace plain, and to the east by the Rhine plain, known as the "Sierentz ditch", between Basel and Mulhouse. In the south it stops on the Swiss Jura range, of which the Ferrette limestone massif represents the first buttress.

Detailed explanation

Measuring network

APRONA manages a piezometric network of 170 points on the Alsace water table, which can be used to: (i) carry out a global statistical analysis and characterise the functioning of the water table, (ii) carry out hydrodynamic and transfer modelling at the scale of the water table or more locally, (iii) establish reference conditions and analyse the representativeness of the monitoring networks, (iv) define and monitor vulnerable sectors within the framework of drought decrees, (v) map areas at risk of flooding by rising water table or preferential infiltration, and (vi) evaluate water table-river exchanges and monitor notable wetlands.

Live monitoring

Live monitoring of the water table is possible for 33 reference points on the network. For each station, graphs established with updated data (refreshed every 12 hours) present the evolution of the water table over the previous 15 days and previous 12 months, and the measurements are automatically put online on the APRONA website. The monthly situations are represented with the help of the standardised piezometric indicator (SPI) which compares water table levels in relation to the whole record and the evolution of the levels over the previous months.

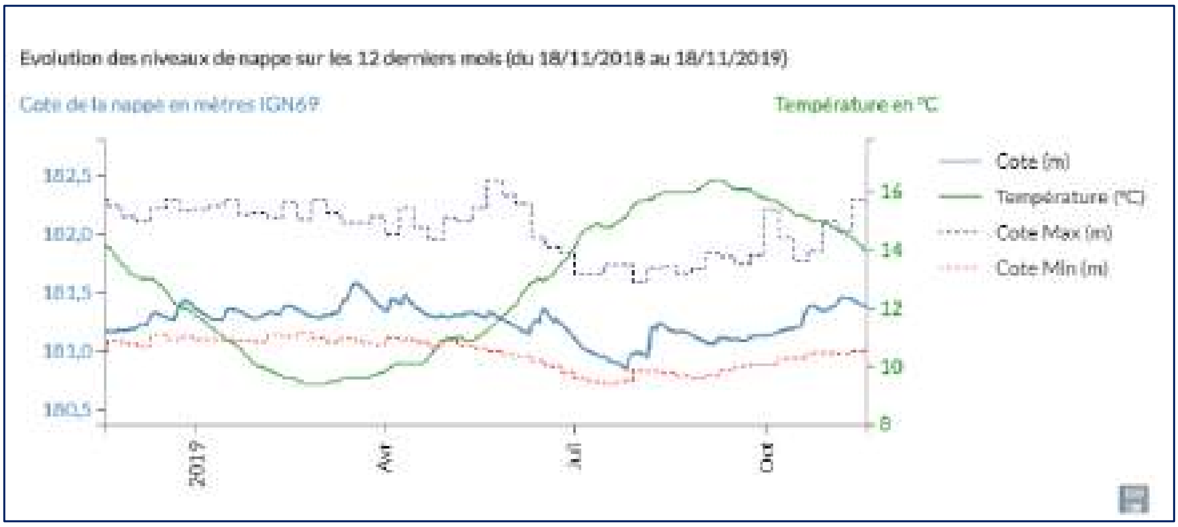

Figure3: Temporal series of groundwater level

State of the art

State of the art updates are regularly published to act in support of improvements in the quality of groundwater. These assessments are carried out approximately every six years. Through analysis of historical pollution and the search for emerging molecules, these assessments help to anticipate, redirect and/or recommend the actions to be implemented to improve and preserve the quality of the water resource. This work also contributes to periodic transboundary inventories of the most important aquifer in Europe by involving the German and Swiss partners in concerned territories.

Historical overview

1995: Creation of APRONA (association for the protection of the groundwater of the Alsace plain) on the initiative of the Alsace Region, the Rhine-Meuse Water Agency, General Councils and the Alsace Regional Prefecture.

1997: First inventory on a transboundary scale of the quality of the groundwater of the Rhine water table (Project manager: Alsace Region).

1999: Organisation of the first APRONA day on nitrate pollution in the Vosges foothills.

2002–2006: Modelling of groundwater pollution by nitrates in the Upper Rhine Valley, setting up of monitoring indicators for actions to protect the Rhine water table in the Upper Rhine Graben, and carrying out the Second Transboundary Inventory of groundwater quality in the Rhine water table.

2009: Completion of the Third Transboundary Groundwater Quality Inventory of the Rhine Groundwater.

2012: Signature of the framework agreement for cross-border cooperation. Setting up of the LOGAR network (Operational Link for the Management of the Rhine Aquifer). Start of the construction of a water observatory.

2015: Launch of the Alsace water observatory.

2016 - 2018: Realisation of the ERMES-Rhine program: Evolution of the resource and monitoring of groundwater in the Upper Rhine Valley and recommendations with regard to historical anthropogenic pollutants and emerging pollutants.

Evidence of benefits from implementation

Monitoring has shown, for example, that between 2003 and 2016, little change was observed in the quality of groundwater, with potability limits often exceeded at certain measurement points.

Replication potential in the SUDOE region

The Alsace water table is a special case because it is the BRGM that manages piezometers in France. Alsace is a particular case which is linked to its historical context.

Seven people are dedicated to the daily management of this practice (which can sometimes rise to thirteen depending on the nature of the projects underway).

The observatory benefits from subsidies of approximately 90% from the Water Agency and the Grand-East Region within the framework of multi-annual contracts on the basis of actions proposed by APRONA. The rest is financed by studies and calls for tender.

Future outlook

In the short term, objectives are:

- The reform of APRONA's statutes.
- Continuation of technical support for the implementation of territorial solution contracts in priority catchment areas with the objective of supporting local authorities and evaluating trends in concentrations in order to establish a link with the actions undertaken.
- The steering of the new ERMES Alsace/Rhine 2022–2025 whose innovative component will have the objective of assessing the sensitivity of the Rhine water table to the transfer of micropollutants via watercourses, taking into account the impacts of wastewater treatment plant discharges.
- An in-depth statistical analysis of the data recorded to lead to relevant information on the evolution of the resource during this period (trends) and provide more detailed forecasts of low water levels or groundwater rises to facilitate decision-making.

The directions to be taken in the long-term aim to be coherent with the environmental challenges identified in recent years and, more particularly, the adaptations to be undertaken in the face of climate change with the intention of consolidating APRONA's status as a reference for stakeholders in the water sector.

It is therefore planned to:

- To perpetuate the provision of decision-making tools and forecasts for public decision-makers, both on the quantity and quality of water resources.
- To extend expertise in groundwater quality monitoring, knowledge of groundwater recharge conditions and interactions with surface waters.
- To deliver adapted and independent information to the public and to reinforce the awareness of the actors for a better shared management of the resource and the improvement of its quality.

Key points of the innovative method

- Monitoring and visualization of a piezometric network in real time.

- Modelling the functioning of the water table.

- Inventory and mapping of pollution.

- Governance organized through the Observatory.

Acknowledgements

The innovative practice was suggested by Yvan KEDAJ (Aqua-Valley). Philippe SCHOTT (APRONA) participated in the interview.

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ICT and modelling

GEO-AQUIFER: Improvement of the knowledge and concerted management of the Aquifer System of the Northern Sahara through the use of satellite images

Figure 1 : Location map of the North Sahara Aquifer System (SASS).

GEO-AQUIFER is a continuation of the SASS project and aimed to improve knowledge and concerted management of the Northern Sahara Aquifer System (SASS) through the use of satellite images. The project created an information and knowledge base to support sustainable transboundary management of the Northern Sahara aquifers at national and sub-regional levels. The project has thus improved the living conditions of the population through the development of knowledge and of sustainable management of transboundary aquifers through the use of satellite data, in order to increase concerted action between Algeria, Libya and Tunisia.

The project was executed by the Sahara and Sahel Observatory (OSS) with the support of the European Space Agency (ESA), and funded by the African Water Facility (AWF) for a duration of 18 months. The objectives of the project were to: (i) optimise the use of satellite data for the knowledge and management of the SASS aquifer shared by Algeria, Libya and Tunisia; (ii) provide the national agencies in charge of water management in the SASS countries with tools to strengthen and improve the consultation mechanism for an efficient and sustainable management of the shared water resource; (iii) to develop the capacities of the national agencies in the use of satellite data and the appropriation of these new technologies in order to obtain reliable data and information quickly and at a lower cost; and (iv) to ensure the replication in other African basins.

The project has thus contributed to strengthening the capacities (use of satellite and geographic data) of the services in charge of water management in the countries concerned with the SASS aquifer system. It has also provided tools to these countries to better identify the uses and pressures exerted by both population and climate change on the aquifer system.

GEO-AQUIFER has thus implemented innovative technologies (satellite images) and has contributed to the strengthening of national capacities from a perspective of sustainability and reinforcement of the SASS concerted consultation mechanism.

Responsible entity

The Sahara and Sahel Observatory (OSS) is an international organisation that operates in the arid, semi-arid, sub-humid and dry areas of the Sahara-Sahel region. Created in 1992, the OSS has been based in Tunis (Tunisia) since 2000. The OSS has 26 African countries and 13 organisations among its members. The OSS initiates and facilitates partnerships around common challenges related to shared water resources management, and implementation of international agreements on desertification, biodiversity and climate change in the Sahara-Sahel region.

The main actions carried out by the OSS are

- The implementation of multilateral agreements on desertification, biodiversity and climate change.
- The promotion of regional and international initiatives related to environmental challenges in Africa.
- The definition of concepts and harmonisation of approaches and methodologies related to sustainable land and water resources management and climate change.

The OSS necessarily relies on knowledge transfer, capacity building and awareness raising of all stakeholders.

The OSS activities and projects are financed by voluntary contributions from member countries, and by grants and donations from development partners. With effective governance mechanisms and a competent, multicultural and multidisciplinary team, the OSS makes a high value-added contribution to the international and African institutional landscape.

Institutional setting

The GEO-AQUIFER project is in line with the 2010 OSS strategy and the priorities of its "Water" program, which in its initial phase focuses on large transboundary aquifers in Africa. The project is consistent with the areas of intervention of the African Water Facility (AWF), namely the management of transboundary water resources by supporting the joint development of shared waters and by supporting the improvement of knowledge in the fields of information systems and water resources management. GEO-AQUIFER is also part of the 2005–2009 operational program of the AWF, by improving the framework of knowledge and concerted management of the SASS aquifer system shared by Algeria, Libya and Tunisia. The project is also perfectly in line with the NEPAD (New Partnership for Africa's Development) priorities of integrated management of transboundary water resources and with the poverty reduction strategies of the SASS basin riparian countries, which have made water resources management a priority for sustainable development.

Geographical setting

The GEO-AQUIFER project covers the Northern Sahara Aquifer System (SASS) and the Tunisian-Libyan coastal aquifer of the Djeffara. The SASS covers more than one million km^2 in Algeria, Tunisia and Libya. The extension and the thickness of the layers have favoured the accumulation of considerable reserves, which are renewed little and are exploitable only in part. Over the last 40 years, the annual exploitation of the SASS has increased fivefold, reaching three times the average level of its natural recharge, and the aquifer is facing several major risks – strong transboundary interference, salinisation of water, disappearance of artesianism, drying up of water outlets, and excessive pumping heights. The Djeffara refers to the Tunisian-Libyan coastal plain, containing an aquifer system whose continental part extends over 40,000 km². In terms of risk, the Djeffara is distinguished by a pronounced level of alert; in 40 years, withdrawals have also increased fivefold. This has resulted in significant drops in the water table in the coastal areas, where exploitation is concentrated, with very dangerous saltwater intrusions.

Detailed explanation

The technical developments made during the project are:

- The extension of the digital mapping of the land use of the AQUIFER project.
- The creation of surface water maps of the SASS-Djeffara basin (Algeria, Tunisia, Libya).
- The elaboration of detailed land cover maps and land cover change maps of approximately 15 sample areas.
- The extension of the DTMs of the AQUIFER project and derived products on the SASS-Djeffara basin.
- The creation of a hydro-geographic repository on the SASS-Djeffara basin, a regional virtual globe, and a data dissemination tool.
- The development of capacities through the continuation of the training undertaken following the AQUIFER project, in particular in the techniques of production, management and exchange of geo-scientific data or research support.

Historical overview

The GEO-AQUIFER project reinforced and completed the AQUIFER pilot project initiated by the ESA which concerned five pilot areas of the SASS. It constitutes its extension to the whole basin.

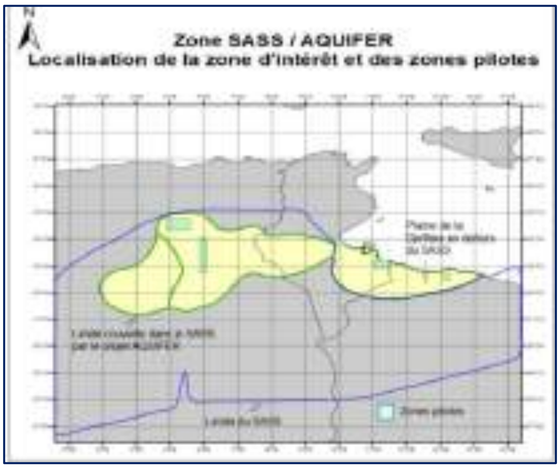

Figure 2 : Location of the area of interest and the study sites.

The experimental project AQUIFER, stemming from the TIGER programme, is an ESA initiative which aimed at valorising satellite data, in particular those issued from the ESA's ERS and ENVISAT satellites, for applications related to the management and monitoring of water resources in Africa. Within the framework of the TIGER initiative and under the impetus of the OSS, the ESA has chosen the SASS (Algeria, Tunisia, Libya) and Iullemeden (Mali, Niger, Nigeria) basins to concretise its commitment to supporting the implementation of the Johannesburg Action Plan. The ESA is financing the AQUIFER project, to the definition of which the OSS has closely contributed by participating in the drafting of the terms of reference of the call for tenders, by assisting the consultancy firm in charge of the implementation of the project, and by ensuring the coordination of the final users for the implementation of the project.

The OSS requested support from the AWF to improve the state of the art and management tools of the transboundary groundwater resources of the Northern Sahara Aquifer System (SASS).

The project started on 6 June 2007 in Tunis with a workshop gathering representatives of institutions in charge of water management in Algeria, Libya, and Tunisia. The project ended in 2009.

Evidence of benefits from implementation

The sustainability of the project's achievements is ensured by the functioning of the SASS consultation mechanism set up by the three countries sharing the same resource. The SASS consultation mechanism, which constitutes a first experience at the international level of common groundwater management, has an operational structure financed by the countries for its functioning and the implementation of permanent activities (management of the networks, production of indicators). The GEO-AQUIFER project, which has certainly benefited from the establishment of the mechanism, has in return strongly contributed to the consolidation of the mechanism by putting into practice the concept of consultation. During the three years of the project, GEO-AQUIFER has mobilised around the same objective the institutions of the water sector of Algeria, Tunisia and Libya, as well as engineering offices and consultants of the three countries. Through its contribution to the inventory of irrigated areas, and to the good knowledge of water withdrawals, it has contributed to ensure an objective, equitable, and sustainable operation of the consultation mechanism. For the national water agencies, it was important to properly locate the irrigation water withdrawal areas and thus facilitate the decisions within the framework of the SASS concertation mechanism with objective, transparent, neutral and comparable data.

Replication potential in the SUDOE region

The project has a strong potential for replication thanks to the strong involvement of the OSS in the implementation of this project. All other African countries are beneficiaries of the methodologies implemented, which can be used for multiple applications related to water resources management. The project shows a strong replicability on other transboundary systems, on condition of having an executing agency with the solidity of the OSS coupled with the pre-existence of an international consultation mechanism. The potential for replication at other scales, particularly trans-regional, is also significant. From a technical point of view, the project can be considered as an original and replicable model considering the following results: (i) the elaboration of digital maps of irrigated areas to serve as complementary and contradictory data, and to ensure a better reliability in the estimation of underground withdrawals, which are generally not very accurate; (ii) the elaboration of a common geographical reference frame for the three riparian countries of the transboundary system and the dissemination of the project's products on the internet, and (iii) the training of hydrology practitioners in remote sensing techniques and hydro-geographical analysis methods.

The cost of the project was estimated at €564,300, and it benefited from grants from the African Development Bank and the OSS.

The key success factors were: (i) the stability of the project team, (ii) the involvement of national policymakers, (iii) the establishment of the concerted consultation mechanism, and (iv) the proactive role of the OSS. However, the project did not have the expected impact because it did not initiate a substantial communication program.

Future outlook

In the near future, the OSS intends to replicate GEO-AQUIFER in other basins, thus fulfilling its function as a partnership platform and centre of excellence for sustainable development in Africa. At the end of the project, a number of challenges remain:

- better knowledge of the irrigated perimeters on the whole Libyan Djeffara;
- better knowledge of the water withdrawals on the SASS and the Djeffara;
- full access to the possibilities offered by the GEO-AQUIFER website; and

- better use of geo-scientific data and satellite images for the management of water resources and the ordinary functioning of the SASS Consultation Mechanism.

All these challenges, which are natural extensions of the project, should be part of future cooperation programs between the Sahara and Sahel Observatory and the African Water Facility.

Key points of the innovative method

- Improved knowledge of trans-boundary systems through the use of satellite imagery.

- Information and knowledge base to support transboundary management.

Acknowledgements

The innovative practice was suggested by Yvan KEDAJ (Aqua-Valley). Abdel Kader DODO, Lamine BABA SY, and Nabil BEN KHATRA (OSS) participated in the interview.

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AQUI-FR : national hydrogeological modelling platform (France)

AQUI-FR is a national hydrogeological modelling platform designed as a tool to valorise hydrogeological modelling work done in France. Started in 2014, AQUI-FR aims to bring together within a single digital platform hydrogeological models developed by different research institutes. AQUI-FR thus brings together eight partners (ENS, CERFACS, BRGM, École des Mines PARIS, Météo France, Géosciences Rennes, LHyges, UMR METIS) with the aim of developing a better knowledge of past, present, and future groundwater resources. AQUI-FR aims to implement forecasts of groundwater evolution in France, on time scales ranging from days to seasons (>6 months), and from atmospheric forecasts via standardised piezometric indicators. The platform also allows for prospective modelling (up to 2100) based on hydrogeological modelling developed and used by water managers where they exist, and to promote the development of such modelling where they do not. A computer structure allows the association of three hydrogeological models (EROS, MARTHE, EauDyssée), a water and energy flow model (SURFEX), and an atmospheric analysis system (SAFRAN). The dynamic coupling of the models is provided by the OpenPALM coupler. The AQUI-FR platform is deployed on the operational machines of Météo-France and benefits from its support for daily monitoring. The platform has been used on a total of 13 distributed aquifer applications and 23 applications on karst systems. In the future, other regional models will be integrated to extend the spatial coverage.

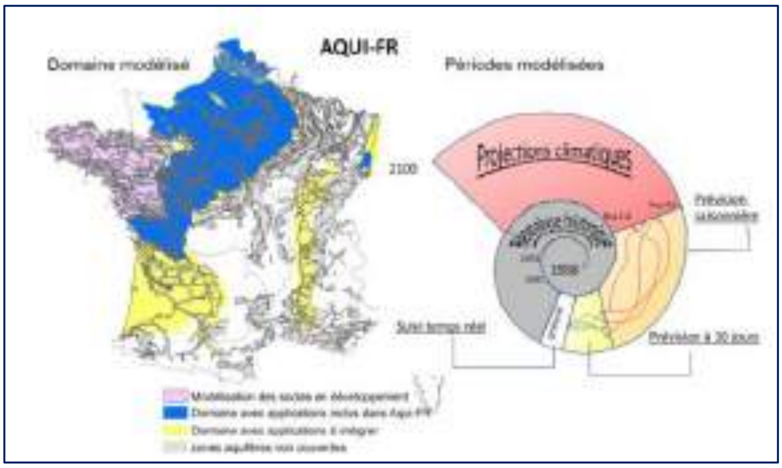

Figure 1: Concept of the AQUI-FR platform.

Responsible entity

Several entities are responsible for the AQUI-FR platform. The Geoscience department of the ENS is the coordinator of the platform.

Institutional setting

As the national model is built on existing hydrogeological applications, each partner remains the owner of its hydrogeological model and the results are available to the general public.

Geographical setting

The simulations from the platform cover 35% of metropolitan France. The EauDyssée model covers Basse-Normandie, Somme, Seine, Loire and four sub-systems: Marne-Loing, Marne-Oise, Seine-Eure and Seine-Oise. The MARTHE model covers Alsace, Basse-Normandie, Nord Pas-de-Calais, Poitou-Charentes and Somme. Finally, the EROS model covers 23 karst systems (median size 99 km²).

Figure 2: Location of aquifers and karst systems simulated in the AQUI-FR platform.

Detailed explanation

The modelling platform represents the main hydrological processes occurring in watersheds, from precipitation to groundwater flow. In its current form, the AQUI-FR system includes three hydrogeological modelling software covering 11 sedimentary aquifers and 23 karst systems: the hydrogeological numerical platform EauDyssée, the MARTHE software, and the EROS software used for karst systems. The three software are embedded in an application developed with the OpenPALM coupling system. All these models cover an area of about 149,000 km2 and contain up to 10 superimposed aquifer layers. AQUI-FR takes into account spatial heterogeneity by using different spatial scales. The SAFRAN meteorological analysis available over the French metropolitan area at a resolution of 8 km provides meteorological variables to the SURFEX land surface model that evaluates the water balance over the French metropolitan area. SAFRAN provides hourly precipitation (rain and snow), temperature, relative air humidity, wind speed and downward radiation. SURFEX uses these atmospheric variables to solve the surface energy and water balance at the land-atmosphere interface at a scale of 1–2 years and a time step of 5 minutes. SURFEX estimates the spatial distribution of flux between surface runoff and groundwater recharge on the SAFRAN. It accounts for different soil and vegetation types and uses a diffusion scheme to represent heat and water transfer through the soil. The soil in SURFEX is represented by a multilayer approach. Its depth varies according to the vegetation (in France from 0.2 to 3 m) and is partially accessible to plant roots. The infiltration of the soil at depth constitutes the recharge flow of the water table. Surface runoff can occur as a function of excess saturation or excess infiltration. The simulation of the watershed depends on its hydrogeological characteristics. For sedimentary basins, these two flows are transferred to the groundwater models MARTHE or EauDyssée. These models simulate transfer to the unsaturated zone, groundwater flows within and between aquifers, runoff to and in rivers, and river-aquifer exchanges. They also take into account the numerous groundwater withdrawals from river basins. The temporal resolution is daily, and the spatial resolution varies from

100 m to a maximum of 8,000 m. The depth of the deepest aquifer can reach about 1,000 m locally. It should be noted that the hydrogeological models could have been conventionally fed with precipitation, potential evapotranspiration, and temperature data from the SAFRAN analysis using their own water balance calculations. However, the combined use of SURFEX and SAFRAN provides a consistent set of hydro-meteorological data on an 8 km resolution grid over France, including groundwater recharge and surface runoff from SURFEX, as well as potential evapotranspiration, precipitation and temperature from SAFRAN. The use of these 8 km resolution flows from SURFEX necessitated recalibration of the hydrogeological models included in the platform. Karst aquifer systems are simulated by a conceptual reservoir modelling approach using EROS software. Each karst system is represented by a reservoir model at a daily time scale. Conceptual approaches are preferred for the simulation of karst systems. Indeed, their heterogeneities make it difficult to use a physics-based approach. EROS uses daily precipitation, snow, temperature and potential evapotranspiration provided by SAFRAN to calculate karst spring flows. Technically, the AQUI-FR hydrogeological modelling platform was developed using the OpenPALM coupling system, which allows easy integration of high-performance computing applications in a flexible and scalable manner. In the OpenPALM framework, applications are divided into elementary components that can exchange data. The AQUI-FR platform is an OpenPALM application that currently includes five components.

A preliminary step is performed to estimate groundwater recharge and surface runoff with SURFEX taking into account SAFRAN atmospheric forcing before launching OpenPALM. This preliminary step gives access to 60 years of daily groundwater recharge and runoff at a regular resolution of 8 km over the entire metropolitan area.

