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How to control groundwater quality degradation in coastal zones using MAR optimized by GALDIT Vulnerability Assessment to Saltwater Intrusion and GABA-IFI models

João Paulo Lobo-Ferreira[1]

[1] Dr.-Ing. Habil., Board of Directors, Coordinator of the Research Partnerships Support Office, former Groundwater Division Head, at Laboratório Nacional de Engenharia Civil (LNEC), Av. do Brasil, 101, 1700-066, Lisbon, Portugal, lferreira@lnec.pt

Abstract. To counteract harmful, eventually with catastrophic consequences, today and future groundwater quality degradation due to saltwater intrusion into coastal aquifers, Managed Artificial Recharge (MAR) is considered the best solution, a sound, safe and sustainable solution. MAR, in coastal areas, depends on the availability of water including waste water appropriately treated. How to control saltwater intrusion in coastal zones implementing a MAR facility? The parameters required to answer that question, include the selection of the most appropriate technology and the best location for MAR. The appropriate location must have good infiltration rates; enough space to store underground the recharged water; guarantee that the travel time of the recharged water in the aquifer is long enough, compatible with the expected frequency of drought periods; economic efficiency maximization; availability of areas for MAR; and, positive impacts on the society. GABA-IFI model addresses those parameters allowing the selection of the most appropriate area for the location of MAR. Complementary, mathematical models are available to quantify MAR water injection rates required to recover groundwater depleted levels. Where should the injection be located? GALDIT is probably, today, the most used model worldwide to assess the vulnerability of saltwater intrusion in costal aquifers by a numerical calculation.

Keywords: Coastal zones, salt water intrusion, mathematical models, GALDIT, GABA-IFI.

1 Introduction

The roles that Managed Artificial Recharge (MAR) may play today, worldwide, within the framework of Integrated Water Resources Management are: short and long term storage for later recovery during dry seasons, recovery of groundwater level of over-exploited aquifers, provision of barriers to seawater intrusion in coastal areas, improvement of water quality, use of the aquifer as a water distribution system for individual users, and flood-prevention by deviating peak-flows. In Portugal, the recent water supply crises caused by recent droughts, within the southern Algarve region, show the necessity to implement new measures for improved water resources management. The surface water reservoirs in the northern mountain areas of the Algarve suffer from significant water losses due to high evaporation rates and are not able to cover the water demand under drought conditions. During the rainy season huge spillway losses have been observed from these reservoirs. In wet years more than 50hm^3. The river water flows to the sea. In drought years a similar value of 50hm^3 is over pumped from the aquifer causing sea water intrusion. MARSOL FP7 INNO-DEMO project Policy Brief clearly summarizes the Legal Framework of MAR (Schüth et al. (2019) available in http://www.dina-mar.es/file.axd?file=2017/8/MARSOL+Policy+Brief_final.pdf): The Water Framework Directive (2000/60/EC) considers 'artificial recharge' of groundwater as one of the water management tools that can be used by EU Member States to achieve a good groundwater status. It has to be ensured, however, that the necessary regulatory controls are in place to warrant that such practices do not compromise quality objectives established for the recharged or augmented groundwater body. It is also acknowledged by the Groundwater Directive (2006/118/EC) that it is not technically feasible to prevent all input of hazardous substances into groundwater, in particular minor amounts which are considered to be environmentally insignificant and thus do not present a risk to groundwater quality. For such cases the Groundwater Directive, under Article 6(3)(d), introduces a series of exemptions. Managed Artificial Recharge is considered as one of these exemptions. MARSOL suggests a Regulatory Framework based on risk assessment, control mechanisms and monitoring as a tool which can facilitate the application of the Water Framework and Groundwater Directives on MAR. It is the intention of such a regulatory framework to provide clear guidelines to Member States on the application of MAR techniques.

2 Materials, methods and results

2.1 Groundwater recharge assessment under climate change conditions

The increase in extreme precipitation phenomena, even at the same annual volumes, can cause a decrease in groundwater recharge because soil infiltration capacity is exceeded more frequently, favoring runoff rather than recharge. The work carried out at LNEC on groundwater recharge (e.g. Lobo-Ferreira et al., 2012), demonstrates the influence of precipitation distribution series on groundwater recharge and the need to use daily sequential balance models (e.g. BALSEQ model, Lobo-Ferreira, 1981) that take into account daily precipitation and evapotranspiration, as well as the area occupied by vegetation and its characteristics. The same authors conclude that, for selected analyzed scenarios, a reduction of the precipitation value down to 70% of the annual average value corresponds to annual recharge down to just 45% of the annual average.

Climatic conditions, such as rainfall, temperature and atmospheric humidity, affects the volumes of water that are spent by the vegetation cover in evapotranspiration and those that are transferred to the recharge of the aquifers. Under climate change conditions these climatic parameters are modified, having direct impacts on evapotranspiration and recharge. There is also an associated impact, which is due to the modification of the vegetation cover, which will affect the volumes of evapotranspiration, surface runoff, soil water content and, consequently, recharge.