Historical overview

The objectives of the first phase (since 2014) was to show the feasibility of such a tool via the construction of the AQUI-FR computer structure and the first evaluations, as well as to ensure the legal possibilities of exploiting hydrogeological applications in operational use, and finally, to identify the elements of interest for the water managers. The construction of the AQUI-FR structure required several steps: (i) to gather the hydrogeological models on the same computer structure that can be mobilised in operational use, (ii) to integrate the different hydrogeological applications available, (iii) to converge towards a homogeneous treatment on a national scale, via at least the use of a common atmospheric forcing, and (iv) to recalibrate the applications to make them more compatible with this new forcing.

This work was accompanied by an effort to process the input and output data. An important aspect of the input data is the integration of groundwater withdrawals over the simulated periods, which are difficult to acquire over long periods and for recent periods (two-year delay). The management of output variables requires specific work, taking into account the variables of interest for managers (variable, depth or geological layer, estimation period, estimation domain) and numerical constraints (disk volumes, calculation time). In parallel, two development efforts were carried out, in order to: (i) include a representation of the basement aquifers, with numerical experiments carried out on the Brittany aquifers, and (ii) to allow a correction of the initial states of the aquifers by integrating the available piezometric data.

Evidence of benefits from implementation

The results of the AQUI-FR project confirm the feasibility of bringing together independent hydrogeological models developed in different research institutes in the same coupling platform. All these models were initially developed and calibrated over shorter periods with heterogeneous geological and meteorological databases, but the evaluation of the long-term simulations that has been carried out shows a good comparison with the observations available for the same period. It confirms the relevance of using the AQUI-FR as a tool for long-term impact studies.

The other advantage of this platform is in its modularity. The AQUI-FR platform encourages the development of groundwater modelling where it is lacking and, more generally, it has the potential to be a valuable tool for many applications in water resources management, , water quality studies and research, for example in climate change studies and seasonal forecasts.

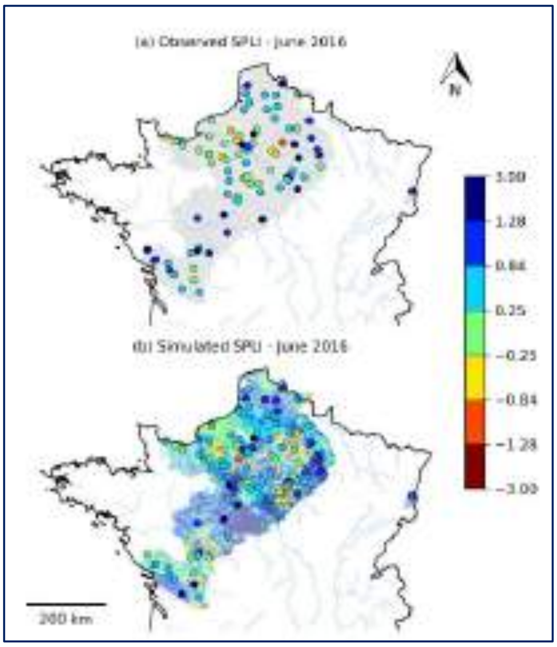

Figure 3: Standardised piezometric level index between observed (a) and simulated (b) piezometers.

Replication potential in the SUDOE region

The trigger for implementing the practice was the publication of the Explore 2070 project results, which showed a disparate analysis, and thus the idea emerged to harmonise the modelling results to make forecasts. From a technical point of view, few obstacles were encountered. The obstacles encountered were in relation to intellectual property. Indeed, it was necessary to reach an agreement on the sharing of the source code of the Marthe model to implement it on the Météo France platform. On the conceptual side, the models were not perfectly calibrated – some model outputs overlap. From an administrative point of view, it was necessary to convince the regions because the hydrogeological models were developed within the regional entities of BRGM. Finally, from a functional point of view, the maintenance of the platform requires a permanent researcher per partner. The project was also able to benefit from subsidies (about €100,000 per year).

Future outlook

In terms of evolution, the project offers several perspectives in terms of: (i) improvement of physical processes – better integration of basement and karst aquifers, and (ii) development– evolution of numerical codes and techniques.

This project also offers prospects for development outside of France, in the French overseas departments and territories, but also prospects within the framework of PEPR (OneWater programme).

In the future, other regional models will be included to extend the coverage of AQUI-FR (bedrock aquifers located in Brittany). A new modelling method based on a rainfall-runoff model will be used to provide upstream river flows as boundary conditions for the MARTHE models that require it. Finally, since errors in the initial conditions can significantly alter the skill of the forecast, studies dedicated to data assimilation to improve the initial state conditions are also performed in parallel.

Key points of the innovative method

- Multi-model numerical platform.
- Daily to seasonal forecasts.
- Prospective modelling (up to 2100).

Acknowledgements

The innovative practice was suggested by Jean-Pierre VERGNES (BRGM) who also participated in the interview.

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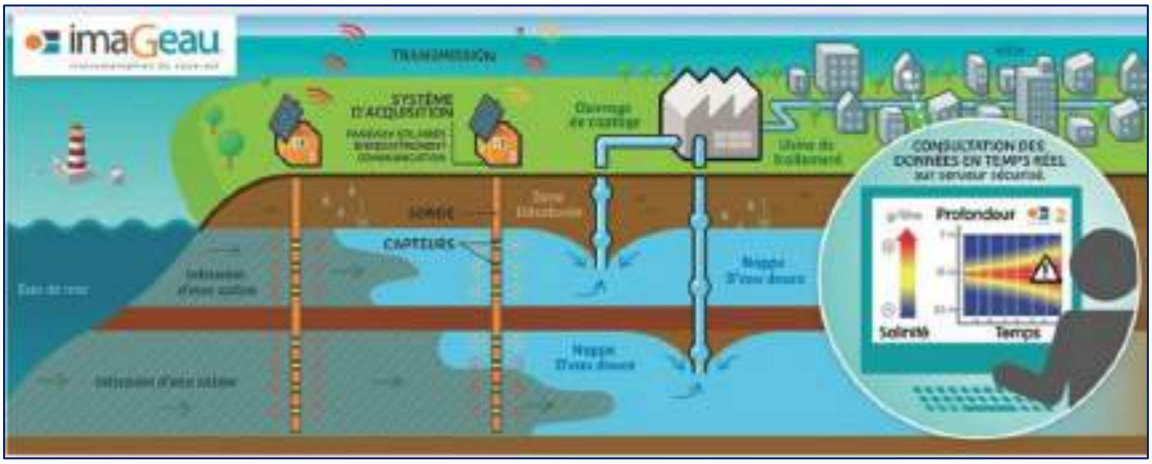
SMD: groundwater monitoring tool for monitoring saline intrusions

SMD (subsurface monitoring device) is a tool for continuous monitoring of saline intrusions in groundwater. The practice was developed by imaGeau and is an integrated solution from data collection on a water column to processing and analysis/interpretation via a specific platform. The objective of this practice is to measure and collect data on the problem of saline intrusion.



Specifically, this practice allows indirect measurement of the salinity of the water through the whole height of the aquifer. The practice allows for logging (vertical profile) in an autonomous and repeated way, using a cable with positioned electrodes. On the surface, an autonomous acquisition box, powered by either a battery or solar panels and controlled by a computer equipped with a GPRS modem, allows the transfer of data files to imaGeau servers. The acquisition system also allows for an electric current to be injected between two electrodes and measures potential difference.

The users of this innovative practice are local authorities, public organisations, research organisations (BRGM, DELTARES), and, sometimes, drinking water producers.

This practice has been developed in a context of a saltwater wedge and lack of knowledge of aquifer systems, to address issues on quality and quantity of the water resource, and its impact on the economic sectors dependent on the exploitation of an aquifer system.

Responsible entity

ImaGeau is a subsidiary of the SAUR group with environmental and digital expertise. ImaGeau has been developing sensors, studies and a WEB application (EMI) since 2009, allowing the actors of water cycles to implement sustainable practices of management and exploitation of water resources.

The missions of imaGeau are:

- To put digital technology and artificial intelligence at the service of water resource preservation.
- Facilitate the understanding and sharing of issues related to water resources.
- Promote the adoption of water resource management and exploitation practices adapted to climate change.
- Reconcile the balance between environmental benefits, profitability and employee development.

Institutional setting

This practice is implemented within the framework of monitoring the qualitative and quantitative status of groundwater. The regulatory framework is then site-dependent.

Geographical setting

The practice is used on the scale of coastal aquifer systems, both in France and internationally. The solution has already been deployed in France, Reunion Island, the Netherlands, Israel, Chile and Morocco (Chtoucka aquifer).

The practice is also used for certain continental aquifer systems in specific geological contexts, such as in Jordan where the saltwater wedge originates from gypsum strata.

Detailed explanation

The SMD consists of two distinct parts: (i) the electric flute, and (ii) the acquisition system.

The electric flute is the probe part in drilling. It is a chain of electrodes made of copper-aluminium, very resistant to corrosion, and which allows resistivity measurements. One or more pressure and temperature sensors are also integrated into the electrical cable installed in the piezometer.

Figure 1: Chain of electrodes.

The acquisition system is composed of:

- A low consumption computer on which proprietary software manages the acquisition of measurements, the processes of the tasks, and remote communication (for sending files and remote control).
- Electronic cards for each electrode in the well.
- A power supply which also acts as a DC current injection source for electrical measurements.

Figure 2: Data acquisition system.

The principle of measurement is as follows. The acquisition software manages the injection power supply and the electronic cards allowing it to inject a known electric current between two electrodes (A and B) and to measure the potential difference induced between two other electrodes (M and N). Using Ohm's law, the average resistivity is then measured around the piezometer between these four electrodes. The repetition of this process on the vertical of the piezometer allows for a profile of resistivity around the piezometer to be calculated (2). Using the Waxman-Smits equation (3), the electrical conductivity of the water in the aquifer is then deduced. This requires knowledge of the formation factor (F) and surface conductivity (Cs) which are determined at the SMD facility using a reduced set of logs (gamma ray for clays, electrical resistivity and sonic P-wave velocity for porosity). Finally, a temperature-normalised, well-corrected electrical conductivity profile of the aquifer water around the piezometer is measured at repeated intervals (4).

Historical overview

Most of the development of this solution was undertaken between 2010 and 2016 with the aim of improving the system and integrating other types of sensors.

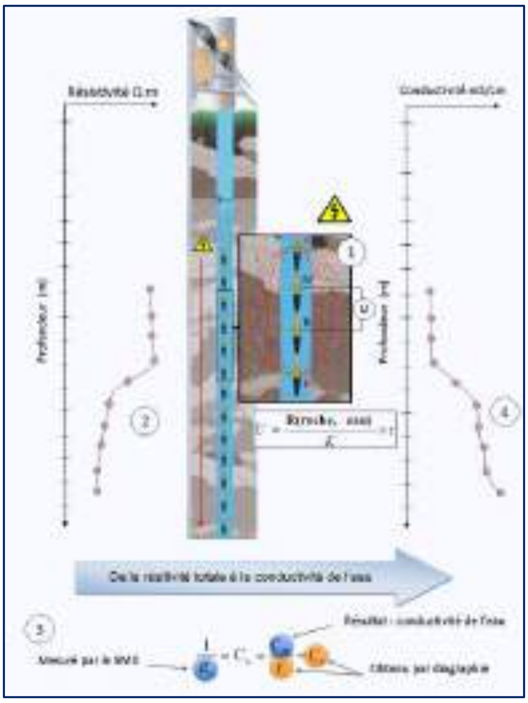


Figure 3: Principle of SMD measurement.

From 2016 to 2017, the solution moved into the industrialisation phase, with the manufacturing of some elements under subcontract.

The key factors in implementing this practice are: (i) study sites with a lot of data available, and (ii) successive experiments that improved the reliability of the measurement and its credibility in order to move to the industrialisation phase.

The obstacles encountered are that at the beginning of the development of the solution, it was not equipped with a platform for processing/analysis of the collected data, and therefore the data were often not used by the customers due to lack of skill.

At the same time, imaGeau was confronted with a problem of acceptability of the innovation; it was necessary to convince the hydrogeology community of the reliability of the solution.

Finally, to make the solution viable for operators, it was necessary to transform the information provided by the data measured in-situ into volumes of water that could be used by water producers.

Evidence of benefits from implementation

The advantages of using this practice are: (i) the absence of electronics immersed in the borehole, (ii) limited maintenance, (iii) a system with a long service life, and (iv) a totally autonomous and remotely controllable system.

The other advantage of using this technique is that the "well effect" is limited because the measurement is extended around the borehole (about 60 cm, depending on the spacing of the electrodes).

The results of various studies where this solution has been deployed have been published in international papers and conferences (SWIMM, IAH). The solution had also been the subject of a patent application.

Replication potential in the SUDOE region

The practice has a strong production potential as it can be deployed on any type of coastal aquifer system (or continental aquifer system with geological formations such as gypseous) subject to saltwater intrusion.

Two people work on a part-time basis on the development and maintenance of the practice (dedicated time is depending on the type of project). The mission now consists of testing the systems, installing them, monitoring them and carrying out maintenance, either remotely or in the field.

Future outlook

A long-term outlook for the solution is the adaptation of the technology to different issues, such as using this technique to perform cross acquisition also called "tomography between wells" to monitor hydrocarbon pollution, landslide areas, CO_2 storage areas, etc. Another prospect concerns the prediction of the risk of a saltwater wedge in the Mediterranean area, based on data collected by the solution, and the coupling of physical models and artificial intelligence models.

Key points of the innovative method

- Monitoring of saline intrusions.
- Can be used for coastal and continental aquifers.
- Stand-alone, plug-and-play solution.
- Data transmission and interface for data processing and analysis.

Acknowledgements

The innovative practice was suggested by Olivier DEPRAZ (imaGeau). Denis NEYENS (imaGeau) participated in the interview.

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ICT and modelling

Sustain-COAST: Sustainable management of coastal groundwater and pollution reduction through innovative governance in a context of climate change

Sustain-COAST is a research project co-funded under the PRIMA 2018 section II programme, for a period of three years from June 2019. The consortium is led by the Technical University of Crete (UTC) and consists of a multidisciplinary team of seven partners from six countries. The project intends to develop a calibrated multi-criteria decision support system (DSS) and a web-based geographic information system platform accessible to water stakeholders and policy makers. The DSS and the platform, combined with a specific animation activity, will allow: (i) the engagement of social actors in a learning process around water issues at the watershed scale, based on the visualisation of interactive thematic maps, (ii) the use of advanced technologies and tools, such as optical sensors and remote sensing capabilities for participatory water monitoring, and (iii) the use of calibrated numerical models for the spatio-temporal simulation of water quantity and quality evolution. Sustain-COAST thus explores new governance approaches to effectively support the conservation of coastal aquifers against anthropogenic and climatic pressures, through the promotion of innovative water management concepts based on the 4R principles: Reduce, Recycle, Reuse and Recover.

Although various measures have been taken by the administrations and agencies of the Mediterranean countries to promote a more integrated and sustainable management of coastal water resources, various management weaknesses persist: pollution from industrial and agricultural activities and poor wastewater treatment (Tunisia); water misuse from the agricultural/tourism sectors and marine intrusions (Greece); excessive consumption by the agricultural sector (Turkey); and conflict between farmers and fishermen over eutrophication problems in wetlands used for both aquaculture and agricultural activities (Italy). These four countries seek to contribute to the improvement of the governance of Mediterranean coastal water resources through a collaborative research project that is designed to explore, design and test innovative governance approaches for coastal groundwater resources in the Mediterranean by promoting stakeholder dialogue and decentralisation and civil society engagement in decision-making processes.

The overall objectives of SUSTAIN-COAST are:

- Design and test innovative governance approaches for Mediterranean coastal water resources.
- Improve water resources management.
- Mitigate pollution of water resources.

- Application of good governance principles: equity, legitimacy, efficiency, transparency and accountability.
- Decentralisation, engagement of civil society in decision-making processes, and engagement of the private sector in strong public-private partnerships.

The project is organised around four founding pillars:

- Strengthening desirable coastal water resources management options.
- Prevention of coastal groundwater pollution.
- Active engagement of relevant stakeholders in a social learning process.
- Strengthening monitoring, communication and dissemination activities.

The project is innovative in that it actively engages stakeholders throughout the basin in a social learning process and spatio-temporally predicts groundwater flow and pollutant transfer based on prevention and mitigation options suggested by stakeholders and climate change scenarios

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Responsible entity

The Technical University of Crete (UTC) is the coordinator of the SUSTAIN-COAST project. UTC has over 6,000 students and 115 faculty members. UTC consists of five engineering schools and conducts research in advanced technological fields in collaboration with other research institutes and industries. The SUSTAIN-COAST project is carried out at the School of Environmental Engineering (EnvEng). Research at EnvEng aims to develop innovative solutions to the most daunting environmental challenges. Whether it is waste management, future energy needs, water resources or climate change, EnvEng's research efforts are strengthened by creative collaborations with leading research institutes and universities around the world. Through various national and international projects, EnvEng has developed significant expertise in coastal groundwater resource management in relation to numerical modelling activities and GIS tools. These topics are directly related to the Sustain-COAST challenges.

Institutional setting

The need to implement innovative governance of coastal aquifers, taking into account technological development as well as socio-economic factors, has become a global necessity. In line with the challenges and scope of theme 1.1.2 of the PRIMA call ""Sustainable and Integrated Water Management", Sustain-COAST has been designed to explore innovative approaches to coastal aquifer governance among multiple water users and beneficiaries, under the uncertainties posed by changing climatic conditions, in four Mediterranean countries.

The technical partners of the project are the Helmholtz Centre for Environmental Research (Germany), the Euro-Mediterranean Information System on Water Expertise (SEMIDE, France), the University of Strasbourg (UNISTRA, France), the University of Sassari (Italy), the Centre for Research and Technology in Water (CERTE, Tunisia), and the University of Mersin (Turkey).

A scientific council has also been appointed involving institutes (GWP, CIHEAM – Bari institute, UFM – Union for the Mediterranean) and companies (Ambienta).

Geographical setting

The project takes place at four study sites, called "Living Labs": Arborea (Italy), Wadi El Bey (Tunisia), Malia (Greece), and Erdemli (Turkey).

Figure 1 : Location of Sustain-COAST study sites.

Arborea (Italy): The case study is located in a 60 km^2 area under the domain of the Consorzio di Bonificadell'Oristanese, a local consortium controlled by the regional administration that is responsible for the distribution of irrigation water supplied by the Eleonora d'Arborea dam, one of the largest in Europe. Agricultural systems range from dairy cattle breeding in a nitrate vulnerable area (the municipality of Arborea) to rice cultivation (over 3,000 ha), horticulture and other rain-fed agricultural activities. Water is key to the economic development of the district: the cooperative system of Arborea is the most important dairy industry on the island, with more than 300 million euros of annual gross income, struggling between the market crisis and the environmental restrictions of effluent management in an area that was drained in the 1930s, with a very shallow water table and sandy soil. Rice cultivation is one of the largest consumers of water per unit area in the district, while providing not only food but, especially, rice seed. Horticulture is one of the main operations on the island, producing artichokes, melons and many other valuable crops.

Wadi El Bey (Tunisia): The Wadi El Bey pilot site is located about 40 km south of the Tunisian capital. It covers an area of 430 km². It is bordered to the north by the Gulf of Tunis and the hills of Tekelsa, to the west by the mountains of Bouchoucha and Halloufa, to the south by the hills of Hammamet, and to the east by the mountain of Abderrahman and the highlands of the eastern coast. The main wadi of this pilot site flows into the Sebkha El Maleh, which is close to the Mediterranean Sea. This pilot site contains various industries operating mainly in the field of textiles and food processing. In addition, it contains extensively cultivated areas (citrus, oranges, grapes and vegetables). The site is characterised by a high level of pollution due to the important development of industrial, agricultural and tourist activities. The main sources of pollution are industrial and agricultural activities and inadequate wastewater treatment.

Malia (Greece): The Malia watershed is located in northern Crete, Greece, 40 km east of the city of Heraklion. Surface and groundwater are used to support the extensive agricultural activity of the area, while, in the last 20 years, increased tourism development has resulted in a significant demand for water consumption. The region's water resources are very important to its inhabitants as they cover their drinking water needs and their well-being depends on agricultural and tourism activities that consume large amounts of water. As a result, groundwater levels have been significantly reduced over the past 30 years, resulting in significant saltwater intrusion into the groundwater. Water quality in the area has been significantly degraded due to the massive saltwater intrusion into the aquifer. As a result, high concentrations of Chloride are found in the groundwater, which, in conjunction with excessive pumping, leads to lower aquifer levels and groundwater degradation. In addition, increased concentrations of nitrates are also found in groundwater due to extensive agricultural activity in the area.

Erdemli (Turkey): The Erdemli Coastal Aquifer (ECA) is located about 30 km west of downtown Mersin (in south-eastern Turkey), covering an area of 45 km². The population of Erdemli district is 140,331, the majority of whom are mainly engaged in agricultural activities. A significant part of the area is made up of agricultural areas such as greenhouses and citrus orchards. The southern part of the ECA area, which is very close to the Mediterranean coast, is mainly composed of alluvial deposits, while the northern highlands are composed of carbonate rocks with many karst features (e.g. sinkholes, caves, etc.). In the region, mainly in the Mediterranean coastal areas, groundwater from the coastal aquifer is used extensively to meet domestic and agricultural irrigation water demands. The main problems in the region are the intensive use of groundwater, the decrease in the quantity and quality of surface and groundwater due to increasing droughts, agricultural activities, and the lack of water quality.

Detailed explanation

The management practice is developed around a multi-criteria DAS (Geographic Information System (GIS)-based multi-criteria decision analysis method) and multi-actor platforms (Living Labs). The DAS is based on multi-criteria factors including local and specific social, economic, technical and environmental constraints. This system is designed and implemented for each case study. The decision rules for the implementation of the DAS depend on quantitative data derived from weighted GIS layers and thematic maps are created for each main criterion. At a later stage, sensitivity and suitability maps are produced using a weighted overlay method in GIS based on the weighted thematic maps. Finally, several "what-if" scenarios are developed and evaluated, considering a wide variety of water management issues, such as satisfaction assessment, water pricing, water saving suggestions to users, new infrastructure proposals and their impact. The ranking of these different alternatives in order of preference can also take place through the use of DAS by considering the principles of game theory in terms of a zero-sum game.

The data sources are scanned and transferred into a GIS tool (ArcGIS), and all data layers are georeferenced with the same projection system. Then all necessary data in the layers will be digitised using the Arc

Editor tool. After digitising the data, vector maps are created for each factor and the attributes are entered manually (lithology, land use and soil type, transmissibility, piezometric water levels, and water quality parameters) or calculated automatically (distance to lineaments, springs and wells, and water bodies) using the ArcGIS tools. All created vector layers are converted to raster format and each sub-criterion is weighted by the value of the assessment. The last action is the creation of the suitability map using the Weighted Linear Combination (WLC) aggregation method with the special data available for each case study area that may cause stress on groundwater pollution.

Finally, a multi-stakeholder platform involving relevant actors, based on participatory and interactive sessions – Living Labs – is designed and implemented

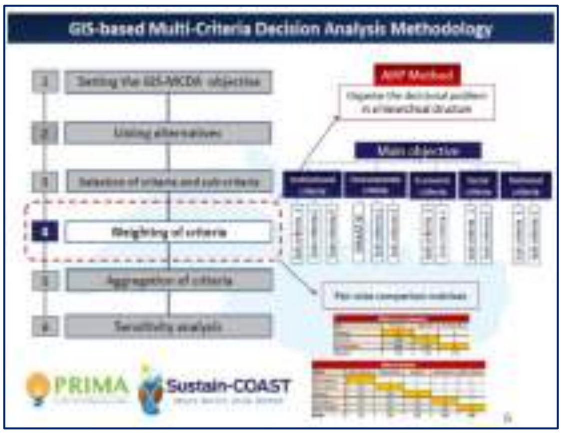

Figure 2: Multi-criteria decision analysis method developed within the Sustain-COAST project.

by the partners in each case study. The main stakeholders interested in the implementation of an innovative governance of the studied sites, taking into account their priorities but also their constraints, are taken into consideration. Consolidating and maintaining the active involvement of the main socio-economic actors concerned (ensuring a public-private-popular partnership) through their early involvement in the overall management and effective governance of the coastal aquifers of the selected case study sites are two of the objectives of Sustain-COAST. To this end, five Living Labs in each case study are co-designed and organised. The ultimate goal of this task is to promote social learning spaces, where integrated scientific and local knowledge is developed to support decision makers in designing adaptive pathways for local communities regarding sustainable water resource systems.

Historical overview

Two main triggers initiated the setting up of this project. First, climate change and its impacts on the groundwater resources of the selected study sites, and second, the absence and lack of data sharing among stakeholders.

No major obstacles were encountered during the project set-up phase. During the implementation phase, the obstacles encountered concerned the commitment of public decision-makers, access to data, and the management of the participatory approach in the context of the COVID-19 pandemic.

Evidence of benefits from implementation

There are no benefits to the use of this management practice yet since the project is still in progress. However, interesting first results on the characterisation of the demonstration sites and on the cost-effectiveness and cost-benefit analysis of some prevention scenarios have been published on the project's institutional website.

Replication potential in the SUDOE region

The project has a strong potential for replication (Mediterranean or wider) as it touches different stakeholders and different groundwater issues that are common to other regions. The financial cost of such a project is €1.12 m, with about fifteen people (six countries, seven partners) dedicated to the implementation of the solution. Each partner was able to benefit from subsidies via the PRIMA program.

Future outlook

The short-term perspective of the project is to extend it by one year because it has been strongly impacted by the COVID-19 crisis. In the longer term, the objective is to valorise the Sustain-COAST results by creating new projects (2 PRIMA projects have been created – INTheMED and AgreeMED), and to transfer tools and practices to the groundwater resources managers of the demonstration sites.

Key points of the innovative method

- Multi-partner project.
- New governance approach to protect coastal aquifers.
- Living Laboratories for a participatory approach.
- Civil society engagement in the decision-making process.
- Social learning process.

Acknowledgements

The innovative practice was suggested by Yvan KEDAJ (Aqua-Valley). Maroua OUESLATI (SEMIDE) participated in the interviews.

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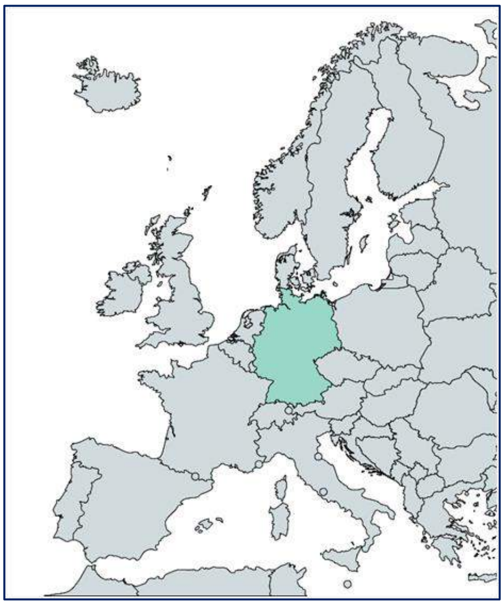
INOWAS – A web-based system to support the successful implementation of Managed Aquifer Recharge methods



The INOWAS is a free, web-based modelling platform for planning, assessment and optimisation of Managed Aquifer Recharge (MAR), a nature-inspired solution that aims at intentionally recharging aquifers for later use or environmental benefits. This platform is comprised of a set of tools for finding the optimal location for MAR schemes, assessing parameters for optimal design and operational management, and quantifying the expected impacts of MAR implementation. It contains a compilation of algorithms of varying complexity to solve empirical, analytical and numerical equations, running on a web server that can be accessed via standard web browsers. It is a non-operating system dependent solution that was primarily developed as a decision support system (DSS) for groundwater management applications using web-based technologies, supported by geographical information systems functionalities, and conducting cloud-based simulations. Its open-source nature allows for easy implementation and dissemination. It has finite-difference MODFLOW numerical modelling and is currently being upgraded with real-time in-situ monitoring data gathering and analysis capabilities to feed and calibrate the groundwater models. The main goal is to bring real-time responsive modelling procedures and decision-making together for the improvement of integrated water resources.

Responsible entity

The INOWAS platform was developed within Dresden Technical University (TUD) by the Managed Aquifer Recharge (MAR) Junior Research Group – the INOWAS Group (Fig. 1). This is a research unit under the Department of Hydrosciences of the Faculty of Environmental Sciences at TUD.

Fig. 1 – INOWAS MAR junior research group logo.

The INOWAS Group is founded on two main pillars: an experimental pillar to understand the processes occurring during MAR and their variability caused by climate change, urbanisation and population growth; and an instrumental pillar for the development of MAR simulation tools with a focus on scenario analysis.

The INOWAS team is composed of 18 persons from 12 different countries and has been continuously engaged in international networking since its creation in 2014. Among the contacts established, the INOWAS, has active networking with international associations such as IAH, UNESCO Institute for Water Education and the Australian CSIRO. The group also contributes with lectures to various study courses such as “Hydroscience and Engineering” and “Groundwater and Global Change – Impacts and Adaptation” and has promoted a series of international summer schools since 2016.

The group is currently led by Catalin Stefan and is responsible for the development of the first global inventory of MAR applications in 2015 (Stefan and Ansems, 2018). This survey covered 62 countries and collected information on 1,200 case studies concerning historical development, site characterisation, operational scheme, objectives and methods used, as well as quantitative and qualitative characterisation of in- and outflow of water. This robust database is currently available in UNESCO International Groundwater Resources Assessment Centre’s web map tool.

Institutional setting

The main driver of the INOWAS research group is MAR, the purposeful recharge of an aquifer for later water recovery or environmental benefits (Dillon et al., 2009; Bouwer, 2002) and has proven to be a reliable instrument for sustainable groundwater management. This concept comprises a series of different methods, from surface spreading methods (i.e., infiltration basins and structures) to borehole injection, each with specific requirements for implementation. Despite its demonstrated economic and ecological benefits, MAR is still not widespread, partly due to poor access to information and lack of knowledge. To help address these challenges the INOWAS promoted technical innovation and the development of tools like the INOWAS Platform to plan, assess and optimises MAR applications.

Geographical setting

The INOWAS MAR junior research group is based on Pirna’s TU Dresden external campus. Pirna is a town of 38,252 inhabitants in the German state of Saxony, the capital of the administrative district of Saxon Switzerland-Eastern Ore Mountains. Under the experimental pillar of the INOWAS Group and its main research subject, a pilot MAR site was developed on Pirna’s TUD campus. This site is located on the banks of the River Elbe and has allowed the group to conduct various investigations both at laboratory and real scale. The pilot is composed of one rapid infiltration basin to simulate MAR scenarios under natural conditions, seven groundwater monitoring wells to perform tracer experiments and determine groundwater flow direction and velocity (useful for aquifer-storage-recovery methods), and eleven small-diameter piezometers (Fig. 2). All of them are equipped with real-time monitoring devices to collect in-situ parameters whose deep analysis allowed for use as input for calibration of numerical models of the vadose zone (fundamental for MAR).

Fig. 2 – Location of the INOWAS rapid infiltration basin and groundwater monitoring wells (adapted from the INOWAS group website).

Detailed explanation

The INOWAS group recognised that most decision support systems for water management are desktop-based, which represented a particular constraint to dissemination. The INOWAS platform is developed as an open-access web service where the whole workflow is managed directly in a web browser without the need to install additional plug-ins. This also allows for online multi-user collaboration between researchers and decision-makers bringing a global perspective to water resources management, simplifying communication and making information quickly available everywhere if needed. Users can work on private, public or shared tasks while the work progress is saved at any stage and can be resumed later.

The INOWAS platform includes the ability to assemble groundwater finite-difference models based on MODFLOW and conduct the simulation calculations directly in the web browser without the need to install any software. This ability decreases compatibility issues related to operating systems, which are recurrent in desktop applications, and requires no update procedures. While modelling, the workflow can be saved at any time and can be continued later from another machine, if necessary, using ongoing integration of cloud-based services (which will in the future allow for very complex numerical model simulations). The platform is structured as presented in Fig. 3.

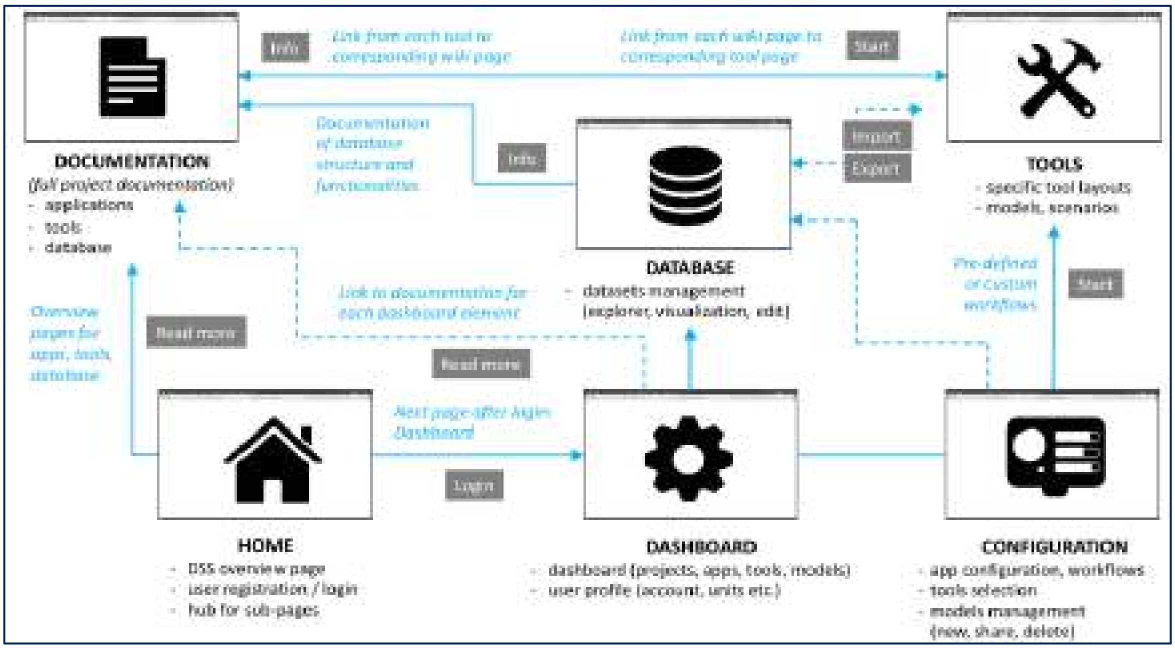


Fig. 3- INOWAS platform structure (adapted from Stefan et al., 2017).

The central place of the INOWAS platform is the personal dashboard which offers the user access to the available tools and user-developed projects. The projects can be either saved as private or public (any registered user can access them) which allow for other users to view its content, clone it and further edit a copy of it. The INOWAS is currently developing shared projects in which a user can create a group to share a project by inviting other users and making it accessible and editable. Unlike in the public option, all members of a group can work together on a single project.

Simulation tools are the strong point of the INOWAS platform. These are hierarchically organised in three types: (1) empirical – derived from data mining such as the global MAR applications inventory or a database for GIS-based MAR site suitability mapping; (2) analytical – based on simple equations for saltwater intrusion assessment, calculation of pumping-induced river drawdown or estimation of groundwater mounding beneath an infiltration basin; and (3) numerical – MODFLOW-based simulations using numerical flow and transport models.

In the modelling procedures, the management and analysis of the user-friendly scenario allow for a flexible interpretation of results and future predictions. The set of numerical tools is composed of T20 real-time modelling, T03c variable-density flow (SEAWAT), T07 MODFLOW model scenario manager, T03b solute transport (MT3DMS), and T03 numerical groundwater modelling and optimisation.

In its current state, access to the INOWAS platform is free for education and non-commercial purposes, but the user must create an account. It relies on a very robust set of open-source libraries and platforms (Fig. 4).

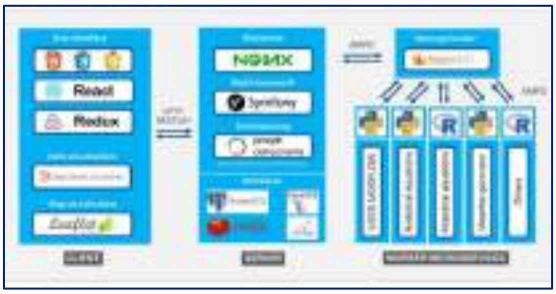


Fig. 4 - INOWAS platform architecture (adapted from Stefan, 2017).

Historical overview

A project with the same name as the platform funded by the German Federal Ministry of Education and Research laid the basis for the development of the INOWAS. The project was conducted between May 2014 and April 2019 and, at the time, aimed at providing stakeholders with a scientifically based decision support system (DSS) for planning, design and management of applications in the water sector. The project focus lay on the qualitative and quantitative assessment of groundwater resources by scenario analysis, prognosis and risk assessment and with regard to the influencing climatic factors. The project presented four main pillars (Qualification, Knowledge, Computing and Applications) and was composed of nine work packages (Fig. 5).

The multi-component DSS was then developed on an interactive web-based platform that combined a comprehensive knowledge base with complex scenario analysis tools. A public blueprint of the platform was presented at the 9th International Symposium on Managed Aquifer Recharge (ISMAR9), organised in 2016 in Mexico City (Stefan et al. 2016).

The official public release occurred in the last months of 2017, while a series of INOWAS Summer Schools on MAR began in September 2016. The first summer school was attended by 26 participants from 18 countries. In 2017 The second summer school, with a duration of two weeks (4–15 September 2017), was structured in two main parts: (1) planning and optimisation of MAR schemes, and (2) practical implementation and case studies. A special session was allocated to computer-aided simulation and analysis of different MAR scenarios using the free INOWAS platform (Stefan et al., 2019).

Evidence of benefits from implementation

Due to the nature of the platform presented no palpable benefits are presented. The tools that are comprised in the INOWAS platform were used to evaluate MAR feasibility in several locations (Glass et al. 2017a; Kwoyiga and Stefan, 2019) which resulted in a substantial amount of scientific and technical documentation. It can be concluded that due to the present well-developed state of the platform the foundational project was successfully completed. The INOWAS group, through the platform, was successful in performing diagnostic analysis of aquifers, accessing MAR implementation schemes, helping to plan and optimise those schemes, promote sustainable water management, develop stakeholders' capacities and academic training, and, most of all, lay the path to improving the link between modelling and decision-making. It was possible to promote MAR through the development of an integrated knowledge base with detailed descriptions and best-practice examples of the most common MAR techniques; and demonstrate MAR's benefits through the simulation of multiple management scenarios (Glass et al., 2017b).

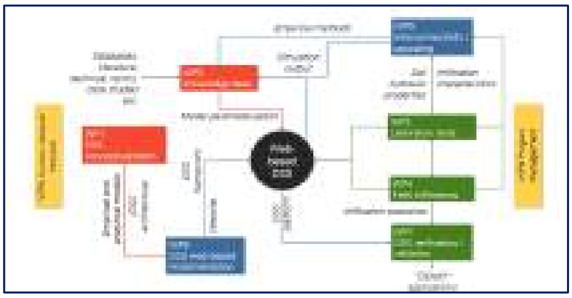


Fig. 5 – The INOWAS project architecture (adapted from the INOWAS project flyer).

Replication potential in the SUDOE region

MAR methods are an important tool in integrated water resources management, particularly in areas prone to water scarcity, such as the Mediterranean region. It is therefore critical to develop models to evaluate the feasibility of those methods and prove them to be both economically and environmentally reliable, for which the well documented and tested INOWAS platform is an already proven tool.

Future outlook

It is expected that the INOWAS platform will be used for modelling MAR in Kathmandu (Nepal) and for teaching groundwater modelling in Brazil. An important step forward for the platform is the ongoing SMART-Control research project, headed by the INOWAS group, funded through the Water Joint Programming Initiative (WaterJPI), and implemented by nine institutions from Germany, France, Cyprus and Brazil. The main objective is to reduce the risks associated with MAR by the development of real-time monitoring and control system in combination with risk assessment and management tools. The project approach relies on coupling a real-time in-situ observation system consisting of online sensors and a web-based groundwater monitoring and modelling platform. The resulting system shall provide operators and managers of MAR schemes with automatic decision support tools for monitoring, controlling and predicting processes occurring during MAR. The approach will be tested and validated at six MAR sites under different environmental and operating conditions (Glass et al., 2020). The INOWAS platform will be upgraded in the SMART-Control project by four additional simulation tools (Fig. 6):

- T1. Initial risk assessment to evaluate the viability of a MAR project and the preliminary assessment of human health and environmental risks with a quantitative microbial risk assessment (QMRA) component consisting of hazard identification, exposure assessment, dose analysis and risks characterisation to predict the risk of infection or disease-related outcome.

- T2. Real-time monitoring and control to facilitate the operational management of MAR sites by conducting real-time integration of time-series data into the INOWAS modelling platform. Sensors installed at MAR facilities worldwide can be connected to the INOWAS platform to transfer collected data in real-time.

- T3. Automatic groundwater model update and simulations relying on the capabilities of the INOWAS platform enabling fast response and optimised management.

- T4. Predictions for advanced system management to evaluate spatial and temporal water availability under different scenarios such as climate and land-use change.

The INOWAS collaborative modelling capabilities will also be the central platform for the forthcoming AgreeMAR project funded by European Union's PRIMA.

This project is expected to start in 2022 and aims to develop an adaptive governance framework integrated with a set of tools that will assist water policy-makers and water managers to reach sustainable integrated water resources management and will be implemented in the Mediterranean regions of Tunisia, Spain, Cyprus and Portugal.

Fig. 6 – SMART-control architecture (adapted from Glass et al., 2020).

Key points of the innovative method

- The INOWAS Platform is a free, web-based modelling platform for planning, assessing and optimising MAR applications

- It was developed by a recently assembled research group based at the Technical Uni-versi-ty of Dresden and is focused on MAR.

- The platform allows the integrated use of various model complexities and provides the best accessibility of project data and multi-institutional collaboration through web-based implementation.

- It makes use of a combination of widely available open-source tools and promotes the case-based analysis approach with sup-port for model parameter estimation and so-lution finding.

- Cloud capabilities are being developed as well as the capacity to analyse real-time data for numerical modelling calibration.

Acknowledgments

This innovative practice was suggested by Teresa Leitão of the Portuguese National Laboratory for Civil Engineering (LNEC) after discussions between the PPA and LNEC.

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SMART-control project information (https://www.smart-control.ino-was.com)

IGRAC GW Resources Assessment Centre MAR Portal (https://ggis.un-igrac.org/view/marportal)

Other sources:

https://tu-dresden.de/bu/umwelt/hydro/inowas/research/projects/inowas

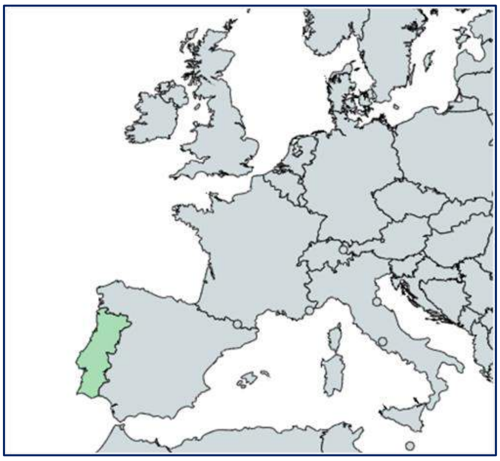
http://en.pirna.de/Home/4188l1/

INOWAS platform participating members:

INOWAS MAR junior research group (https://tu-dresden.de/bu/umwelt/hydro/inowas/about)

Technical University of Dresden (https://tu-dresden.de/)

Portuguese National Water Resources Information System (SNIRH) - A public web portal with all the available information on water resources



The Water Framework Directive, which requires European Union Member States to achieve good ecological status in all water bodies by 2027, outlines the planning and management procedures of water resources relying heavily on base information collected on those resources. In a situation of extreme events and accidents, systems must be put in place for real-time information to be provided to the authorities allowing for an adjusted response.

The Portuguese National Water Resources Information System (SNIRH), launched in 1997, is the technological structure in the form of a web portal where the Portuguese Environmental Agency uploads, validates and makes available water resources related data to the public, including hydrometeorological, and quantity and quality information datasets for surface, coastal, transitional and groundwater bodies. The system has reporting capabilities and provides technical information for several entities, from academic and public entities (national and European) to private companies and consultants. The system has seen several developments and includes extreme events reporting capabilities that support the actions of national civil protection entities. The SNIRH also promotes educational content for children and includes an extensive library of water-related documents.

Responsible entity

The National Water Resources Information System (SNIRH) (Fig. 1) was initially developed within the Portuguese Water Institute (INAG). This was the institution within the Portuguese National Protection Action Scheme that coordinated water management.

Fig. 1 - SNIRH logo.

In 2012 INAG was integrated into the Portuguese Environment Agency (APA), which also acted at the national level but incorporated extended functions compared to the former INAG. The APA combines in one single entity the national and regional competencies for managing the water domain as well as other environmental components, such as waste licencing. This agency aims to define standardised national instruments and procedures for a more efficient service to citizens and companies (Lacerda et al., 2013).

Procedures for monitoring water status was made a priority of the agency. The APA presently manages the following networks, all of them reporting to the SNIRH:

- A meteorological network, consisting of 561 meteorological stations that measure precipitation, wind speed and direction, evaporation, radiation, temperature, and humidity.
- A hydrometric network, consisting of 256 stream gauge stations that measure hydrometric levels.
- A piezometer network to measure the groundwater level comprising 602 stations.
- A groundwater quality network comprising 848 stations.
- A surface water quality network comprising about 2,065 stations in rivers and reservoirs, assessing ecological and chemical status, and 213 stations to assess the status of transitional and coastal water bodies.

Institutional setting

The European Union Water Framework Directive (WFD) was adopted in 2000 with the objective of establishing a framework for Community action in the field of water policy. This extensive and pioneering European legislation aims to protect and enhance aquatic ecosystems and promote sustainable water use in European territories. It sets the framework for analysis planning and management of water resources by establishing environmental objectives for water bodies to achieve good ecological status by 2027. It also defines the creation of management mechanisms, such as River Basin Management Plans, to identify and assess pressures to water bodies and develop specify responses and programmes (Carvalho et al., 2019; Collins et al., 2012). Most importantly, the WFD established the requirements for monitoring the surface water and groundwater status and protected areas (Article 8) as well as the specific parameters to be considered (European Commission, 2003).

At the national scale, the WFD was transposed into the Portuguese Water Law, which aimed to prevent further degradation and protect and improve the status of aquatic ecosystems, promote sustainable use of water based on the long-term protection of available water resources, mitigate the effects of floods and droughts, and ensure a sufficient supply of good quality surface and groundwater for sustainable, balanced and equitable use.

The transposition of the WFD to the national legal framework represented an opportunity to modernise and increase the geographical extension of the already existing Portuguese monitoring networks. Although the SNIRH is older than the WFD and the Portuguese Water Law, this public database is the perfect platform to store monitoring data and make it available to the public.

Geographical setting

The SNIRH monitoring networks cover the entire mainland Portuguese territory (Fig. 2), and includes hydrological and meteorological data for the Azores and meteorological data for the Madeira islands. This system is particularly relevant in monitoring extreme events such as droughts and floods, which are expected to become more common with climate change.

Detailed explanation

Technically, the SNIRH is a public web portal (https://snirh.apambiente.pt/) supported by a database that concentrates, stores and disseminates hydro-meteorological and water quality data, from both surface water and groundwater, collected by the Portuguese Ministry of the Environment's water resources monitoring network.

The monitoring network consists of automatic and conventional stations, some of which are equipped with a remote transmission system. The web portal also publishes monthly water availability reports, technical summaries, and cartography on water resources, such as flood zones. The SNIRH database also encompasses technical documents and photographs related to water resources.

The web-portal presentation is divided into five different sections: (1) synthesised data, (2) base data, (3) big numbers, (4) media library, and (5) international relations.

Fig. 2 – Location of the SNIRH's monitoring networks (adapted from the SNIRH flyer).

The synthetised data section is a report and information database which has a set of report bulletins related to rainfall, surface water flow, surface water storage, and temperature, along with a special section dedicated to groundwater, where static information regarding 22,763 wells, 7,964 of them with detailed information (depths, screening, geological profiles, etc.), is stored. The groundwater card also provides reports. For example, it allows the user to check the status of a specific groundwater body for both quantity (groundwater depth) and quality (with parameters such as chlorides, nitrates or electrical conductivity) (Fig. 3). The system generates geostatistical surfaces based on point data gathered from the monitoring network.