According to studies by Lobo-Ferreira et al. (2012), using BALSEQ model, we expect that the average recharge of the Torres Vedras aquifer system, in Central Portugal, will be between 84% and 98% of the recharge of the period 1979-2009, depending on the series of precipitation, temperatures, and reference evapotranspiration used. For the 2080 horizon, depending on the climatic series used, the average recharge will be 60% to 82% of the recharge of the period 1979-2009. It is impressive the expected potential reduction of aquifer recharge that can be observed in Fig. 1 (green, yellow and orange areas correspond to losses greater than 50% in annual groundwater recharge).

2.2 GALDIT method

The original development of GALDIT index was done in the framework of the EU-India INCO-DEV COASTIN project, proposed by Chachadi and Lobo-Ferreira (2007), aiming the assessment of aquifer vulnerability to sea-water intrusion in coastal aquifers.

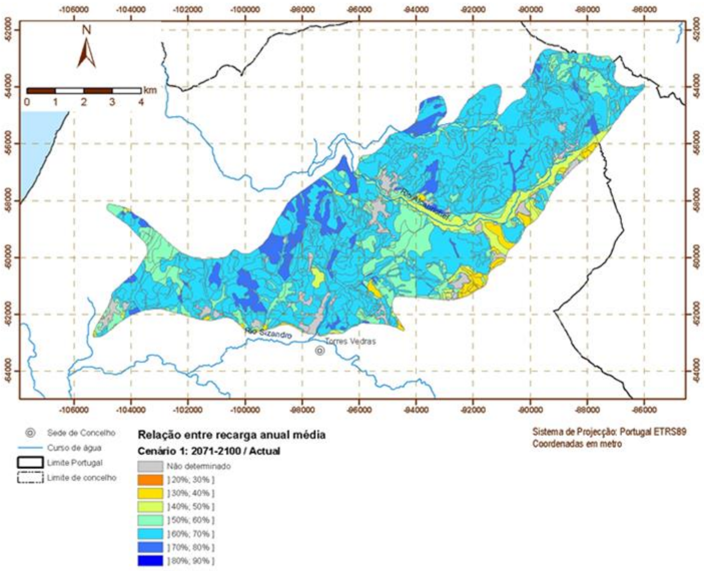

Fig. 1 - Relation between the current average and the expected annual recharge for Scenario 1 in 2071-2100 of the aquifer system of Torres Vedras, Central Portugal

The most important factors controlling seawater intrusion were found to be the following: ***G***roundwater occurrence (aquifer type; unconfined, confined and leaky confined); ***A***quifer hydraulic conductivity; Depth to groundwater ***L***evel above the sea; ***D***istance from the shore (distance inland perpendicular from shoreline); ***I***mpact of existing status of sea water intrusion in the area; and ***T***hickness of the aquifer, which is being mapped. The acronym GALDIT is formed from the highlighted letters of the parameters for ease of reference.

In Fig. 2 a comparison between GALDIT scores for normal and raised sea levels in North Goa coast (left figure for normal sea level and right figure for raised sea level) is presented. One can easily see which areas will be more affected by see level rise.

2.3 Managed Aquifer Recharge Response Strategy

Managed Aquifer Recharge (MAR) permits the managed conjunctive use of surface- and ground-water resources and, therefore, is an important component of Integrated Water Resources Management (IWRM). Decision support for MAR planning in the context of integrated water resources management, the implementation of a MAR system requires careful planning in terms of achieving efficient integration into the water resources system and the overall water resources management objectives.
Environmental and socio-economic impacts of MAR planning options have been investigated in this context. The new H2020 MARSoluT project, i.e. a follow-up of FP7 INNO-DEMO MARSOL project addresses MAR research via 12 PhD theses, one of them under development in LNEC on MAR GW quality in a large physical model.

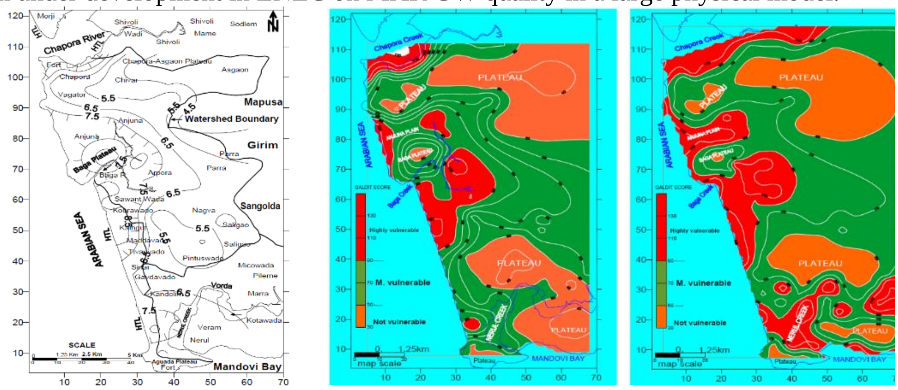

Fig. 2- Comparison between GALDIT scores for normal and raised sea levels in North Goa coast (left and center figures for normal sea level and right figure for raised sea level; high vulnerable areas in red)