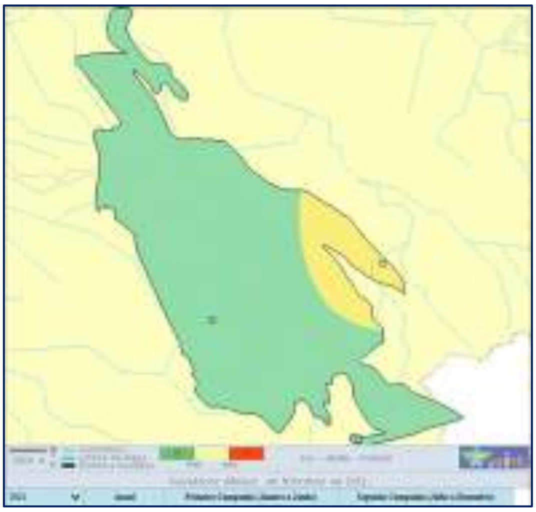


Fig. 3 – Example of a report card for the geographical distribution of nitrates in groundwater.

This synthetised data section also comprises reports on the quality status of coastal water in the bathing season, surface water reservoir characteristics with detailed data of dam constructive aspects, groundwater wellhead protection areas, and extreme events reports for drought and forest fires (reporting on the effects on water quality, loss of soil and related flood events).

The base data section is divided into two main sub-sections: the raw data from the monitoring networks, including point data from surface and groundwater quality and quantity as well as meteorological data (which are used for generating reports in the synthesised data section); and the Floods Observatory.

The Floods Observatory has a surveillance system (SVARH) and includes a flood risk cartography database and reports. The Flood Surveillance and Warning System (SVARH) is a sub-set of the real-time global water resources management scheme and is composed of four components:

- Sensors with remote transmission.
- Protocol data from the upstream country (Spain) and reservoir operations from hydropower companies.
- Hydrological and hydraulic models.
- IT systems for storing, validating and broadcasting hydrometeorological data.

Rainfall forecasts and soil moisture evolution assumptions are used as a basis to model and generate hydrological and hydraulic forecasts. These forecasts are established for priority critical points/areas: (1) upstream flow to dam, (2) water levels for urban areas, and (3) flow and water levels in the stream gauge stations (Fig. 4).

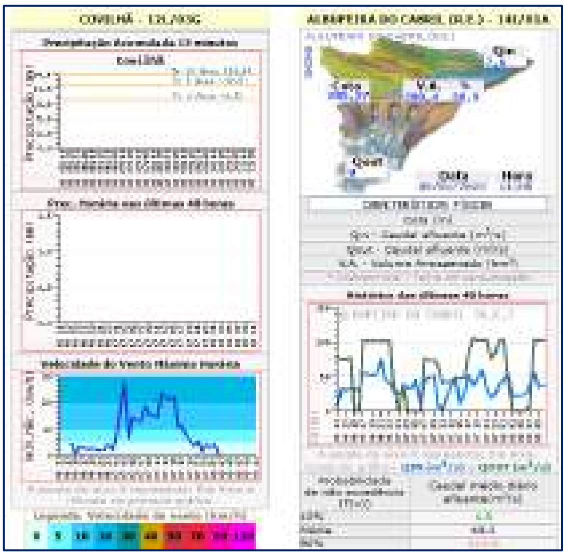


Fig. 4 – SVARH system (example of meteorologic station and dam station data).

Although not yet visible in real-time, areas of flooded surfaces are generated by coupling GIS capacities with the hydraulic forecasts.

In transboundary watersheds with Spain, all upstream relevant information is sent to Portugal in the framework of the Convenção de Albufeira Protocol. The SVARH uses an alert system that notifies the National Civil Protection Agency Centre (Autoridade Nacional de Proteção Civil) and respective regional dependencies in case of an emergency.

The big numbers section contains a water atlas, a geographical database of water characteristics of Portugal, divided into the main watersheds, and including information from average evapotranspiration to soil types and uses. It also contains a detailed geological, hydrological and hydrogeological description of the Portuguese groundwater bodies.

The media library currently has five sub-sections: hydro-library, hydro-album, legislation, glossary, and a “What is the SNIRH?” sub-section. The hydro-library is a public literature database with historically relevant documents on water resources in Portugal, as well as a repository of footage that integrates users’ contributions. The hydro-album is a collection of photographs relating to the different themes of the SNIRH. Legislation is an up to date repository of all Portuguese legislation related to water since the 1932. The glossary contains the definition of 315 terms related to water resources. The “What is the SNIRH?” sub-section contains a general description of the SNIRH and claims that it is accessed more than 600 times a day by students, teachers, researchers, educational establishments, designers and consultants, companies, social media, and central and regional public administration.

Finally, the international relations section presents detailed information on the transboundary Albufeira Protocol as well as European and Portuguese Legal Framework summaries and briefs, such as the Nitrates Directive (91/676/CEE) reports.

The web portal allows the user to directly search for a specific monitoring station with a given reference code, explore the raw data and download usable CSV files. Within each station’s card, it is possible to check statistics on monitored parameters or to generate a temporal evolution graph for specific parameters (Fig. 5).

The user can use the public platform to clarify any doubts related to water resources.

From the SNIRH main page, users can also access a secondary web portal (the SNIRH-Junior) whose educational contents are directed at children, including didactic games and online galleries for the presentation of teaching articles related to water resources.

Historical overview

The SNIRH was created by the INAG in 1995 and launched officially on Portuguese Water Day, 1 October 1997. It was the 1990–1995 drought period (which was ended by the heavy floods period of 1995/96) that made it necessary to create hydrometeorological automatic systems to allow authorities to provide a proper and immediate response. Between 1996 and 1998 several types of equipment were tested and laid the guidelines for establishing the Portuguese monitoring networks, which were fully operational at the beginning of the twenty-first century (Lacerda, et al., 2013).

Fig. 5 – Temporal evolution of Nitrates in a groundwater quality monitoring point (246/C52).

In 2000, Portuguese-Spanish relations concerning water resources were discussed and outlined in the Cooperation Convention for the Protection and Sustainable Use of Water from Portuguese-Spanish River Basins, also known as Convenção de Albufeira (Albufeira Protocol). It integrates the WFD guidelines, creating a cooperation and coordination protocol for the protection of water bodies, aquatic and terrestrial ecosystems, and aiming for the joint sustainable use of water resources. This represented an important step in sharing information between the two countries, feeding data to the SNIRH and allowing for forecasts in transboundary watersheds.

In 2012, the APA was created. The SNIRH web portal has been managed by the APA since then. is the APA also currently supervises the operation of the Albufeira Protocol and integrates transboundary data into the portal database.

Evidence of benefits from implementation

One of the most important benefits of the SNIRH is the acquisition and inclusion of telemetric stations that remotely send information in real-time and allow for decision-makers and emergency responders to take quick action in case of adverse conditions.

The SNIRH databases have also been contributing greatly to scientific water research conducted in Portugal. Once the platform was open to public access there was an internal discussion related to the possible commercialisation of available data. The INAG then took a pioneering position in establishing free access to environmental data. This allowed the recently developed web interface to be awarded the Descartes Award in 1997, promoted by the Portuguese Institute of Informatics, for provision of information on water resources via the internet.

The SVARH also received third prize in the Management category of the Microsoft Software Contest in 2003.

Today the SNIRH continues to allow the use of published content as long as the source is cited.

Replication potential in the SUDOE region

Systems like the SNIRH already exist in Spain and France where they are fully operative and reporting on the ecological status of water bodies based on monitoring data.

Similar to the SNIRH, other smaller monitoring and reporting platforms were also assembled in Portugal with specific purposes. For example, the Portuguese Irrigation Technology and Operational Centre (COTR) has established the SAGRA (Agrometeorological System for Irrigation Management in Alentejo). Given the strategic importance of the Alqueva surface water reservoir for agricultural uses, a platform that helps the management of irrigation water was established with a set of 14 automatic meteorological stations that determine the actual evapotranspiration in the Alentejo region, southern Portugal (Fig. 6). The main difference from the SNIRH is that access is restricted to CODR associated members.

Future outlook

The web portal is currently in the Portuguese language only. The interface would benefit from some updates and modernisation. Some improvements were conducted to achieve portal compatibility with portable devices, but it still lacks some of the functionalities of the desktop web browser version, allowing the user only to observe brief reports on precipitation, gauge stations and dams.

In the near future, important technological innovations are expected to be implemented in the monitoring procedures, which ultimately will end in significant changes in platforms like the SNIRH. Through questionnaire analysis of almost 100 experts, it was highlighted that EU member states should examine including new technologies that have become available in recent years, in monitoring programs. The use of satellite data for surveillance and operational monitoring may allow for increased frequency and spatial coverage. It is also noted that those methods coupled with machine learning, improved sensor technologies and citizen science concepts may greatly enhance monitoring with effective cost reduction and increased data quality/precision (Carvalho et al., 2019).

It is expected that the SNIRH may undergo significant changes to keep up with those technological advances.

Fig. 6 – COTR-SAGRA monitoring network for irrigation management in the Alentejo region.

Key points of the innovative method

- The National Water Resources Information System (SNIRH) is a public web-portal that allows users to access data related to water resources in Portugal, the Azores and Madeira.

- The system is comprised of 14 independent monitoring networks including meteorological, surface water and groundwater data.

- The SNIRH includes a vast collection of water resources related documents including histori-cal photographs.

- The SNIRH reports on extreme events situations such as droughts and includes a flooding alert system (SVARH).

- Although fully operational, the SNIRH web-portal is currently showing some signs of an ageing web-interface.

- Due to specific operational problems, the information from some monitoring stations may take a few months to become available.

- A significant amount of historical hydrometeor-ological data can be consulted and be used freely in water-related research.

Acknowledgements

This innovative practice was suggested by Miguel Carrinho of Águas do Ribatejo, SA, Portugal.

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SNIRH flyer (https://snirh.apambiente.pt/snirh/download/relatorios/SNIRH_folheto_16_01_2006.pdf)

SVARH Flood Surveillance and Warning System brochure (https://snirh.apambiente.pt/snirh/download/relatorios/Folheto_PT_EN_FINAL.pdf)

COTR-SAGRA brief description (http://www.cotr.pt/servicos/sagra.php)

APA's SNIRH brief description (https://apambiente.pt/agua/sistema-nacional-de-informacao-de-recursos-hidricos-snirh)

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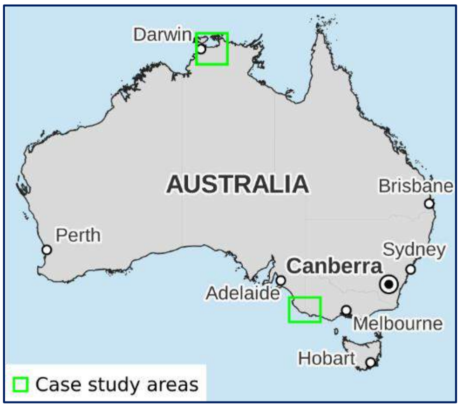
https://snirh.apambiente.pt/snirh/download/relatorios/monitoricao_recursohidricos2.pdf

Participating members:

Portuguese Environmental Agency (APA) (https://apambiente.pt/)

Monitoring groundwater-dependent ecosystems using synthetic aperture radar (SAR) imagery in Australia



Groundwater Dependent Ecosystems (GDEs) are highly sensitive environments that provide several services from extreme events mitigation to recreational uses and can be heavily affected by human activities such as groundwater abstraction or contamination. To properly identify GDEs and their relationships with surrounding ecosystems is fundamental to monitor environmental impacts to achieve effective integrated water resources management.

The present factsheet will investigate the use of Sentinel-1A satellite Synthetic Aperture Radar (SAR) imagery in the remote identification of GDEs in two Australian study areas (Castellazzi et al., 2019). The technique's authors presented acceptable results in comparison to the previously developed Australian GDE Atlas, a continental scale GDE database based on field works and literature. Further developments are expected in this field with the latest advances in SAR-based imagery acquiring methods with increased resolution and lower assembling costs coupled with enhanced computational power. This type of information has provided good results in different applications from forestry to coastal surveillance, even in regions prone to cloud formation which ultimately do not allow observation of Earth's surface variations. Further technical fine calibration may allow for application in other regions and the high coverage continuous acquisition of SAR imagery.

Responsible entity

The use of Synthetic Aperture Radar (SAR) is today relatively widespread. In the case study presented in this factsheet, the entity that supported the use of such method for Groundwater Dependent Ecosystems (GDEs) detection was the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's national science agency, founded in 1949. This Government agency is divided into eight research areas/business units, which include land and water. It is in the latter business unit that groundwater related research is developed.

The Groundwater Management Group seeks to study and evaluate groundwater resources and develop fit-for-purpose technologies. This multi-disciplinary team has been developing work in the following areas:

- Adaptation of remote sensing techniques to solving groundwater management problems.
- Data analytics making use of big data and machine learning.
- Groundwater flow modelling and integration of environmental and social aspects into groundwater management solutions.
- Assessing the feasibility of groundwater resources enhancement methods such as Managed Aquifer Recharge.

In relation to GDE's, CSIRO, through the Bureau of Meteorology (Fig. 1), is building a comprehensive and reliable picture of Australia's water resources to support policy and planning – the GDE Atlas.

Fig. 1 – Commonwealth Scientific and Industrial Research Organisation (CSIRO) (left) and Australian Bureau of Meteorology (BOM) (right) logos.

It collates and manages water data and information as part of its role and responsibilities for water information under the Water Act 2007. The GDE Atlas was initially developed with funding from the National Water Commission and significant support from State and Territory water agencies. The GDE Atlas is now maintained by the Bureau of Meteorology and updated with new data from State and Territory water agencies (Doody et al., 2017).

The GDE Atlas was constructed by combining already identified GDEs, available literature, geospatial layers and remote sensing data making use of robust GIS technologies (Merz, 2012). It represents the most exhaustive inventory of GDEs that has been accomplished at a continental scale (Pérez Hoyos et al., 2016). This web-based application can visualise, analyse and download GDE information for an area of interest without specialised software. Data from this platform was used to validate the SAR based approach to defining GDEs.

Institutional setting

Water management is a fundamental issue in Australia. While legislative action to allow water authorities protect streams has been taken since the late nineteenth century, only in the 1980s did water management actions begin to consider other water bodies and start to take into consideration water allocation procedures coupled with environmental (and social) objectives, laying the basis for a water economy. In the 1990s, the incremental cost of water, increasing demand and rising environmental problems pushed public institutions to adopt alternative methods of management and moderate conflicts between stakeholders (Tisdell et al., 2002).

Doody et al. (2017) noted that since water reform began in 1994, the environment has been recognised as a legitimate user of water. Prioritisation was given in environmental water uses and, in the case of GDEs, water allocations were to be clearly defined to maintain riparian, terrestrial, wetland, marine and subterranean ecosystems that depend on groundwater. The identification and mapping of GDEs has been identified as a critical investment to achieve water reform objectives.

The acquisition of water information is central to sustainable water planning, water trading and, in particular, environmental management (Doolan et al., 2016).

Geographical setting

Australia has a high variability climate with clear evidence of recurrent droughts followed by extreme flooding events. Highly irregular rainfall and high evapotranspiration create an increased challenge in water resources management, particularly for surface water. The Murray-Darling Basin authority accounted groundwater for around 30% of the water used in the continent, being in many areas the only reliable water source (Dabovic et al., 2019).

The construction of the GDE Atlas concluded that 34% of Australia's landscape potentially contains GDEs, of which 5% are classified with a high GDE potential (Doody et al., 2017). The use of SAR for GDE detection was tested in two contrasting study sites in Australia, one in Victoria and South Australia and one in the Northern Territory (Fig. 2). Site 1 (the Mount Gambier area) corresponds to a karstic aquifer system, and Site 2 (the Wildman-Kakadu area) corresponds to a monsoonal coastal floodplain to inland semi-arid grassland (Castellazzi et al., 2019).

Detailed explanation

Groundwater Dependent Ecosystems are those that require access to groundwater at some stage in their life cycle in order to maintain structure and function (Dabovic et al., 2019). Those include: (1) terrestrial ecosystems that seasonally rely on groundwater, (2) aquatic and riparian ecosystems dependent on the input groundwater baseflows. especially in dry seasons, (3) cave ecosystems, (4) groundwater-dependent wetlands, and (5) estuarine and near-shore marine ecosystems that rely on groundwater discharge (Murray et al., 2003; Eamus and Froend, 2006).

GDEs provide many ecological and socio-economical values – biodiversity, flood mitigation, erosion prevention, fishing, forestry, agriculture, recreation and tourism.

Successful maintenance can only be achieved by understanding the distribution of GDEs while assessing

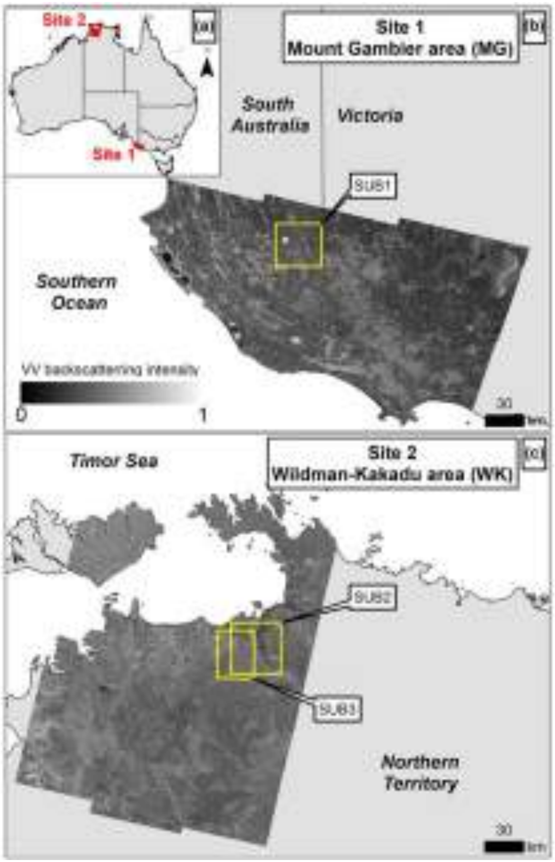


Fig. 2 - Location of sites and footprints of the 90 Sentinel-1 scenes composed of three spatial subsets (SUB) (adapted from Castellazzi et al., 2019).

water requirements within management plans (Doody, et al., 2017). In many parts of Australia, there is an increasing pressure on groundwater resources from activities including agriculture, mining, urban and commercial developments. GDEs can be degraded by the modification of flow regimes and salinisation or pollution of groundwater as a result of these activities (Kuginis et al., 2016). GDE detection can be a challenging and lengthy process and remote detection methods can significantly speed it up.

The Synthetic Aperture Radar is a high-resolution spaceborne sensor source of information that allows earth observation in different weather conditions (Moreira, 2007). It is used in a wide range of applications from environmental monitoring to security and reconnaissance uses.

The SAR active antenna sends an EM wave to Earth and the measured response is the strength of the signal bouncing back to the satellite along the same angular plane. This produces one or two "like-polarised" images: horizontal-horizontal (HH) and/or vertical-vertical (VV) bands. Some sensors can also record the signal returned along a perpendicular angular plane, producing "cross-polarised" images: horizontal-vertical (HV) or vertical-horizontal (VH) bands. Global and automatic acquiring SAR systems like Sentinel-1, used in the present study, are dual-polarised, acquiring simultaneously VV and VH bands (Castellazzi et al. 2019).

InSAR is formed by interfering radar signals from two spatially or temporally separated antennae. An interferogram is created by co registering two SAR images and calculating the difference between their corresponding phase values on a pixel-by-pixel basis. The change in the interferogram is caused by five effects: (1) differences in the satellite orbits when the two SAR images were acquired, (2) landscape topography, (3) ground deformation, (4) atmospheric propagation delays, and (5) systematic and environmental noises (Lu et al., 2007).

Castellazzi et al. (2019) proposed an index derived from SAR observation data (SARGDE) for capturing vegetation reliance on groundwater during dry periods. This analysis is based on the condition that, due to GDEs ability to supplement natural water needs using groundwater in water deficit periods, vegetation is expected to have a permanent canopy over longer periods of time compared with non-GDE associated vegetation. This results in the assumption that the proportions of volumetric, soil and double-bounce scattering mechanisms are expected to be relatively stable in time (Fig. 3).

Ninety Sentinel-1A interferometric wide images were used, acquired in 2017. Each image is composed of 30 consecutive SAR acquisitions – one image every twelve days for each of the three sub-datasets in the two study areas (Fig. 2).

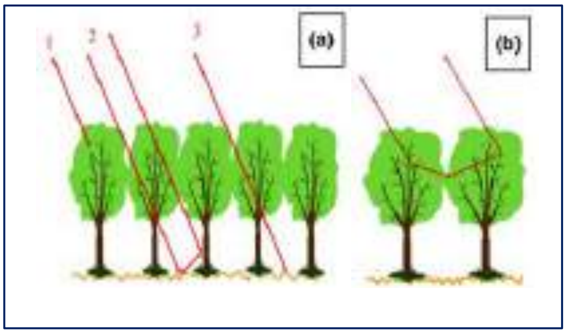


Fig. 3 – Simplified SAR signal scattering mechanisms in vegetation (a) 1, canopy-only direct scattering; 2, soil-trunk or trunk-soil double-bounce scattering; and 3, soil-only scattering; and (b) volumetric scattering (adapted from Castellazzi et al., 2019).

All information extracted from the SAR imagery is structured into stacks, where every pixel of each SAR acquisition is projected to the same ground footprint, forming a 3D data matrix [Space] x [Space] x [Time], referred to as a data-cube. Images were processed using SARSCAPE software. Coherence matrixes, derived by comparing the phase of two polarised bands of two subsequent acquisitions, were computed using a regular matrix grid with approximately 30 m resolution. All data cubes were analysed to generate those coherence matrixes and later normalised (mean value = 10, st. dev. = 1), easing the interpretation by spreading values over a domain in which statistics offer equal weighting as a final index.

To help explore possible varying spatial and temporal patterns in data-cubes a machine-learning technique was used to reduce the time-series into a 2D map – Generative Topographic Mapping (GTM), which considers non-linear structured datasets. Generated results were compared with the Australian GDE Atlas to compare the coherence of GDE marked areas (Fig. 4). This allowed the authors to understand that in floodplains (high possibility of GDE occurrence) seasonal patterns are less pronounced than surrounding areas, as primarily inferred, indicating vegetation persistence throughout the year. It is possible to relate GDEs with low InSAR coherence with limited seasonal changes in this parameter (stable dense vegetation with associated increased scattering due to moving branches and leaves).

The SARGDE index for GDE detection is defined by using the statistics of normalised datasets that include annual mean and standard deviation of InSAR coherence (σ_cc, μ_cc) and the annual mean of VH intensity data-cube (σ_vh). It is expressed with the following equation:

$$SARGED = {}^{1}\!\Big/_{\sqrt[3]{\sigma_{cc}\sigma_{vh}\mu_{cc}}}$$

In this case, the VH intensity refers to vertical-horizontal bands generated from "cross-polarised" images from signal returns along perpendicular planes. SARGDEv1 is ~90% similar to the GDE Atlas on a pixel-per-pixel comparison (Fig. 5)

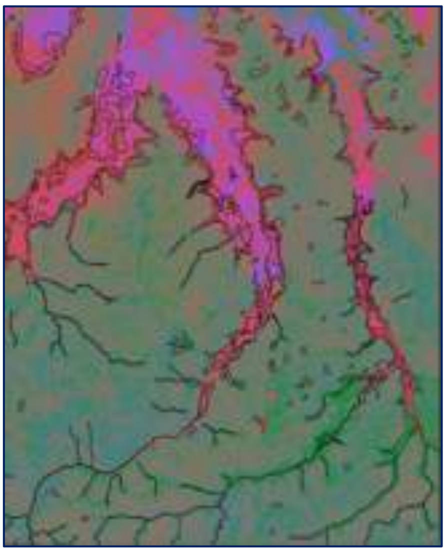


Fig. 4 – Low InSAR coherence in floodplains (Black contours are GDEs identified in GDE atlas, the difference in colour means the difference between coherence time-series) (adapted from Castellazzi et al., 2019).