Water availability during the dry period is nowadays the main constraint for the development of the Algarve region. Further exploitation of the already over-exploited Querença-Silves aquifer system is no sustainable response strategy to the water supply problem. The enormous losses of surface water resources in connection with over-exploitation of the local aquifer systems indicate the necessity of the conjunctive management of surface water and groundwater resources in order to guarantee water supply during droughts, to mitigate their impacts and provide conditions for sustainable development of the Querença-Silves region.

Therefore, MAR is a potential response measure to the prevailing water management problems of the region, transferring surface water of the nearby Arade Dam to the upper part of the study area (cf. Fig. 3) and recharging this water to the Querença-Silves aquifer. The proposed water management response strategy uses the aquifer as a water transfer and storage system. The high residence times of the infiltrated water in the aquifer system would guarantee long-term storage of the recharged water in the underground with water recovery by wells in the lower part of the aquifer system located at strategic places, e.g. Vale da Vila near Alcantarinha. The application of infiltration techniques would permit the recharge of large volumes of water during the time of surface water surplus. EC sponsored GABARDINE and MARSOL projects and PT FCT sponsored PROWATERMAN projects (Lobo-Ferreira et al. 2011) studied the viability to implement infiltration ponds in the upper parts of the aquifer system by studying the suitability of areas for MAR implementation. The water recovery by pumping well groups in the lower aquifer system requires further groundwater modeling efforts besides those presented in MARSOL White Book on MAR Modelling (Lobo-Ferreira et al. (2017), available in https://www.researchgate.net).

2.4 GABA-IFI index for optimizing MAR facilities location

For the choice of sites favorable to the recharge GABA-IFI index was developed in FP6 EU GABARDINE Project (Oliveira et al. 2008) allowing the computation of the areas with more favorable natural conditions for MAR (in particular good recharge; good space for underground storage, and high residence time of the water in the aquifer system). The parameters considered relevant for the assessment of GABA-IFI index are the distance to the point of discharge of groundwater, the depth to groundwater level, the vertical transport time and the horizontal hydraulic conductivity. Fig. 3 shows the application of this index to the aquifer system of Querença-Silves aquifer in the Algarve (yellow less suitable; blue optimal place for MAR).

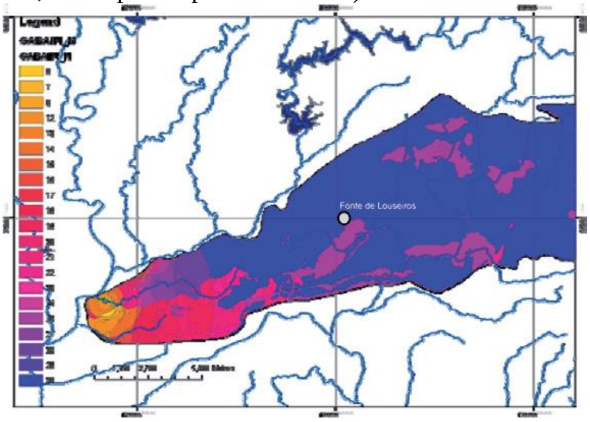

Fig. 3 - GABA-IFI_N index representing more favorable locations to the installation of MAR

3 Concluding Remarks

The growing imbalance between water supply and water demand in many coastal areas around the World, exacerbated by climate change, population growth, agriculture needs and urbanization, requires more efficient water resources management. Storing water in aquifers during times of excess or with treated waste water can help address water scarcity challenges. Managed Aquifer Recharge (MAR) and Aquifer Storage and Recovery (ASR) can be a key to solving water crisis by linking water reclamation, water reuse and water resources management. MARSOL Policy Brief (Schüth et al., 2019) mentions that MARSOL operated eight demonstration sites in six countries around the Mediterranean (Portugal, Spain, Italy, Greece, Malta, Israel) applying various technologies, i.e. infiltration ponds, river bed infiltration, direct injection wells, canals, river bank filtration, to infiltrate various water sources, i.e. river water, surface runoff, treated waste water, desalinated seawater. Now is the time to move on applying MAR, in a scientific based way, to cope with expected dramatic climate change consequences, including those in ecosystems dependent from groundwater and sea water intrusion in coastal aquifers caused by sea level rise. This approach fulfil the hydrogeoethical approach as "….MAR is a sound, safe and sustainable strategy that can be applied with great confidence", confirming uncertainty reduction in MAR modelling in eight MARSOL demo sites, improving the Campina de Faro, Algarve, groundwater quality.

Acknowledgements

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