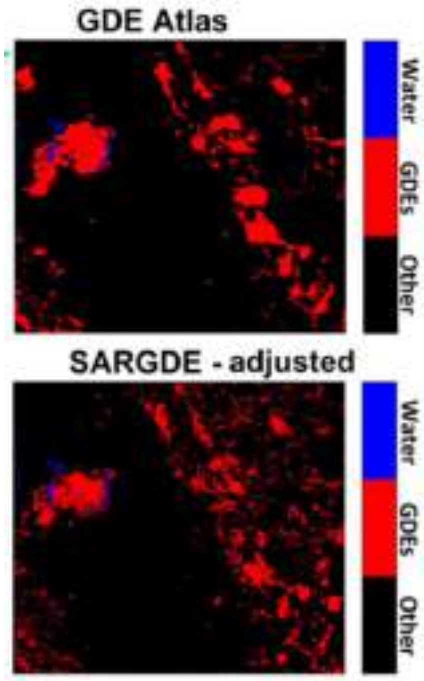


Fig. 5 – Comparison between GDE Atlas and generated index map (adapted from Castellazzi et al., 2019).

Historical overview

The first space-borne SAR system was launched in 1978 and has been used in a wide range of applications (Moreira, 2007). Globally acquiring SAR satellites opened the door to potential applications in GDE monitoring. Automated and global SAR acquisition began in 2014 with the launch of the Sentinel-1A satellite, followed by its synchronous twin satellite Sentinel-1B in 2016 (Castellazzi et al., 2019).

In relation to GDEs, in 1994 the Council of Australian Governments (COAG) endorsed reforms to move towards a sustainable water industry that included allocations for the environment and greater environmental accountability of water resource developments. In 1996 the National Principles for the Provision of Water for Ecosystems was signed to provide a basis for considering Ecological Water Requirements (EWR) as part of water allocation decisions by water resource managers. EWR should be based on the best available scientific information. For GDEs, groundwater is considered in terms of flow, level, pressure and quality required by an ecosystem, and is to be studied through strategic scientific research. The EWR contribute with socioeconomic evaluation and water consumption demands to the development of Ecological Water Provisions (EWPs) within water management plans. EWPs are a management tool used to achieve ecological objectives, often expressed in terms of a target to maintain, restore or rehabilitate (Richardson, et al., 2011).

Evidence of benefits from implementation

The identification of GDEs often requires site-specific information on various indicators such as plant information on water use and groundwater depth. which at a regional scale is impractical and cost-prohibitive (Kuginis et al., 2016). Field-based GDE inventories are not convenient for state-wide, regional, national or global maps; are labour intensive; and represent one point in time. The use of remote sensing greatly improves data acquisition and is a cost-effective technique (Pérez Hoyos et al., 2016).

Referring specifically to SAR, if compared with the imagery from multispectral platforms, available since the early 1970s, SAR offers the advantage of global day-and-night sensing capability and insensitivity to cloud cover, making SAR data particularly suitable for monitoring changes in Earth's surface (Castellazzi et al., 2019). The technique presented – the SARGDE index – offers improved yearly monitoring, with high resolution, and even of cloud covered areas. It is also relatively user-independent as it requires only routine SAR processing.

Such methods, coupled with already existing tools (GDE Atlas), ensure that consistent data is available to provide the basis for better-informed decisions.

Replication potential in the SUDOE region

The identification of GDEs is particularly relevant in the southern European regions, which are prone to scarcity phenomena and in which these ecosystems can play a significant role in mitigating extreme events. Terrestrial GDE protection is enforced by the Water Framework Directive (WFD) and member-states are required to act to prevent damage (Rohde et al., 2017). Monitoring networks of surface and groundwater bodies play an important role and ecosystem identification may benefit significantly from the space-borne acquired information.

Concerning possible implementations of the SARGDE outside the territories in which it was tested, the authors note that some additional research is needed to adapt it to non-Australian vegetation. The index lacked testing for the ability to temporally monitor GDEs impacted by groundwater pumping or to be compared with acquired data from in situ monitoring networks (Castellazzi, et al, 2019).

European projects such as SAR2CUBE are looking into defining prototypes to integrate SAR data into everyday processing chains and reduce the entry-level barrier of the InSAR-derived products by providing analysis-ready data (ARD) specifically defined to achieve efficiency and flexibility. This may significantly increase the user base and range of SAR applications in European territories.

Future outlook

Moreira (2007) reported that, at the time of publication, increased demand for this technology drove several nations to project and launch more than 20 space-borne SAR systems. Other authors also noted (Lu et al., 2007) that InSAR promising applications can drive scientific breakthroughs. These advances are based on longer wavelength SAR images, fully polarised SAR sensors for better characterisation of vegetation and ground features, and the lessening of InSAR atmospheric delays, which increase the technology's accuracy. It is also noted that advances in data mining, with multi-temporal and multi-dimensional techniques, can allow, for example, mapping of time-variant ground surface deformations (natural or caused by human actions) by improving deformation measurements.

Innovation in monitoring procedures, which scientists refer to as a necessary step forward (Carvalho et al., 2019), can imply the integration of technologies such as InSAR in real-time monitoring with greater spatial cover with decreased costs. As an example, the use of satellite data for surveillance of water bodies status within the framework of the WFD has encouraged several projects based on the European Space Agency's Copernicus programme looking into aiding almost real-time machine-learning supported decision-making in water resources management.

Advances in the technology may help in its application. The development of a miniaturised version of SAR satellites, by both private and public initiatives, are expected to decrease the cost of the technology and open the way to SAR satellite constellations that can increase global coverage.

Key points of the innovative method

- SAR imagery can be less time consuming and lower cost compared to field-based GDE inventories.

- The developed index generated good results when compared with existing GDE mapping with ~90% of similarities.

- The technique is rather simple but requires the use of commercial software for image manipulation.

- As it is band-related, testing is still necessary if the index is to be applied in other regions with a different type of vegetation.

- Further advancements are expected with the development of more cost-effective SAR systems with increased resolution and acquiring capabilities.

Acknowledgements

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SARSCAPE software description (https://www.sarmap.ch/index.php/software/sarscape/)

SAR2CUBE project webpage (https://eo4society.esa.int/projects/sar2cube/)

Other sources:

https://spacenews.com/spacety-releases-first-sar-images/

Participating entities:

Commonwealth Scientific and Industrial Research Organisation (CSIRO) (https://www.csiro.au/)

Australian Bureau of Meteorology (http://www.bom.gov.au/)

ICT and modelling

Vadose-zone monitoring system for real-time characterisation of contaminants leaching to groundwater in Israel

Groundwater contamination from anthropogenic origin is the result of the activities on the land-surface and in the topsoil. Contaminants are transported through the vadose zone to the groundwater below, imposing severe threats to the quality of all related water resources, such as rivers and lakes, sometimes supporting groundwater dependent ecosystems. A lag time of years to decades between processes occurring in the root zone and their final imprint on groundwater quality prevents proper decision-making on land use and groundwater resource management. A key-solution is monitoring the vadose zone (or unsaturated zone).

This study implemented an innovative system, Sensoil's Vadose-zone Monitoring System™ (VMS), which enables continuous monitoring and water sample collection directly from the vadose zone, providing real-time, continuous tracking of water percolation and contaminant transport across the vadose zone, from land surface to groundwater. Once installed, the VMS forms an accessible monitoring station (or network of stations) of the vadose zone.

Fig. 1 – Sensoil's logo.

Fig. 2 – Promoting entities' logos.

Responsible entity

Sensoil Innovations Ltd. (Fig. 1) is a company developing and implementing smart soil sensing technologies and solutions, for the protection of groundwater and the environment.

Founded in 2013 to commercialise sub-surface technologies developed at the Ben-Gurion University of the Negev, Israel, Sensoil patented Vadose-zone Monitoring™ (VMS) technology.

The two main entities connected to this study are the Ben Gurion University of the Negev and The Volcani Center, Agricultural Research Organization (Fig. 2).

Institutional setting

Sensoil's real-time monitoring technology is a crucial early-warning tool, recommended by government organisations and regulatory agencies.

Customers around the globe utilising and relying upon Sensoil's robust technology include governments, regulatory agencies, municipalities, industrial and engineering companies, and academic and research institutions.

Geographical setting

Israel (Fig. 3) is a country with low water availability, which has experienced almost seven consecutive years of drought between 2003/04 and 2010/11, and a five-year long drought between 2013 and 2018 (Gruère et al., 2020; OECD, 2020b).

Israel's agriculture plays an important role in the country's economy, producing significant volumes of fruit and vegetables, as well as cereals and legumes. Between 2000 and 2018, agriculture's share of freshwater abstractions has halved (decreasing from 64% to 35% of total water abstractions), largely due to changes in water management, especially the use of treated wastewater for irrigation (OECD, 2020c).

Fig. 3 – Location of innovative practice (Red square).

However, nutrient surpluses have grown significantly: the nitrogen balance increased between 2000 and 2018 from 189 kg/ha to 236 kg/ha, reaching a level seven times above the OECD average, whereas the phosphorus balance has gone up from 66 kg/ha to 69 kg/ha during the same period (OECD, 2020a). VMS offers a system for real-time measurements of nutrient levels in the soil, providing farmers with relevant and timely data enabling fertilisation and irrigation optimisation to increase agricultural yield and quality, but also to protect groundwater.

Detailed explanation

The protection of groundwater resources from contamination is vital for the protection and sustainable use of this important water source.

In most situations, groundwater quality is assessed and sampled from wells and therefore the concentration of contaminants can already be at levels that will lead to disqualification of the aquifer as a source of drinking water, base flow for rivers or ecosystem support (Fig. 4).

Fig. 4 – Illustration of contamination leaching through the vadose zone with until reaching groundwater (https://sensoils.com/technology/).

The transfer time of contaminants within the deep vadose zone has been estimated to take from weeks to decades, depending on the water regime, thickness of the vadose zone and lithological characteristics of the subsurface (Spalding et al., 2001; Scanlon et al., 2010). Contaminants' fate and transport below the root zone depends on issues such as recharge, soil spatial variability, soil chemistry and biology. Therefore, estimates of fluxes in the vadose zone have shown significant differences in the timing and concentrations. Furthermore, the cumulative effect of contaminants leaching from the root zone through the unsaturated zone on contaminant levels in the groundwater is blurred by mixing and dilution in the aquifer water.

The knowledge of the time lag between initiation of a contamination process in the vadose zone and its final effect on aquifer quality are fundamental to providing decision-makers the opportunity to implement measures and more time to make possible alternative plans for water supply.

The Sensoil VMS is a recently developed tool that enables continuous monitoring of the hydrological and chemical properties of percolating water in the deep vadose zone under agriculture settings (Turkeltaub et al., 2014, 2015) and other hydrological settings (e.g., Dahan et al., 2009; Baram et al., 2013) (Fig. 5).

Data collected by the system comprises direct measurements of the water-percolation fluxes and the chemical evolution of the percolating water across the

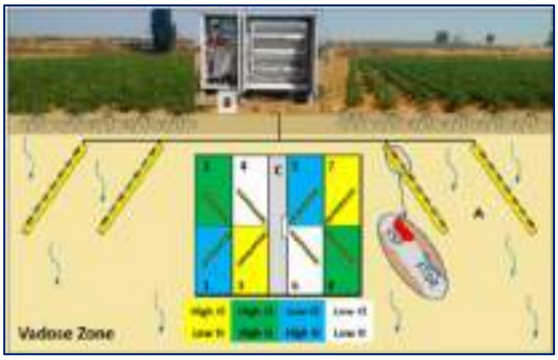

Fig. 5 – Schematic illustration of the vadose zone monitoring system, not to scale. (a) Side view and zoom in of the monitoring units: vadose zone pore water sampling ports (VSP) and flexible time domain reflectometers (FTDR). (b) All water content data are recorded and water samples are collected through a single control panel. (c) Top view, eight monitored plots. The plots are numbered and coloured according to the treatment schemes referred in Weissman et al., 2019 (https://doi.org/10.1002/vzj2.20041).

entire vadose zone.

The VMS (Fig. 6) is composed of flexible sleeves (1) implemented in uncased, slanted boreholes. The flexible sleeves host multiple monitoring units, distributed along their length. Each monitoring unit is comprised of water content sensors, vadose zone sampling ports and gas sampling ports for frequent sampling of the vadose zone. VMS data collection and water sampling is managed through Sensoil's unique VMS control panel (2), installed on-site. Full access to real-time data, is available from anywhere, via the cloud (3). Data access is dedicated and customised to each customer (4).

The VMS sleeve is made of a chemically resistant thin flexible liner, with integrally embedded monitoring units along its length. All monitoring units are connected to a control panel which is installed on the land surface. It is adapted for installation in a 6″ diameter borehole drilled at 35º (to vertical), 55º (to horizon).

Flexible Time Domain Reflectometry (FTDR) probes for monitoring of the sediment enable continuous measurement of the water content and temperature of the sediment. Each and every FTDR sensor is tested for quality and performance and pre-calibrated for permittivity measurement in a test medium of known dielectric properties.

Sampling of the vadose-zone pore water by the VSP (Vadose Sampling Port) is similar to standard tensiometers and suction cups, the hydraulic continuity is achieved via a fine flexible porous medium. The VSP operates through a set of small diameter access pipes and control valves. The VSP is installed on the VMS sleeve together with the FTDR. The gas sampling probe (GSP) enables collection of the gas phase from the vicinity of the VSP. As such, comparison of the contaminant's content in the water and gas phase may be achieved across the entire vadose zone.

Fig. 6 – Sensoil's Vadose-zone Monitoring System (VMS) (https://sensoils.com/technology/).

The control panel is encased in a standard weather protected closet. A set of pressure manifolds valves and pressure gauges in the control panel allow direct access to each of the monitoring units for frequent sampling and regular maintenance.

A data-logger is used to collect data on water content, temperature and pressure measurements, providing real-time continuous data and advance warnings for decision support solutions. The software is capable of receiving, storing, data-logging, processing, producing graphic charts, sending, and accessing the raw and processed data. Access is dedicated and customised per customer. All data is protected by high-end security standards under the required privacy policy.

Fig. 7 shows an example of the results that can be obtained using the Sensoil system. The objective of that study was to demonstrate the water flow and nitrate transport through the deep vadose zone underlying the crop field, with respect to rain patterns as well as the agricultural and fertilisation setup.

It is possible to see the nitrate migration deeper into the vadose zone for different depths and the effect of rainy winters (e.g., 2012/13), with substantial nitrate breakthroughs noticeable throughout most of the vadose-zone cross section (marked with arrows in Fig. 7).

The nitrate concentration time series, which included variations of nitrate in time and at multiple depths, revealed in real time a major pulse of nitrate mass propagating down through the vadose zone toward the water table. These results indicate that nitrate fluxes in the unsaturated zone underlying agriculture land uses were associated with high nitrogen application rates and coarse-textured soils. Furthermore, pollution events that originated from agricultural land uses can

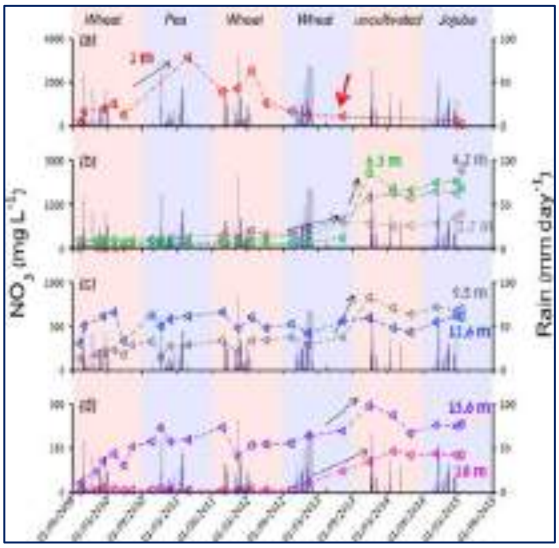

Fig. 7 – Time series of observed nitrate (NO_3^-) concentrations in the vadose zone and daily rainfall for six consecutive years (https://sensoils.com/technology/).

be monitored in their early stages, long before pollution accumulates in the aquifer water.

Historical overview

This technology is the result of about 20 years of research led by Professor Ofer Dahan, Ben Gurion University of the Negev, (Israel) and University of Nevada, Reno (USA).

Its application has started more recently (in 2016) and systems have been installed and applied in over 100 sites including in the EU, USA, China, Australia and Africa.

Evidence of benefits from implementation

Over 100 Vadose-zone Monitoring Systems have been installed around the globe over recent years. Aquifer and natural water source pollution occurrences have been avoided, remediation processes have been optimised, and scientific knowledge and research has improved. Also crop fertilisation and irrigation schemes have been optimised.

Under References, a set of case-study sites and applications are listed, together with the achieved benefits.

Replication potential in the SUDOE region

The Sensoil VMS offers the possibility of real-time monitoring of the vadose zone, having as its main goal the protection of groundwater quality.

In agricultural areas, real-time measurements of nutrient levels and moisture sensors in the soil can provide farmers with relevant and timely data, enabling fertilisation and irrigation optimisation, to increase agricultural yield and quality, and protect groundwater.

These systems can be installed in a range of applications in the SUDOE region, where monitoring of the vadose zone, in addition to the saturated zone, is important, such as water resources protection, remediation, dam safety, landfill or mining. Some examples of achievements are:

- Real-time information on pollution processes taking place in the vadose zone, supporting decisions and measures to protect aquifers.
- Assessing transport and degradation pathways, and remediation treatment impacts, enabling optimisation of in-situ remediation.
- Providing continuous information on dam sediment moisture and real-time seepage, essential for improving dam embankment safety programs.
- Providing real-time data on water flow velocities and chemical evolution of the percolating contaminants in and under a municipal landfill, allowing timely measures in landfill management.

Future outlook

Developing and implementing smart soil sensing technologies and solutions for the protection of groundwater, and the environment, is being done in over 100 sites including in the EU, USA, China, Australia and Africa.

These early warning systems are likely to expand due to their ability to bring real-time information on pollution processes taking place in the unsaturated zone, long before contaminants accumulate in the aquifer.

Key points of the innovative method

Sensoil's Vadose-zone Monitoring System™ provides a unique integrated solution that incorporates (1) continuous monitoring of and water sample collection in the vadose zone, (2) a management control panel, installed on-site, (3) full access to real-time data, available from anywhere, via the cloud, and (4) data access dedicated and customised to each project's needs.

Sensoil's VMS allows the:

- Early detection of contamination sources in the vadose zone.

- Timely application of the necessary measures to avoid further contamination before reaching groundwater.

- Following remediation processes, giving the necessary information for its continuous optimisation.

- Costs may be a drawback for some users.

Acknowledgments

This innovative practice was suggested by Teresa E. Leitão of the LNEC.

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Other sources:

https://www.linkedin.com/company/sensoil/?originalSubdomain=il

https://twitter.com/sensoil1

Project participating members:

Ben Gurion University of the Negev https://in.bgu.ac.il/en/

The Volcani Center https://www.agri.gov.il/

Factsheets of “Governance” cases.

Governance

Adaptive Groundwater Management in the Benalup aquifer

The Benalup aquifer in the Barbate River basin (MAS 062.14) is affected by the economic model of the region: livestock and agriculture that for years have been overexploiting the aquifer affecting its quality and quantity. The University of Cádiz, through the RNM-373 Geosciences Group and the REMABAR project, has proposed alternatives for management based on the knowledge generated regarding the aquifer and its social and geographical environment. In order to generate proposals and manage the conflict between the use and the state of the aquifer state this project investigated the relationship between pressures and impacts, including the existence of unauthorised catchments.

Finally, dialogues were held with the local population to transfer knowledge and raise awareness of the state of the aquifer, obtain information from the users themselves and expose the problems in the context of climate change.

This project presents an innovative methodology on an environmental, social and economic scale in the context of climate change applicable to the SUDOE region.

Responsible entity

The Geosciences Group of the University of Cádiz (UCA) led by Santiago García López is responsible for the project which involved 12 researchers. The group was founded in 2009 and has participated in 83 projects, 35 journal publications, 6 patents and various other activities.

At present, the Group's activity is diverse and comprises the following areas:

- Dynamics of extinctions in marine environments.
- Groundwater: systems modelling and water resources assessment.
- Functioning of karst aquifers: hydrodynamics and hydrochemistry.
- Diagnosis and evaluation of groundwater contamination.
- Genesis, uses and contamination of soils.
- Integrated biostratigraphy.
- Storage and capture of CO2.
- Palaeoclimatic and palaeoecological reconstructions.
- Palaeoceanography.
- Carbonation of alkaline solid waste.

Source: https://rnm373.uca.es

Institutional setting

The Department of Earth Sciences of the University of Cádiz launched the REMABAR project with the support of the Biodiversity Foundation of the Ministry for the Ecological Transition in the context of the research and transfer work of the University with the aim of improving knowledge and awareness of aspects related to water and adaptation to climate change (MITECO, 2019).

Geographical setting

The study area is located on the Atlantic coast of Andalusia in the province of Cádiz. The Benalup aquifer is part of the Barbate River basin in the watershed of the Guadalete-Barbate.

Figure 1: Location of the Barbate River basin.
Source: Vélez Nicolás, 2020

Figure 2: Benalup aquifer and municipalities it includes. *Source:* Vélez Nicolás, 2020.

The area has a population of 7,038 spread over 32.59 km^2. The water resource in the area is in poor quantitative condition since extractions are higher than the recharge rate (exploitation 118%). It is important to note that in the last cycles of hydrological planning the aquifer had been catalogued as in poor quantitative condition with an exploitation index of 0.8. For this reason, the value of the exploitation provided by the study is exaggerated as the aquifer is not in a situation of overexploitation. The chemical status of the aquifers of the Guadalete-Barbate River basin district is also deficient due to there being areas where the nitrate concentration exceeds the established limits (50 mg/L) (Junta de Andalucía, 2015).

Detailed explanation

The Benalup aquifer is located in the La Janda region of the Barbate watershed. The economic model of the region largely supports agricultural and livestock activities. The surface water comes from the reserves of Barbate, Celemín and Almodóvar. However, groundwater is obtained from the Barbate and Benalup aquifers, which are subject to a high degree of exploitation and lack a regulatory entity, resulting in an uncontrolled situation of overexploitation of the aquifers. In the case of Benalup, multiple unauthorised and unregistered farms and the land use have reduced both the quality and quantity of the water bodies.

To resolve the conflict between the state of these bodies of water, the users and the environment, the REMABAR project was developed.

The project included the following tasks:

Data was collected by consulting cartographic databases, hydrogeological data, information and documents predating the project, as well as data from the existing monitoring network. This information combined with GIS was managed and analysed to obtain significant information for the project.

The levels and qualitative status of the aquifer were then monitored. This stage helped define the recharge and discharge zone, the direction of the flow, the relationship between the river and the aquifer, and the influence of exploitations. The 1993 data were taken as a reference to study the evolution of the aquifer. The Benalup aquifer has a free / semi-confined aquifer behaviour, the aquifer is mainly constituted of Miocene biocalcarenites with calcareous fossiliferous remains. The permeable formations of quaternary wind sands that form the upper part of the aquifer contribute greatly to the infiltration of rain (20–30%). The aquifer interpretation describes a conceptual model in which there is no connection between the aquifer and nearby rivers. In this context, the importance of the return of irrigation water and its influence on the state of the aquifer should be highlighted. On a hydrochemical scale, facies are mostly calcium bicarbonates, given the abundance of limestone in the region.

A geophysical campaign (ERT) provided knowledge regarding the geometry of the aquifer, enabling the productive levels to be discerned. Of the three formations that constitute the aquifer, the lower one is the most productive, being formed by calcareous rocks (biocalcarenites). The upper level, formed by a mixture of sands and silts of the Quaternary, presents lower porosity.

To identify the properties of the aquifer, the porosity, permeability, transmissivity and storage coefficient of the materials were evaluated.

Based on satellite images, the NDMI (Normalised Difference Moisture Index) was used to identify those plots that in the dry season and without previous rains, were wet, and so attributable to irrigation. Cross-referencing the official records of land authorised for irrigation by the Junta de Andalucía (SIGPAC) and the identified plots, it was possible to discriminate between authorised and unauthorised irrigations.

Finally, dialogues were held with users to transmit knowledge and inform on the state of the aquifer to its users. Round table sessions and information sessions were held where different agents involved in the use and management of water congregated. Likewise, a survey campaign was carried out to understand the vision of the users and their knowledge of the exploited water bodies and climate change.

As a result, the study of the Benalup aquifer has allowed the identification of multiple aspects to be taken into account for groundwater management (Vélez-Nicolás, 2020). These include:

- The geometry and storage volume of the aquifer.
- The recharge and unloading areas.
- The hydraulic disconnection of the aquifer from the main hydrographic network.
- Identification of the three hydraulically differentiated aquifer sectors that constitute the aquifer and the direction of flow.
- The chemical characteristics of the water.
- An approach to the possibility of carrying out actions of artificial recharge of the aquifer in order to achieve a joint management of surface water and groundwater and improve the qualitative status of the aquifer.

The use of surface water as a complement to supply the population is considered, a factor that will contribute to improving the quantitative status of the aquifer.

Historical overview

Great advances have been made in the management and protection of groundwater throughout the twentieth century. Even so, there are many problems that the authorities and those responsible for water resources must address (Simpson, 2020).

At the beginning of the twentieth century, there was a growing trend in the exploitation of groundwater and unauthorised construction of wells (Stephano et al, 2015). The main user was agriculture, a strategic sector, which generated jobs and food that had an impact on the economy. A lack of understanding of the rational use of water resources, together with the possibility of obtaining water near the fields without the need to transport it, led to the drilling of multiple wells without authorisation or control by the hydraulic authorities, hindering the correct management of the resource and leading to impacts on the quality and quantity of the local water resource (Vélez-Nicolás, 2020).

Stephano et al. (2015) state that in the face of this situation, users begin to come together to protect their activities, avoid sanctions and acquire recognition as water users. In order to improve the quality and quantity of water bodies technological solutions were applied to: (i) modernising irrigation; (ii) finding new sources of supply; and (iii) applying methods of managed aquifer recharge.

In the case of Benalup, management falls to the regional water authority and the community of water users The Junta de Andalucía, the body responsible for ensuring the state of the body of water and its management, is overwhelmed and does not have the capacity to exercise its powers effectively. Thus, it is recommended that the community of irrigators of Benalup, with greater capacity to exercise change at local level should be provided with the necessary knowledge and assume the management of the resource. For this reason, the Water Law in Spain promotes the creation of user communities to manage groundwater problems (Vélez-Nicolás, 2020).

Evidence of benefits from implementation

This project provides knowledge from scientific studies and communication with users. Hydrogeological knowledge related to the volume and geometry of the aquifer, flow direction, compartmentalisation of the aquifer, and information to understand the quantitative and qualitative state are highlighted.

The innovative aspect of the project highlights the need for a community of users responsible for both underground and surface water bodies, and the need to transfer knowledge to the users. It is necessary to have knowledge of the operation of the hydrogeological system, its particularities and influences to allow the possibility of exercising effective control of the exploitation of the resource and generating participation policies. With this support, a local user body has the potential to be capable of meeting the demands and making sustainable decisions around the water resource in cooperation with the regional hydrological authority.

Replication potential in the SUDOE region

The methodology used in the study is applicable to all areas, especially arid regions with scarcity of resources, with water management problems at an environmental, social or economic scale. From generating knowledge and understanding of the case, involving the users established in the community, the proposed solutions are suitable to face any conflict regarding the state of the water bodies themselves and satisfying of demand.

Future outlook

The work carried out within the framework of the REMABAR project is a step for the local water resource to improve quality and quantity.

With the evidence of the water need in the territory, it is expected that new policies focused on self-regulation by users will be necessary.

To contribute to the good practice and management of users, it is necessary to promote the study and generation of knowledge related to the aquifer system.

Political and economic regulations together with the necessary knowledge provide three pillars to recover and maintain the good state of the local water resource.

Key points of the innovative method

- Mechanisms of dialogue and pedagogy with users at the local level.
- Social acceptance.
- Use of decision support technologies, modelling and simulation around the aquifer system.
- Generating knowledge and transferring it to users to improve resource management in an area of aridity and scarcity.

Acknowledgments

The innovative practice was suggested by Sergi Compte of the Catalan Water Partnership (CWP).

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Governance

User community involvement in water resources management: The Baix Ter Basin case

The Junta Central d'Usuaris d'Aigua del Baix Ter (JCUBT) arises from the need to protect the Ter River and the water resource of the region. The JCUBT ensures the availability of water resources in both quality and quantity.

New European and local policies establish a community framework of action that regulates the rights of water users to constitute a community of users in order to protect the priorities of use, the rights of citizens to the use of water resources, participate together with the authorities in water management, and to implement new measures that allow sustainable use.

Responsible entity

The Junta Central d'Usuaris d'Aigua del Baix Ter (JCUABT) is a public law corporation created in April 2015 to protect the water of the Ter River and its aquifers, and to ensure that its availability, both in quantity and quality, is guaranteed for all uses, that is: the municipal supply of the 40 municipalities of the Baix Ter plain; the development of agriculture, tourism and industry; and the hydrogeological support of the historic landscape.

These principles of defence of the water of the Ter and its aquifers are based on a hydrological management model based on the local territory and committed to the participation of the users in an agreement for water management, of wider scope, which allows for the rational and cooperative development of the structures to satisfy the current and future needs of water in the region.

Institutional setting

The axes that underpin the operation of the JCUABT are the priorities of the uses, the right to the use of water by communities and other users, and the participation of users in decision-making, both those related to water management and the implementation of measures for its sustainable use. All of these principles are shared with the Water Framework Directive and are being exercised at the local level.

The functions of the JCUABT are those of management, planning and control of water and its use; the application of efficiency programmes; the containment of salinity and overexploitation; the recharge of aquifers and wetlands; and the improvement of the circulation of river flows, drainage and irrigation. An additionally, and in a very specific way, the function of the JCUABT is the generation of new specialised knowledge that, together with current knowledge, allows us to liaise with the Catalan Hydraulic Administration on developing policies for better management and protection of water resources.

Geographical setting

The JCUABT deals with the bodies of surface and underground water that run within the delimitation of the Waterbody 33 or Fluviodeltaic of the Baix Ter. It includes the lower course of the Ter River from Celrà to its estuary, the Daró River and the Pals Stream, from Palafrugell and la Bisbal to L'Escala. This area also includes groundwater from the aquifers of the Baix Ter alluvial plain, the Celrà basin aquifer, the Daró aquifers and the Palafrugell basin, including a total of 40 municipalities.

Organisations involved with the JCUABT include: the Community of Irrigators of the Colomers Dam, the Community of Irrigators of the Rec del Molí de Pals, the Community of Irrigators of Cervià-Sant Jordi-Colomers, and the Community of Irrigators of the Sèquia Vinyals, with almost 10,000 ha under irrigation, in addition to approximately a thousand wells.

Detailed explanation

A model of progress

In addition to sustaining the economy of this area, the water of the Ter feeds landscapes that are reservoirs of biodiversity and nature. The existence of two Natural Parks linked to the lower plain of the river are a sign of the importance of the natural values of the area. The region increasingly recognises these values and the role of the rural, water and agricultural landscapes as an asset to its municipalities both economically and socially for the improvement of the quality of life of the population.

Water solidarity with the country

The functions of the Ter extend to its hydrological field since the role this river exercises in the water supply of the region is well recognised in the Llobregat basin. A role that, for 50 years, has made it possible to satisfy the demand for water in the city of Barcelona and its metropolitan, urban and industrial environment, generating wealth and levels of prosperity that have had a positive impact on the whole country.

The historical role of the Baix Ter has been exemplary, since it has been exercised without conditions and despite the not insignificant cost that the transfer of water has had on the economy, the environment and the landscape of the region. Hydrological predation, with a flow derivation that has easily exceeded 200 hm3/year on average, has transformed the landscape, soil and customs, in addition to significantly damaging the natural hydrological dynamics and the native ecological values of the Baix Ter.

The problems of water in the Baix Ter

The problems of water in the Baix Ter are well known given the publication of the studies and controls that are carried out by the region itself, the administration, various groups and universities. The hydrological and ecological indicators that record the evolution of the water of the Ter show a persistent loss of quality in the ecosystems linked to the river and the wetlands of the Baix Ter plain, as well as a decrease in water tables and groundwater quality, mainly due to salinity, and the presence of biocides and nitrates. Not surprisingly, the bodies of surface and groundwater of the Baix Ter are at quantitative and qualitative risk as can be seen from the studies to update their status that were carried out within the framework of the regional Management Plans required by the Water Framework Directive.

Apart from the problems manifested by the hydrological and ecological indicators of the area, there is also an important problem associated with the risk of water restrictions for irrigation, with the real possibility of high production losses. In the same vein, the risk of collapse of the main water supply to the tourism sector and the wider population, in areas such as Torroella, Palafrugell and L'Escala, is a possibility that cannot be overlooked.

A historical claim

Demands for more respect for the Ter and an integrated water management plan for the region have been a constant for decades, with laudable efforts by community groups, institutions, businesses and agricultural organisations. However, and even after the experience of the extreme hydrological drought of the years 2007–2008, none of the political developments in the region has met this historical demand with sufficient consideration, firmness or future proofing.

It is in this context, and as a result of the mobilisation initiated during the last drought before 2015 by municipalities, institutions and groups downstream of the reservoirs, that the Girona region has organised and taken a new direction, the first milestone of which was the creation of the JCUABT.

Historical overview

The creation of the JCUABT was the rational response by the region to the need for the protection of the Ter River and its aquifers. and that has the justification in its function recognises and supports the role of its water in the socioeconomic growth of the region, which extends from the environs of Girona to the lower plain of the river, an area of quality tourism activity and important agricultural production.

The JCUABT was recognised by the Catalan Water Agency (CWA) on 9 April 2015 and appointed its governing bodies at the General Meeting of 7 May 2015. Earlier, the Committee for Drafting the Statutes had submitted, on 31 October 2014, the application for the constitution and approval of its statutes.

In its daily work, it has developed an extensive knowledge of the hydrology and hydrogeology of the area, with advanced monitoring and the use of detailed predictive models. The use of this information, together with the political will of a joint management of the resource, allows it to face the many problems derived from the use of water in an area with an economy based on agriculture and tourism.

Evidence of benefits from implementation

Since 2015 the JCUABT has initiated opportunities to channel and structurally rethink the hydrological functioning of the region; extending the principle of hydrological solidarity to all the basins of the Catalan territory, working for a real application of the principles of the Water Framework Directive, and implementing the necessary actions to compensate for the historical neglect of the Ter River basin.

It was in this context that the JCUABT was able to support a project – between 2018 and 2023 – involving consolidation, specialisation and territorial projection (PECT Girona, Water Sensitive Region). It has also allowed it to sign a management entrustment agreement with the Catalan Water Agency – between 2019 and 2021 – to carry out various studies related to the improvement of the Baix Ter groundwater body and the improvement of its water management.

Replication potential in the SUDOE region

Within Spain, where the general legislation on water is the same, the possibilities of replication are direct. In other countries, an in-depth study of state regulations would be necessary to assess a potential direct replication. Nonetheless, the type of benefits achieved by the JCUABT should be the same in the case of entities from other countries with similar objectives.

Future outlook

The work to be addressed in the immediate future is to implement the best practices achievable in the territory of the Baix Ter as a result of the conclusions of the different studies carried out within the framework of the PECT Aigua and the agreement with the Catalan Water Agency. These have to do with the priority areas of recharge of the deep aquifer, with the preservation of the quality and quantity of water in the areas and perimeters of protection of the municipal catchments or, among others, with the protection of the aquifer environment before the expectations of exploitation of aggregates in areas of special hydrogeological sensitivity.

Key points of the innovative method

- The JCUABT is an example of cooperation between diverse users in the same territory.

- Positive impacts on water needs, improvement in the efficiency of use of the resource, and protection of the socio-economic and environmental values in the interests of the users.

- The decisions taken by the JCUABT are based on intense monitoring of surface and groundwater.

- Advanced knowledge and political will together allow actors to coordinate hydrogeological management and are a great example of good governance.

Acknowledgments

The innovative practice was proposed by Josep Mas-Pla (ICRA and GEOCAMB).

References

The information presented has been collected directly from the Central Board of Users of the Baix Ter.

GICRESAIT: Integrated and concerted management of water resources of the aquifer systems of Iullemeden, Taoudéni/Tanezrouft and the Niger River

GICRESAIT is a replication of the Geo-Aquifer project which focuses on the integrated and concerted management of water resources of the Iullemeden, Taoudéni/Tanezrouft and Niger River aquifer systems. The project, led by the Sahara and Sahel Observatory (OSS) and conducted between 2010 and 2016, focused on the entire basin of the Iullemeden-Taoudéni-Tanezrouft Aquifer System (SAIT) which forms a single transboundary aquifer system. The objective of the project was to significantly improve the concerted and sustainable management of the water resources of the SAIT as well as that of the Niger River in a context of climate change.

The GICRESAIT project was based on a participatory approach with all stakeholders and has three components:

1. Improving the knowledge of the SAIT.
2. Assessment of the vulnerability of the SAIT and the establishment of a consultation framework.
3. Capacity building, awareness and communication.

Figure 1: GICRESAIT project intervention zone.

The main steps in this project were:

- The collection of data related to hydrogeology, the water cycle and reservoirs from technical services in charge of water resources management in the seven riparian countries, international and sub-regional research organisations as well as from internationally recognised experts.
- The setting up of a Geographic Information System (GIS) and of a structured and homogeneous database for the whole basin.
- The use of Earth observation data and Digital Terrain Models (DTM) to help model recharge and crop water withdrawals.
- Spatial modelling of the aquifer system

Responsible entity

The Sahara and Sahel Observatory (OSS) is an international organisation that operates in the arid, semi-arid, sub-humid and dry areas of the Sahara-Sahel region. Created in 1992, the OSS has been based in Tunis (Tunisia) since 2000. The OSS has 26 African countries, 7 non-African countries, and 13 organisations among its members. The OSS initiates and facilitates partnerships around common challenges related to shared water resources management, and implementation of international agreements on desertification, biodiversity and climate change in the Sahara and Sahel region.

The main actions carried out by the OSS are:

- The implementation of multilateral agreements on desertification, biodiversity and climate change.
- The promotion of regional and international initiatives related to environmental challenges in Africa.
- The definition of concepts and harmonisation of approaches and methodologies related to sustainable land and water resources management and climate change.

The OSS necessarily relies on knowledge transfer, capacity building and awareness raising of all stakeholders.

The OSS activities and projects are financed by voluntary contributions from member countries, and by grants and donations from development partners. With effective governance mechanisms and a competent, multicultural and multidisciplinary team, the OSS makes a high value-added contribution to the international and African institutional landscape.

Institutional setting

- The stakeholders of the GICRESAIT project are:
- The OSS as project owner, and the technical services of the seven riparian countries:
- The National Agency for Hydraulic Resources (ANRH, Algeria)
- The General Directorate of Water (Benin)
- The General Directorate of Water Resources (Burkina Faso)
- The National Directorate of Hydraulics (Mali)
- The National Centre for Water Resources (Niger)
- The Nigeria Hydrological Services Agency (Nigeria)

Project partners and financiers:

- The Niger Basin Authority
- The AGRHYMET Regional Center
- The African Water Facility
- The French Global Environment Facility

Geographical setting

The study area of the GICRESAIT project covers an area of 2.6 million km² shared by seven countries:

- Algeria (450,952 km²; 17%)
- Benin (57,338 km²; 2%)
- Burkina Faso (130,174 km²; 5%)
- Mali (1,089,407 km²; 41%)
- Mauritania (256,374 km²; 10%)
- Niger (524,813 km²; 20%)
- Nigeria (120,272 km²; 5%)

The system studied is the Iullemeden, Taoudéni/Tanezrouft Aquifer System (SAIT) and the Niger

River, which is a collection of several groundwater aquifers located in geological formations dating from the Primary to the Quaternary period. The groundwater resources considered are those of the intercalary continental aquifers dated from the Upper Cretaceous and the terminal continental aquifers dated from the Tertiary to the Quaternary. The main course of the Niger River crosses the aquifer system over nearly 2,480 km, 1,700 km of which are in Mali (forming a floodplain called the interior delta), 540 km in Niger, 140 km in Benin in the form of the border with Niger, and nearly 100 km in Nigeria (crossing the Sokoto basin). The SAIT system basin is characterised by several climates, from north to south: arid, semi-arid and dry sub-humid. Annual rainfall fluctuates from over 1,000 mm in the south to less than 100 mm in the north of the basin.

Detailed explanation

The management practice implemented in the GICRESAIT project is based on different steps.

Hydrogeological investigations

Investigations were used to highlight the presence of areas that appear to have particular potential for groundwater exploitation as follows.

(i) A connection with surface water, which ensures a regular supply that sustains the water resource, even during episodes of rainfall deficit due to climate variations. These are:

- the interior delta of the Niger River in Mali;
- the downstream sector of the Dallols in Niger and Nigeria;
- the Mouhoun basin upstream of the Gondo plain in Burkina Faso; and
- the Gao Gap in Mali and Niger.

(ii) The high strength of the aquifer formations and their permeability, which leads to the possibility of high unit flows in the catchment works. These are:

- the Tahoua sector in Niger;
- the southern sector of the Dhar de Néma in Mauritania; and
- the Nara ditch in Mali.

Data base

The objective here was to create a simple and user-friendly tool to allow the database managers (the OSS and partner countries) to consult and valorise the data from the water points in a transboundary context. The database has made it possible to integrate information on approximately 123,000 water points (time series of levels for the available piezometers), rainfall data (monthly rainfall levels from 1960 to 2011 for 50 stations), hydrological data (quarterly average ratings and monthly average flows from 1960 to 2012 for five stations on the Niger River).

Among the water points integrated in the database, some points have no altitude information, and for others it is uncertain. Thus, a specific tool was developed based on the use of a Digital Topographic Model (DTM) to compensate for this deficiency. The altitudes of the water points allow for a unique reference and can be used to elaborate geo-referenced piezometric sections and maps.

Use of geo-spatial data

An assessment of the available geo-spatial data for the area was conducted and the data was selected to provide a comprehensive and undisturbed representation of the SAIT area. The geo-spatial data selected were:

- MODIS for land cover mapping at 1:2,000,000 scale;
- GlobCover data (ESA GlobCover project) in support;

- LANDSAT for land cover mapping at a scale of 1:200,000 on a South-North transect as a pilot area; and
- SRTM v4.1 data for the DTM in order to have a homogeneous and continuous topography on the intervention area.

Modelling of the SAIT system

The aquifer systems of Iullemeden, Taoudéni-Tanezrouft have therefore been modelled according to two distinct mathematical models. However, in order to guarantee geological continuity, the western part of the SAIT model has been extended to the eastern part of the SAIT, over a 125,000 km2 strip with identical hydrodynamic characteristics (Gao Graben).

The mathematical model was developed to establish the water balance of the entire SAIT and to (i) define the hydraulic relationships between groundwater and the Niger River flows, and (ii) simulate the behaviour of groundwater resources in the face of climatic variations, particularly in the event of a decrease in rainfall.

Vulnerability assessment

Two main axes were studied by the managers, namely: (i) the drop in aquifer levels caused by climatic stress and increasing exploitation of the resource, and (ii) chemical and bacteriological pollution of aquifers by human activities.

A risk information system, built from the SIRIS (Scores Interaction Risk Information System) method, integrated both the "physical" constraints of the aquifer systems and their environment (recharge, permeability, water depth, free/captive) as well as the anthropic pressures (populations, water demand, well density). The results of the studies have led to a mapping of vulnerable and at-risk areas, which are therefore priority sectors for management.

Monitoring and evaluation indicators

Monitoring and evaluation indicators have been proposed in order to: (i) better understand the social and development dynamics in the SAIT area, (ii) monitor the effects of these dynamics on the environment and on the aquifer systems, and (iii) identify the actions to be taken in terms of development and preservation.

The indicators proposed for monitoring were:

- Driving force indicators: population, agricultural areas, census of wells, boreholes and dams, industrial activities, and livestock.
- Pressure indicators: quantity of pesticide, volume of production of factories, etc.

Historical overview

The first studies of the Iullemeden Aquifer System (IAS; 2004–2009) led to the adoption of a memorandum of understanding creating a consultation mechanism for the management of the Iullemeden Aquifer System by the Ministers in charge of water in Mali, Niger and Nigeria.

In 2013, a diagnostic study on the general, legal and institutional framework of the countries was conducted during the GICRESAIT project.

Its results were the subject of a meeting of the ministers in charge of water resources of the SAIT, held in Abuja in March 2014, which resulted in an agreement in principle on the protocol for the creation of a consultation mechanism, with a legal personality, for the integrated and concerted management of water resources of the SAIT.

Evidence of benefits from implementation

The project has identified the presence of sectors that have a particular potential for groundwater exploitation due to either:

- a connection with surface water, which ensures a regular supply that supports the water resource, even during episodes of rainfall deficit; or

- important and very permeable aquifer formations.

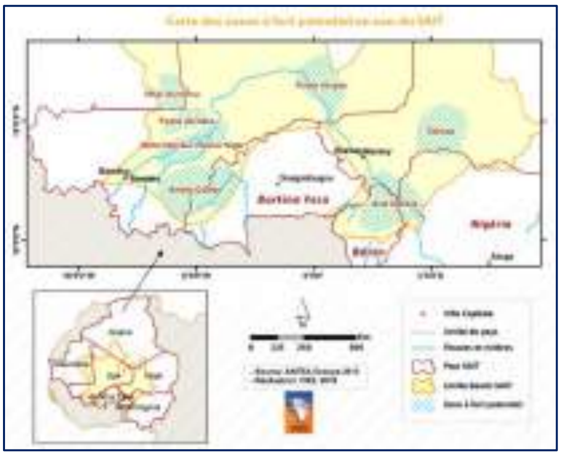

Figure 2 : Map of areas identified as having high groundwater potential.

Replication potential in the SUDOE region

The practice has the potential to be reproduced if sufficient data (piezometric, rainfall) are available to feed the mathematical model.

It should be noted that this type of project applies preferentially to transboundary aquifers and their governance and resource sharing issues.

This type of project presents an interesting potential for replication in the context of a downscaling for transregional management issues.

This type of project also requires significant financial support since the project has received financial support from the African Water Facility (AWF) and the French Global Environment Facility (FFEM) for €1.7 m.

Future outlook

The work carried out within the framework of the GICRESAIT project is a first step on the scale of the transboundary basin and complementary work is necessary to deepen the knowledge of the sectors with strong potential identified.

The indicators developed within the framework of the project are intended to be expanded as national IWRM progresses in the SAIT areas and is integrated into a monitoring framework for this integrated management strategy.

As a result of the project findings, the OSS has proposed the development of a regional master plan containing planned actions for the resources of the Niger River, included in the Niger Basin Authority (NBA) Sustainable Development Action Plan (SDAP).

The planned actions are:

- To establish a regional diagnosis on the current and future water needs of the countries by 2030 and 2040 in terms of drinking, agricultural and industrial water supply, in relation to adaptation to climate change.
- Identify the potential for agricultural, mining and industrial development by country.
- Plan water allocation from high potential areas by 2030 and 2040 and related investments.
- Strengthen the role and action of a consultation mechanism.
- These actions are aimed at:
- The progressive satisfaction of the water needs of the populations.
- The development of the basin's arable land, estimated at over 137 million hectares.

- The improvement of the quantitative and qualitative food security of the countries.
- The establishment of a transboundary regional infrastructure promoting economic development.
- The creation of jobs and increased income for farmers.

However, capacity building of staff and technical services is needed to contribute to the development of a regional master plan for the allocation of shared water resources.

Key points of the innovative method

- Integrated management of a transboundary aquifer.

- Identification of areas with high groundwater exploitation potential.

- Concerted management

Acknowledgements

The innovative practice was suggested by Yvan KEDAJ (Aqua-Valley). Abdel Kader DODO, Lamine BABA SY, and Nabil BEN KHATRA (OSS) participated in the interview.

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Northern Sahara Aquifer System (Algeria, Libya, Tunisia)

The Northern Sahara Aquifer System (SASS) shared by Algeria, Libya and Tunisia, is a basin that covers an area of nearly 1 million km² and whose water resources are not very renewable. With the objective of establishing sustainable development in the region, the Sahara and Sahel Observatory (OSS) has conducted studies through three projects (SASS I, SASS II, and SASS III) between 1999 and 2015. The SASS project, which started in 1999, has thus reached the third phase of its implementation. After having deepened the knowledge of the resource during the previous phases (hydrological and hydrogeological aspects), the third phase focused on water uses (mainly agricultural) and, more generally, on the socio-economic and environmental aspects related to irrigation practices in the basin.

Figure 1 : Northern Sahara Aquifer System (SASS).

These studies allowed a better hydraulic knowledge of the system, the setting up of a common information system and the establishment of a permanent consultation mechanism between the three countries. In addition, these studies have highlighted the fact that agricultural development in its current form (based on supply), is a source of risks related to the costs of mobilising water and its salinisation as well as the degradation of soil quality. They have also shed light on the lack of efficiency of irrigation and the low value of water. This situation is likely to worsen in the future given the growth in demand and the impacts of climate change. Finally, these projects have produced operational recommendations for sustainable agriculture with the preservation of water and soil resources.

Responsible entity

The Sahara and Sahel Observatory (OSS) is an international organisation that operates in the arid, semi-arid, sub-humid and dry areas of the Sahara-Sahel region. Created in 1992, the OSS has been based in Tunis, Tunisia, since 2000. OSS has 26 African countries and 13 organisations among its members. The OSS initiates and facilitates partnerships around common challenges related to shared water resources management, and implementation of international agreements on desertification, biodiversity and climate change in the Sahara-Sahel region.

The main actions carried out by the OSS are

- The implementation of multilateral agreements on desertification, biodiversity and climate change.
- The promotion of regional and international initiatives related to environmental challenges in Africa.
- The definition of concepts and harmonisation of approaches and methodologies related to sustainable land and water resources management and climate change.

The OSS necessarily relies on knowledge transfer, capacity building and awareness raising of all stakeholders.

The OSS activities and projects are financed by voluntary contributions from member countries, and by grants and donations from development partners. With effective governance mechanisms and a competent, multicultural and multidisciplinary team, the OSS makes a high value-added contribution to the international and African institutional landscape.

Institutional setting

The stakeholders of the project are the OSS as the project owner. The first phase of the SASS project was carried out with the support of SDC Switzerland, IFAD, FAO, UNESCO and GIZ. The second phase was carried out with the support of SDC Switzerland, FFEM (France), Global Environment Facility (GEF), United Nations Environment Programme (UNEP), UNESCO and GIZ. The third and final phase was carried out with the support of the FGEF and the GEF.

Geographical setting

The SASS is a deep aquifer shared between Algeria, Tunisia and Libya. The SASS designates a complex superposition of aquifers with two main layers housed in two different geological formations: the Continental Intercalary (CI or Albian) and the Terminal Complex (TC). The SASS extends over one million km² and contains considerable water reserves, but they are not very renewable and cannot be fully exploited. The situation of overexploitation, confirmed by the model set up by the OSS SASS project, has exposed the SASS to increased risks of water salinisation, disappearance of artesianism, and drying up of water outlets. The SASS area covers regions ranging from desert areas (with annual rainfall <100 mm and evapotranspiration >3,000 mm) to arid areas (with annual rainfall of 100–200 mm and evapotranspiration of the order of 2,000–2,500 mm).

Detailed explanation

Different developments were carried out within the framework of the SASS project according to the different phases.

SASS I

Phase I consisted in an improvement of the hydraulic knowledge of the aquifer system. Concretely, this resulted in: (i) the creation of a common database with more than 9,000 water points; (ii) the development of a hydraulic management model to evaluate the impacts of withdrawals on the resource; and (iii) the establishment of a consultation structure at the technical level.

SASS II

The second phase of the SASS project aimed to achieve the following objectives: (i) the realisation of two submodels (Biskra and Western Basin in Algeria) and the model of the Tunisian-Libyan Djeffara; (ii) the establishment of a diagnosis on the agricultural practices; and (iii) the setting up of a Concertation Mechanism at the institutional level between the three countries whose coordination unit is hosted by the OSS.

Figure 2: Map showing the location of the survey areas.

SASS III

Phase III consists of two components. The socio-economic component aimed at describing the functioning of the farms and the behaviour of the main user, namely the irrigator to enable a quantitative and qualitative inventory of irrigated agriculture throughout the basin to be drawn up. After consultation between the OSS and the partners of the three countries, thirteen areas were initially selected for their representativeness of the agricultural, environmental and economic problems observed throughout the basin. In the end, ten areas were investigated. A sample of 3,000 farms was selected from the ten survey areas on the basis of several criteria to ensure its representativeness, including the proportion of irrigated areas, the size of the farms and the type of access to water. Two survey campaigns were conducted on this sample (4,139 surveys out of 4,500 planned). The survey questionnaire was developed on the basis of twelve themes covering both the quantitative and qualitative aspects of the irrigators' activity. In order to provide decision-makers with an appropriate tool to help them design and implement agricultural development policies through the SASS, a hydro-economic model was developed. It is a tool that explicitly integrates economic calculation into the heart of water resource management by evaluating the goods and services generated by the different agricultural uses of this resource; it allows the simulation of scenarios on a quantified and adequately quantified basis. This hydro-economic model has been designed and made operational thanks to the global and micro-economic data collected, and the results obtained from the quantitative analysis. Its application is possible on a regional or local basis within the basin. The model, whose objective is to maximise the income of all irrigated activity under appropriate economic and hydraulic constraints, allows the calculation for any scenario of: (i) the maximum volume to be pumped from the aquifer, and (ii) the maximum revenue generated. Depending on the results obtained, the decision-maker in the field will thus be able to base their policy on the scenario they prefer.

For the agricultural demonstration pilots component, six demonstration pilots representing four main problems of Saharan agriculture were selected in close collaboration with the institutions in charge of water

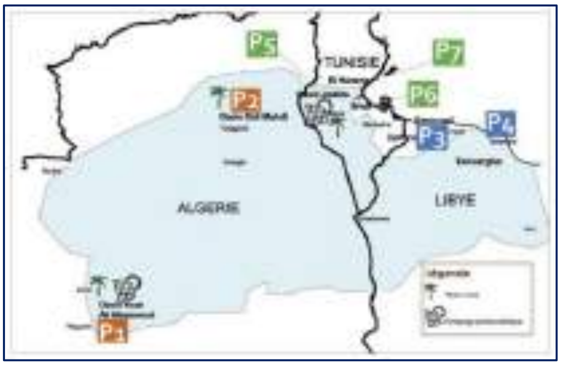

Figure 3: Map of the location of the pilot agricultural demonstration sites.

management in the three countries. The issues addressed were: (i) water scarcity, (ii) water salinisation, (iii) irrigation inefficiency, and (iv) soil quality degradation.

Historical overview

1950s–1960s: Tunisia and Algeria noted a drop in pressure in their hydraulic works.

Years 1970–1980: ERES project for the study of the water resources of the Northern Sahara.

From 1999 to 2002, a first study was carried out within the natural limits of the basin, which until then had been considered on a national scale or in the framework of bilateral collaborations. In 2003, new studies to consolidate knowledge on hydraulic aspects and agricultural diagnoses were launched. They shed light on the lack of efficiency of irrigation, the poor use of water and the degradation of soil quality. These observations highlighted the fragility and unsustainability of the cropping systems prevailing in the SASS basin. In 2006, and following a process led by the OSS during the previous study phases, the three countries set up a common management framework, the Concertation Mechanism, with the mission of carrying out a concerted policy for sustainable groundwater management at the basin level. The overexploitation of the SASS, with the environmental and socio-economic risks that this implied, led the countries to agree on objectives to control water demand, improve its productivity and protect the environment. Efforts have focused on the agricultural sector, which is the largest user of groundwater in the basin. In 2009, the OSS initiated the third phase of the project. This third phase of the SASS project developed recommendations for the implementation of a basin-wide sustainable land and groundwater resources management strategy.

Evidence of benefits from implementation

The SASS project has resulted in significant water savings of up to 45% and a tenfold increase in farmers' income.

Socio-economic component

The considerable number of farms surveyed has expanded the field of knowledge of the behaviour of agricultural water uses and users in the three SASS countries. The analysis of the data has made it possible to quantify the impact of salinisation on water productivity and the effect of the price of water on its consumption. The considerable contribution of the socio-economic component was, on the one hand, to allow a readability of the viability of the exploitation when the quality of the water is degraded and to give simple economic indicators which must alert decision makers. On the other hand, the study highlighted the importance of structural factors for the viability of farms. In particular, it emphasised the importance of the social organisation of the farm (involvement of the family workforce, level of education of the farmers, experience in irrigation, farmer/breeder combination) as a determining factor in water productivity. The socio-economics component showed that it was possible to value water in a sustainable way, provided that the determining factors of the farmer's behaviour were taken into account – who consumes water, in what order and how. In this approach, it was also shown that in the SASS, the main users of water were the farmers with individual access by private drilling. This category of farmers is also the one that produces the most wealth per m3 of water. The relatively high water productivity of the "private" group is thought to be due to the fact that paying for water makes the farmer more efficient.

Demonstration pilots

This component had a primarily agri-environmental focus; however, it is important to note that an innovative social approach achieved through multi-stakeholder consultation and participation contributed to the achievement of the objectives. Farmers, as the main decision-makers, were strongly involved in the realisation of the work in an exemplary synergy with the partner research institutions. The pilots demonstrated that it is possible to convince farmers to adopt sustainable water and soil management practices, including more efficient irrigation. They have also demonstrated to farmers, in a concrete way, that it is possible to make better use of water while preserving the ecosystem.

The pragmatic and pedagogical way of convincing farmers made them willing to pay for irrigation water and to invest in better efficiency. It was the perception of the value of water that changed for the farmers. The pilots promoted dialogue between farmers and acted as a vehicle for agricultural extension and the dissemination of innovations. On the other hand, they have facilitated the social acceptability of innovations. These dynamics are promising and can help revitalise interest in irrigated agriculture in certain regions throughout the basin. The "agricultural demonstration pilots" component has paved the way for improved living conditions for farmers, stabilisation of populations and better conservation of the resource.

Replication potential in the SUDOE region

The main success factors of the project were to reach a consensus between the three countries to face this problem. Additionally, the support of a structure such as the OSS, which listens to the countries and their needs, makes it possible to encourage better management of the transboundary resource. Strong involvement of civil society in this project should also be noted. Although the project has been able to benefit from subsidies (each year, each country contributes €30,000), one of the issues raised is the lack of financial means for the field part. Human resources are dedicated to the daily management of this practice, including units to organise training workshops and water workshops. This type of project also has a strong potential for replication for trans-regional water resource management issues.

Future outlook

There are prospects to continue the practice and to manage to reverse the trend of depletion of water resources, but the process involving three different countries is long.

Key points of the innovative method

- Mechanism of dialogue between countries.
- Pedagogy of proximity with the farmers.
- Social acceptability.
- Socio-economic approach.

Acknowledgements

The innovative practice was suggested by Yvan KEDAJ (Aqua-Valley). Abdel Kader DODO, Lamine BABA SY, and Nabil BEN KHATRA (OSS) participated in the interview.

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GEF : http://www.thegef.org/

PNUE : https://www.unep.org/

Governance

Groundwater licensing and trading - the case of the state of Victoria, Australia

Water markets have arisen as promising instruments in water resources management in the Australian state of Victoria. Groundwater trading through entitlement emission has been increasing but, in comparison with surface water markets, groundwater trading faces some issues concerning the definition of sustainable volume caps and a lack of knowledge associated with groundwater bodies. On the other hand, the sustainable private use of this resource may have additional benefits if compared with surface water, such as lack of evaporation losses, while market dynamics are pushing the increase in environmental benefits.

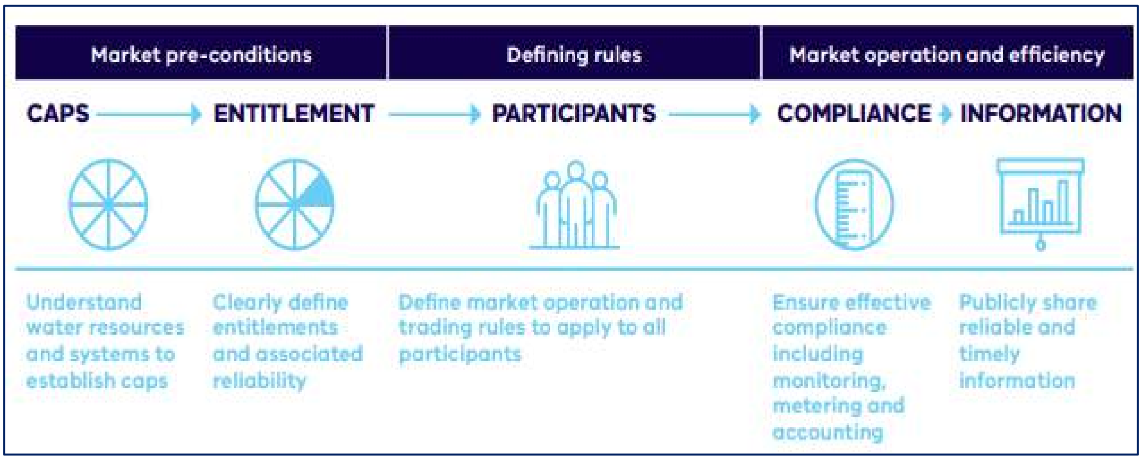

Fig. 1 – Elements of the Victorian Water Market (adapted from DELWP, 2019a).

Responsible entity

The Victorian Water Market design comprises several participants (Fig. 1), from individual entitlement holders to water corporations. The Victorian Minister for Water has the overall responsibility for market design while other entities, such as Murray-Darling Basin Authority, push to remove artificial barriers to water trade and prevent insider trading and discrimination for traders. Water corporations are responsible for assessing applications for water shares trading (DELWP, 2019a). The Crown delegates authority to government departments and water corporations to develop and manage groundwater resources for all users and the environment.

Water corporations are divided into three categories: (1) Urban-metropolitan (Melbourne area), (2) Urban-regional (providing water and sewerage services in regional cities and towns across the state), and (3) Rural water (providing rural water services for irrigation, livestock, domestic, environmental and recreational purposes).

Victoria state has eighteen government-owned water corporations whose responsibilities include: (1) the supply of drinking and recycled water, and the removal and treatment of sewage and trade waste – known as 'urban' water services; and (2) water delivery for irrigation, domestic and livestock purposes, drainage, and salinity mitigation – known as 'rural' water services.

Some of these water corporations also provide water for environmental purposes, manage bulk water storage and designated recreational areas, and help the Minister for Water operate the Victorian Water Register.

Water corporations operate and maintain treatment plants, pumping stations, pipes, channels, reservoirs, dams, gates and meters.

Groundwater licencing and trading for all uses except urban supply in the state of Victoria is implemented by rural water corporations – Southern Rural Water, Goulburn-Murray Water, Grampians Wimmera Mallee Water and Lower Murray Water (Fig. 2)

Institutional setting

The Victorian Water Act (No. 80 of 1989) provided the necessary regulatory framework for the State management of water resources and defined a system of rights and entitlements which laid the bases for water trading. The Act aimed to provide for the integrated management of all elements of the terrestrial phase of the water cycle; to promote the orderly, equitable and efficient use of water resources; and to make sure that water resources were conserved and properly managed for sustainable use for the benefit of present and future Victorians. It also pushed for the maximisation of community participation in making and implementing plans related to the use and protection of water. Under the Act, the State Government has the right to the use, flow and control of all water in a waterway as well as all groundwater for the benefit of the community, users and the environment.

Fig. 2 – Victorian rural water corporation boundaries.

Fully functional water markets began to arise under the Australian National Water Initiative (NWI) which defined a nationally compatible, market, regulatory and planning based system of managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes. This forced states and territories to adopt water planning regimes that allowed for the clear articulation of the trade-offs between the achievement of ecological and consumptive water uses. Murray-Darling Basin was recognised in the NWI as a priority area for protection due to its national importance. A plan for investment in water infrastructure, the purchase of water on the market, and changes to river or wetland management was laid.

The development of the Murray-Darling Basin Plan was instrumental in implementing and guiding water trading. This important management tool determined an average amount of water that could be extracted or taken annually from the Murray-Darling Basin for consumptive use (urban, industrial and agricultural) called the sustainable diversion limit (SDL) (DELWP, 2019a).

Geographical setting

Victoria is a southern state which represents 3% of Australia's total area and it is characterised by the second-highest population density in Australia. It is a very economically relevant region as it represents 23% of the country's GDP. Historically, mining occurred over a large proportion of the state's area in the nineteenth century and water management issues were then common. The economic importance of agriculture increased and today Victoria is the largest supplier of premium food and fibre products, exporting 77% of Australia's dairy exports, 50% of Australia's horticultural exports and 32% per cent of Australia's prepared food exports. This sector represents most of the water consumption in the territory – Fig. 3.

Although Victoria is the second wettest Australian State, between 1996 and early 2010 it experienced unprecedented dry conditions – the Millennium Drought. More than 50% of the state experienced the lowest rainfall on record (particularly during the 2006/07 hydrological year) – Fig. 4 (DELWP, 2016).

Water shortages were exacerbated by water quality problems such as algal blooms and contamination resulting from wildfires, reducing the availability of clean water and supply shortages in many regions across the state. This extreme event ended in major flooding events in 2010/11 and highlighted the need for dynamic planning, which has served to reinforce the relevance of Victoria's water entitlement, planning framework and principles, based on the uncertainty surrounding a wide range of plausible future climate scenarios.

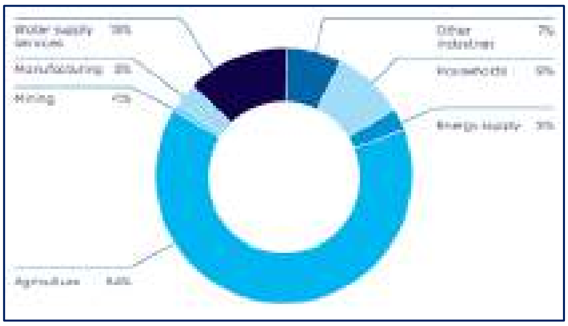

Fig. 3 – Water consumption by sector for 2013–2014 (adapted from the DELWP website).

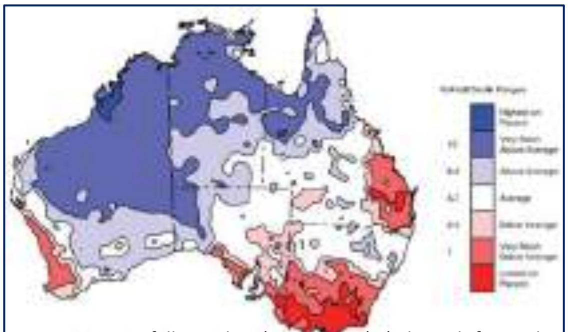

Fig. 4 – Rainfall Deciles (1996–2010) (adapted from the DELWP, 2016).

The Murray-Darling Basin takes up most of the Victorian state area and covers 14% of Australia's land area. It is divided between four states (Fig. 5) and includes 75% of Australia's total irrigation agriculture. Human practices of the past 150 years have had a serious destabilising effect on the groundwater systems of the Murray-Darling Basin with consequent degradation problems such as land salinisation and soil erosion. Growing water demand also resulted in greatly reduced flows and changes to seasonal flow patterns (Murray-Darling Basin Commission, 1999; Grafton and Connell, 2011).

The Murray-Darling Basin contains 20 surface water resource plan areas and 22 groundwater water resource plan areas, as well as six combined groundwater and surface water resource plan areas (DELWP, 2019a).

Fig. 5 - The Murray-Darling Basin (adapted from the MDB Authority website).

Detailed explanation

Water trading is a necessary tool when the water resource available for commercial or intensive use (i.e., irrigation) is fully allocated (DPI, 2012). This trading system may be useful or necessary for users who, for example, have a licence but no longer need all of it or intend to expand, implement water use efficiency measures, or require more water to get through a dry season.

The basis for this market is a water entitlement. Entitlement holders are responsible for managing their own water needs as well as the risks of any water scarcity. These entitlements are protected by a statutory framework that ensures the amount of water that can be taken is capped and makes it an offence to take water without authorisation (DELWP, 2019a). The cap is established annually, which prevents new entitlements from being issued, to protect the resource and prevent it from being depleted or causing adverse impacts such as reduction of base-flows in rivers/streams, changes in quality and saltwater intrusion.

The entitlements issued under the Victorian Water Act are of different types depending on expected use and are recorded in the Victorian Water Register. This platform provides information on the entitlement volumes, transactions, allocations and trade.

The entitlements are of several types depending on use, including bulk/environmental, individual arrangements and supply arrangements. As an example, individual entitlements are held as a licence, also referred to as a “take and use” or a “section 51 licence”. The licence includes the location from where the water can be taken and the land where it can be used, not allowing for the construction of infrastructures to retain or extract water. It might include limits to annual and daily extraction rates. Licences allow water to be extracted on an annual basis from 1 July to 30 June (DPI, 2012).

When the cap has been reached, both in surface and groundwater systems, a user may transfer their licence permanently or temporarily. Water trades must be assessed and approved by the issuing water corporation, ensuring that there are no adverse impacts on other users or the environment. Trading water entitlements is a private negotiation between buyer and seller, set by open market rules. This process is usually initiated by advertisement. The prices may be evaluated by consulting the Victorian Water Register or a water broker.

Water allocation is the amount of water distributed yearly to different licensees. This volume changes according to rainfall, inflows and how much water is stored (Fig. 6).

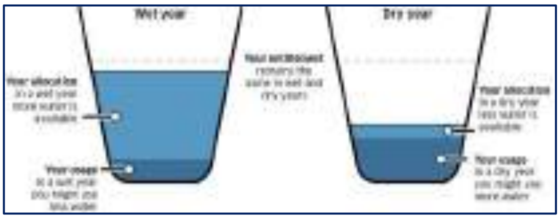

Fig. 6 – Water entitlements allocations and usage (adapted from MDBA website).

In relation to groundwater trading, a permissible consumptive volume (PCV) – the maximum volume of water that can be allocated in an area – is set by the government. PCVs are imposed to protect the resource and prevent it from being depleted or causing adverse impacts such as:

- Loss of water supply.
- Reduced base flows in rivers and streams.
- Changes to water quality/saline intrusion.

Groundwater Management Units have been established as a part of the framework for managing groundwater reserves. These units cover 24% of the state and are of two types: groundwater management areas – GMA; and water supply protection areas – WSPA (Fig. 7). GMAs are areas where groundwater has been intensively explored or has the potential to be developed. WSPAs are declared by the government to protect stressed groundwater or surface water resources through the implementation of a management plan. Unincorporated Areas are areas where the resource is low yielding or its quality has traditionally severely limited its use (low development) and PCVs do not apply.

In areas where the PCV is fully allocated, no new licences can be issued and trading with an existing groundwater licence holder is the only way to acquire groundwater.

Under the Murray-Darling Basin Plan framework, water trading is prohibited unless a specific set of conditions are met (DELWP, 2019a):

- There is sufficient hydraulic connectivity between the extraction points subject to the trade.
- The trade is within the consumptive limit for extraction from the resource.
- A mechanism is in place to account for the trade such as the Victorian Water Register.
- The characteristics of the entitlement are maintained (such as volume, timing and conditions), subject to conversion rates.
- Measures are in place to address third party impacts.

Rural Water Corporations are responsible for assessing license applications, deciding whether to issue licenses, and the terms and conditions on which a license is issued (DPI, 2012). Those entities will consider a range of matters when assessing groundwater license applications including:

- Whether there is any water available for allocation under the PCV for the area.
- Any restrictions required by an approved management plan for any groundwater supply protection area.
- Any adverse effect that the allocation or use of groundwater might have (i.e., impacts on existing authorised users; a waterway or aquifer; the drainage regime; or the environment).
- Any water the applicant is already entitled to.
- The purposes for which the water is to be used.

Licenses are issued for between 1 year and 15 years with conditions relating to the exact location and depth from which groundwater can be extracted, the annual volume of water that can be pumped and the rate at which pumping can occur. When making a license application, applicants may be required to undertake investigations commensurate with the volume applied for. These investigations may include pumping tests and environmental impact reports to ensure the extraction will have no adverse effects.

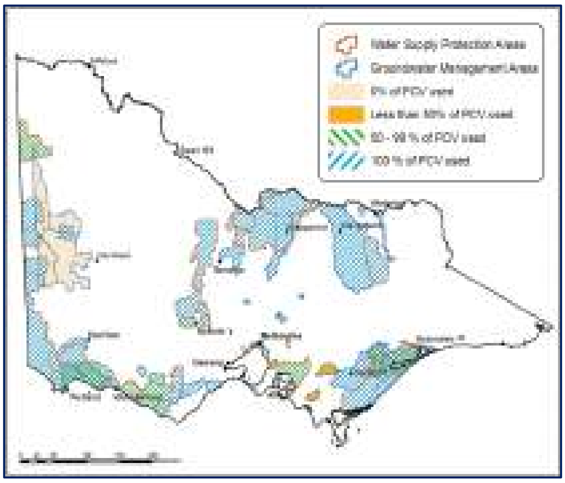

Fig. 7 – Victoria's Groundwater Management Units and respective PCV.

Finally, the carryover concept must be considered. This was initially introduced in northern Victoria in 2007 as an emergency drought response measure and allowed for water not used in a season to be taken and used in the next season. Carryover gives water entitlement holders flexibility to hold, use or trade their water when it is of greatest value to their business. This helps to manage risks, to prepare for shortages due to drought and to secure water for the start of the season, allowing irrigators to set up their farming business for the year. Carryover may help to reduce reliance on the market to meet water needs in future years. This is particularly valuable going into dry years when market prices are highest.

Groundwater carryover operates on the same principles as surface water and enables the licence holder to carry over a fixed percentage of their unused licenced volume to the following year, with no deduction for losses or evaporation.

Historical overview

The main steps in developing a water market in Victoria started in 1905–09 with legislation setting out water rights with an annual charge based on volumes available in the land. There is a record from the 1940s of informal short-term transfers during a severe drought that hit the region. From the 1970s through to the 1990s, state governments undertook initiatives to sustainably manage land and water while facing water deterioration. In 1981 there was a recommendation that allocations of water should be market-driven and in 1987 the temporary transfer of water rights started. The framework for trading was fully developed in 1989 with the Water Act. Official trading started in 1991 with successive updates and revisions, while in 1996 the volume cap was introduced. In 1998 the Northern Victorian Water Exchange started operation and would later (Lewis et al., 2001) be supported by the Victorian Water Register platform. In 2007, the Water Act provided the modern legislative framework for water trading and established the Murray-Darling Basin Authority. Under the framework, water trading was allowed for the relative stabilisation of available water under different hydrological conditions (Fig. 8)

Fig 8 -Evolution of the available water and their price

Evidence of benefits from implementation

Fig. 8 illustrates how allocation prices vary depending on water availability in northern Victoria, climatic conditions and water availability in the upstream New South Wales (NSW) Murray section. Upstream water availability has a very strong influence on market prices in Victoria. In 2018–19, market prices rose sharply due to a drought in NSW and hot and dry conditions that resulted in increased competition for water to meet irrigation demands in the southern Murray-Darling Basin. This was also associated with reduced water availability, with zero general security allocations in the NSW Murray, lower carryover in northern Victoria, and external factors such as commodity prices for many key horticultural crops.

Little information is available on the status of the groundwater trading market in the state. In 2011 it was reported by the National Water Commission (NWC, 2011, in Wheeler et al., 2016) that groundwater trading is comparatively much less developed in Victoria than in New South Wales. It was reported that in Victoria, less than half of the Groundwater Management Units were considered over-allocated, while 12 % were considered less than 50 % allocated. This resulted in new licenses being issued within under-allocated units, with a decreased incentive for trade. However, it was also reported that groundwater levels are declining, which, coupled with the predicted consequences of climate change and expected decrease in natural recharge, implies demand for trade is bound to increase.

The report also pointed out that a barrier to groundwater trade is the lack of planning for management of groundwater resources. For example, in water supply protection areas trading is not permitted until a management plan has been developed. Delays in development are associated with a lack of knowledge about aquifers and sustainable yields – again due to historical reliance on surface water systems and a lack of development on groundwater (Wheeler et al., 2016; DELWP, 2018). Surface and groundwater interaction is also key information in established caps which is sometimes difficult ascertain (Aither, 2017).

Although not specifically related to the groundwater market, the general water trading market in Victoria allowed for environmental benefits to be achieved. The Victorian Environmental Water Holder (VEWH), responsible for holding and managing Victoria's environmental water entitlements, reported that uses of environmental water in a coordinated way through exchanges maximised water availability across all regions, allowing for the return of unused water to the source environmental water holder. A large proportion of trade is simply moving water between systems and environmental water accounts. For example, water allocated to the Commonwealth Environmental Water Holder was transferred into the VEWH to use in northern Victorian rivers and floodplains in 2014–15, which benefited several lakes and resulted in golden perch spawning in the Goulburn River and improving fish passage and habitat.

The DELWP (2016) has emphasised that market participants are becoming more sophisticated in how they manage and trade water, and that the market has changed because the pool of consumptive water entitlements has been reduced by the recovery of water for the environment (Fig. 9). The recovery of water for the environment, the increase in perennial horticulture and changes to the traditional irrigation landscape are altering the dynamics of the water market which has created economic value for Victoria's irrigators. This has allowed some irrigators to expand their high-value, water-dependent irrigated enterprises, while other irrigators have improved their economic wellbeing by selling either permanent or temporary entitlements. During drought conditions, irrigators use the market to manage production and financial risks; alleviating the economic losses associated with scarcity (Department of Sustainability and Environment, 2008).

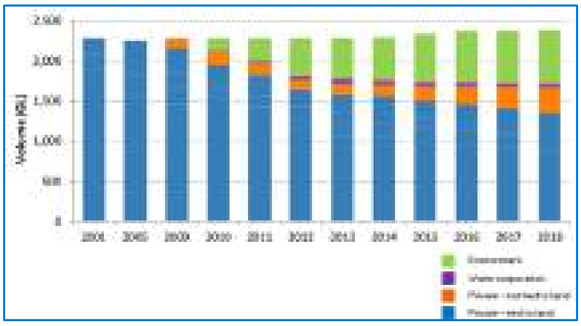

Fig. 9 – Changing ownership of high-reliability water shares in northern Victoria (adapted from DELWP, 2019c)

Replication potential in the SUDOE region

Before the establishment of water markets in any area, four broad elements are needed to drive efficient use and outcomes (Wheeler et al., 2016):

- A fixed limit to resource availability based on accurate science, monitored and sustainably explored.
- Secure property rights in the form of entitlements.
- Water allocated seasonally is tradeable under low transaction costs and entry/exit barrier conditions, allowing dynamic ownership over time.
- Prices are established in a market that uses the value placed on water use by a large pool of buyers and sellers.

For groundwater markets, there need to be well-defined rights with limited groundwater use allocations and monitoring of groundwater extraction by all users. These rights and allocation levels need to be based on a good understanding of the hydrogeology of a groundwater area, groundwater mobility and its sustainable yield, along with knowledge of dependent ecosystems and the way the aquifer responds to extraction. This is particularly relevant in scarcity prone regions such as southern Europe.

A similar platform to the Victorian Water Register is fundamental to the good implementation of the modern water market. This public register holds all water-related entitlements in Victoria and has been designed to provide crucial information for managing the state's water resources. Such a platform must:

- Hold water shares, together with mortgages and limited term transfers (leases) relevant to these water shares, licenses to take and use both surface and groundwater and respective seasonal allocations.
- Track volumes of water entitlements by water system and trading zone as well as the inventory of water-use licenses and delivery shares that are managed by entities similar to water corporations.
- Include workflows to process water dealings, keep audit trails and generate statistics and reports on levels of use, directions of trade and prices paid.

Although similar approaches have been introduced in Spain, in the Sudoe Region, water management is generally based on the common property regime, holding collective resource use rights and excluding permanent individual appropriation of natural resources (Rinaudo et al., 2020).

Future outlook

Victoria's water market has emerged and grown rapidly (Lewis et al., 2001). Groundwater markets are less common than surface water markets, but some exist also in China, Oman, India, and the United States. Comparatively, those are harder to implement than surface water markets that occur mainly in semi-arid regions (e.g., in the United States, Chile, Spain, Canada, South Africa, China, Brazil, Mexico and Tanzania) (Wheeler et al. 2016).

Although groundwater trading may be difficult to implement due to the intrinsic characteristics of this resource, with the support of big data and modern increased computational power, this seems like an achievable goal at a national scale and possibly at a European scale.

Key points of the innovative method

- Water licence trading is a market regulated system in which entitlement holders can decide the amount of water to use seasonally based on their business model, and freely trade the surplus/unused volumes.

- The water market is subject to price fluctuations reflecting hydrological conditions (wet/dry years).

- Water is allocated by entitlements in response to storage levels and rainfall. Allocation is the amount of water distributed to users each year.

- The water market created incentives for water to be used in higher-value uses as well as improved water usage (i.e., better irrigation methods and environmental purposes).

- Groundwater trading is comparatively more difficult to implement due to the difficulty in clearly evaluating this resource's availability, and a lack of monitoring and knowledge.

Acknowledgements

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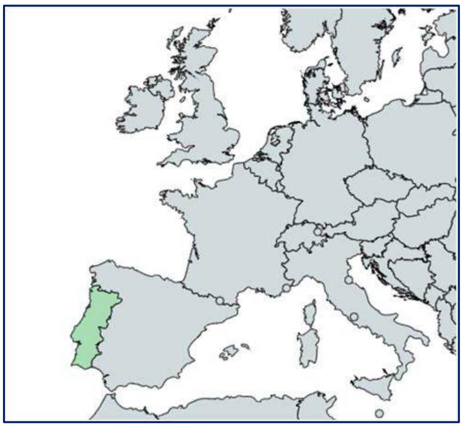
The Portuguese Corporate Manifesto for Water Stewardship



Water is a fundamental resource for our survival and well-being. The supply of water of adequate quality is essential for the production of almost everything around us; from agriculture to industry, from energy production to the most diverse services, from health to technology, the availability of water is a factor which is critical along the different value-chains.

Acknowledging the importance of water sustainability is to integrate water stewardship into businesses and to create business value from providing the correct funding and qualified staff to address these problems. This is better achieved by clearly defined shared goals with partners in different business areas by joint manifestos such as the Portuguese Corporate Manifesto for Water Stewardship (PCMWS). The partner entities of this initiative assume the responsibility to adopt more sustainable measures to contribute to water management that guarantees the effective response that the aforementioned challenges require, achieving the sustainable use of water in member activities. From an initial, very diverse, fourteen founding members, the PCMWS continues to receive interest from partners in various business areas, and it is expected that its reach will expand, and its principles will be translated into the industrial and commercial practices of more and more businesses.

Responsible entity

The Portuguese Corporate Manifesto for Water Stewardship (PCMWS) is an initiative of Católica-Lisbon School Centre for Responsible Business & Leadership (CRB) (Fig. 1, Fig. 2).

Fig. 1 – Portuguese Corporate Manifesto for Water Stewardship logo.

Fig. 2 – Promoting entity and founding member, Católica-Lisbon School (CRB).

The CRB aims to become a European reference in corporate sustainability knowledge through research, teaching and consulting, acting as an agent of change among students and executives, helping them to understand the impact of responsible business and its value creation in corporate strategies.

The CRB has been developing research to promote knowledge, tackling water management as a key value driver for sustainable growth (Pires de Almeida et al., 2021), with a robust analysis of how the corporate value-chain can be affected in water-stress situations.

Institutional setting

The PCMWS governance model is comprised of a Steering Committee that manages the Working Groups with external Advisory Board guidance (Fig. 3). Decisions are made based on a consensus between members.

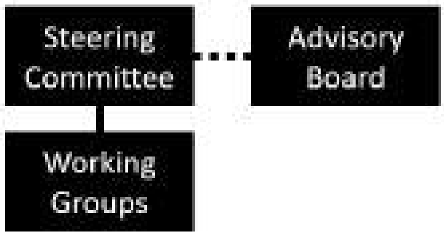


Fig. 3 – The PCMWS governance model.

The founding members and the associated businesses may join one or more working groups (awareness and reuse), reporting to the Steering Committee through a coordinator. The number of working groups may be expanded as necessary.

The composition of the Advisory Board is defined by the Steering Committee and may include representatives of other entities that share the interests and vision of different stakeholders (NGOs, research entities, government institutions and business associations). The Advisory Board acts as a consultant on potential good practices and actions to be implemented, thus collaborating in the fulfilment of joint commitments. Its members may also contribute to the promotion and communication of this initiative.

Each of the founding members is expected to financially contribute towards administrative expenses related to the launch and operation of the PCMWS. The financing of budgets depends on a unanimous decision of all the members of the Steering Committee and is expected to be based on the use of European and national structural funds to support the activities that will be conducted by the PCMWS.

The PCMWS was originally made up of fourteen founding organisations from different economic sectors, from food and beverage companies to textile industries (Tab. 1).

Since the signing of the agreement, more partners have joined, such as Bondalti – Evolving Chemistry, which is actively participating in the PCMWS's Reuse Working Group given its robust expertise in this area.

Tab. 1 – PCMWS founding members.

Organisation	Business activity
beta-I	IT
BGI – Building Global Innovators	Innovation hub
Calouste Gulbenkian Foundation	Private philanthropic institution
Católica-Lisbon School	Private University of business & economics
Esporão	Wine and olive oil production; tourism activities
Pestana Hotel Group	Tourism industry
Jerónimo Martins	Specialized retail & food distribution
L'Óreal	Beauty tech & consumer products
Microsoft	IT
Scubic	IT
Sugal Group	Food services and processing consortium
Super Bock Group	Beverage production
Tintex Textiles	Textile industries
Veolia	Water, energy and waste services

There is no specific legislative framework for implementing this agreement. However, its implementation seeks to follow the general lines of the national and European frameworks for water management and protection of water resources established in the Water Framework Directive and Portuguese decree 58/2005.

The main driver for development of the Manifesto is the European Green Deal, which aims to transform the EU into a modern, resource-efficient and competitive economy, ensuring zero net emissions of greenhouse gases by 2050 and economic growth decoupled from resource use. This includes the reduction of water pollution, increase of water reuse, and aiding industries in green and digital transitions to achieve increased competitiveness.

The Manifesto also states that it aims to integrate the UN Sustainable Development Goal 6 – "ensure availability and sustainable management of water and sanitation for all".

Geographical setting

Different regions need different approaches and, although Portugal is a small country, the situation in the southern region is very different from that in the north. Water management at the national scale requires supervising the origins, flows and uses of water, as well as the challenges of its storage and associated energy production. The main focus of the PCMWS is on sustainable water management and how it is used today. One of the biggest challenges for the public sector is the fact that today around 30% of treated water is lost in its distribution (ERSAR, 2021). This in itself represents an important opportunity for improvement and has been the basis for several projects. At the same time, the reuse of water from treated wastewater should be promoted as a way to meet the needs of some sectors, such as industry. In addition to the most obvious solutions, the desalination of seawater should also be part of the water sustainability plan, to address the issues of water scarcity, an increasingly common issue that will worsen in the coming decades.

Detailed explanation

The PCMWS is the main outcome of the Water Summit event that took place in July 2020, organised by the Católica-Lisbon School Centre for Responsible Business & Leadership.

This forum discussed the importance of water in the world and, in particular, for companies, with significant relevance for the Portuguese economy. The participating entities illustrated how the rapid changes that we are currently witnessing in terms of climate, supply networks, demography and the environment, are contributing to the rapidly growing dangers of water scarcity and subsequent economic impacts. The European Green Deal is the context in which to amass the mitigation measures necessary to cope with climate change and establish subsequent adaptation actions.

The Water Summit underlined the importance of an integrated water management perspective on which the decision-making of any company, sector or entity, whether at the local or national level, should focus. Although this represents a global challenge, the Water Summit participants recognised that Portugal must be prepared to adapt to the various climate change scenarios and believed that water management has increased in effectiveness, starting at the local level.

The PCMWS initiative aims, according to the Manifesto itself, to amplify the dissemination, intensify awareness and expand knowledge of good practices in the following key areas:

- Water as a valuable resource in the country's ecological transformation and its impact on health, economy and society.

- The need to adapt and accelerate mitigation measures in the context of climate change associated with the risk of scarcity and water pollution.

- The importance of water reuse in the sustainable development of industry and cities.

- Better practices for sustainable water management.

- Integration and cooperation strategies between the private sector, the public sector and relevant authorities – the vision of the European Green Deal.

Historical overview

The manifesto participants defined the following areas of action:

- Saving water, minimising losses and ensuring its efficient use.

- Promoting the circularity of water and its smart allocation, adapting its quality/source to its use.

- Promoting the proper treatment of wastewater throughout the production chain, taking into account the sustainability of the reuse of treated water as a measure to combat water scarcity. The reuse of treated water not only increases the amount of drinking water available but also has the double benefit for the environment of minimising the use of natural resources and significantly reducing the discharge of pollutants into the environment.

- Investing in wastewater infrastructure and adapting water infrastructure to the challenge of climate change.

- Investing in rainwater harvesting for compatible non-potable uses, to alleviate pressure on water resources by promoting a circular economy.

- Developing a long-term plan for seawater desalination.

- Investing in training and in innovation to cope with water challenges, enhancing recognition of the need to save and reuse water, particularly for large water consumers, which may include restrictions on the use of drinking water for activities that can be carried out with treated wastewater (watering green spaces, sanitary discharges, etc.).

- Raising awareness among the population, agriculture and industry on issues associated with water scarcity and on the implementation of more sustainable policies.

Evidence of benefits from implementation

The initiative is relatively recent, therefore it is not yet possible to clearly evaluate the PCMWS benefits. Benefits are expected from integrating into the participating members' value-chain innovative methods to maintain or increase competitiveness in different climate change scenarios by adapting water usage.

Replication potential in the SUDOE region

Due to the SUDOE region's exposure to climate change and water scarcity, initiatives like the PCMWS have a high potential for implementation. Stresses affecting natural resources are expected to compel the main sectors that rely on them to rethink management strategies to maintain or improve competitiveness in scenarios of extreme scarcity. The EU business environment may also provide the ideal framework for transnational companies to collaborate and exchange knowledge. IT and big tech may also facilitate similar agreements by providing technological support for participating companies.

Since one of the main objectives is to cope with water scarcity, such initiatives can be reproduced in other non-SUDOE regions which may already be facing the same problems.

In Portugal, the National Programme for Water Use Efficiency (Programa Nacional para o Uso Eficiente da Água – PNUEA) was established by the Portuguese Environmental Agency (APA) and shares similar objectives with the PCMWS, involving different levels of public institutions, who in turn define efficiency indicators for urban supply, agricultural and industrial stakeholders, to help establish efficient water use. The programme focuses on those economic sectors that are the main water users/consumers (APA, 2012).

This programme has as its main strategic objectives the reduction of losses in water supply systems in the urban sector and through irrigation systems in the agricultural sector, as well as optimising the use of water in the industrial sector and limiting the impacts on the environment associated with discharges from industrial wastewater (Fig. 4).

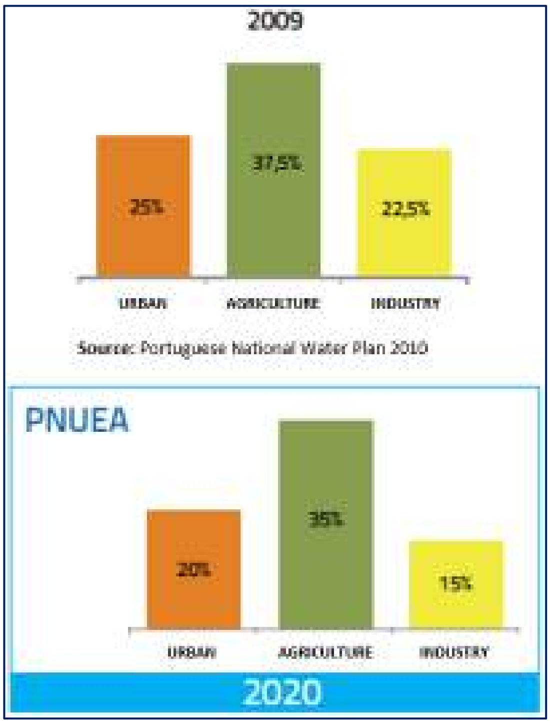


Fig. 4 – PNUEA goals. Adapted from APA (2012).

The draft programme was initially proposed in 2000, saw a parliamentary resolution approved in 2005 to lay the basis of the legal framework of action, and the final version was published in 2012 setting a period of eight years to achieve the main targets. It is expected to go through a revision and evaluation every two years.

Water use efficiency measures the extent to which water abstracted from nature is optimally used to efficiently produce the desired service (where efficiency measures the extent to which defined objectives are effectively met). The useful consumption corresponds to the minimum consumption necessary in a certain sector to guarantee the efficiency of use, corresponding to a specific reference for that use. The effective demand corresponds to the volume used, being naturally equal to or greater than the useful consumption. The closer the effective demand is to the useful consumption, the closer it is to 100% water use efficiency, a naturally desirable but unrealistic situation.

Another similar action to the PCMWS is the European Water Association (EWA) Water Manifesto 2020. This document draws attention to current challenges in European water management and makes proposals for sustainable solutions to meet these challenges, calling upon civil society and all relevant stakeholders to contribute to the implementation of such solutions and encouraging the dialogue between the decision-makers and the national and regional authorities. It is divided into four main branches: (1) nature-based solutions to respond to climate change, (2) financing water services investments, (3) asset management and digitalisation of water infrastructure, and (4) boost water demand management.

The EWA is a non-governmental, non-profit organisation that brings together corporate and research associations involved in the water cycle. The main aim is to exchange and transfer information and know-how across the European water landscape on a technical and scientific level, not only between the national member associations and with the corporate members but also for distribution of information from the EU to the members and from the members to the EU. The manifesto resulted in several publications and ongoing collaborations, both in the public and private sectors.

The Manifesto for Water, an initiative promoted by Aqua Publica Europea, aims to push EU decision-makers to commit to making water a priority by emphasising three main lines of action: (1) to guarantee safe, accessible and affordable water for all, (2) adopt a sustainable approach to protect finite resources and face climate change, and (3) to support efficient, forward-looking water management contributing to sustainable economies.

Under each line of action, the Manifesto for Water defines clear milestones such as the creation of a European observatory on water poverty, fostering improved access to water, the definition of strong environmental standards for natural water protection (e.g., from plastics and pharmaceutical contamination), and facilitating smart investment in water management that focuses on improving performance (based on the "water pays for water" concept).

Aqua Publica Europea, created in 2009, is the European Association of Public Water Operators, uniting publicly owned water and sanitation services and other stakeholders working to promote public water management at European and international levels. It is an operator-led association that looks for efficient solutions that serve the public rather than corporate interests. It represents over 60 institutions.

Several other similar manifestos and water stewardship manifestos were signed in other regions (the EU, UK and USA), including multi-level public and private entities researching water resources management.

Future outlook

The United Nations World Water Development Report (UNESCO, UN-Water, 2020) clearly states climate change is the main challenge to sustainability of water resources. Climate variability will decrease water sources and reliability of supply, which will be particularly severe in already water-stressed regions (such as is the case in southern Europe). It is therefore essential that adaptation and concrete action can be achieved by water-related climate change initiatives, which will also provide co-benefits such as job creation, improved public health, reduced poverty, the promotion of gender equality and enhanced livelihoods, among others, further strengthening their appeal from an economic viewpoint. Both private and public agreements, such as the PCMWS, with clear lines of action, can be the first step to tackle the scarcity problem, involving the main stakeholders around a set of shared responsibilities and making the necessary know-how and expertise available.

Key points of the innovative method

- The manifesto is comprised of private sector companies that acknowledge the importance of water management as a strategy to improve business competitiveness under climate change.

- Includes members from different economic sectors from textile to food and beverages production.

- Presence of IT companies may allow taking advantage of technology for successful implementation.

- Aims to amplify the dissemination, intensify awareness, and expand knowledge of good practices in water management.

- Actions rely on national and European funding programmes.

- Self-governance model open to new members.

- External Advisory Board composed of NGOs, research entities, government institutions and business associations. May provide new ideas and perspectives to decision-making within the Steering committee.

- Rely on EU, national funding programmes and member contributions to implement working group initiatives.

- Early-stage project implementation does not allow for evaluation of the success of the initiative at this time.

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