12th International Hydrogeological Conference

Groundwater resources in an ever -changing environment

12° Διεθνές Υδρογεωλογικό Συνέδριο

Το υπόγειο νερό σε μεταβαλλόμενο περιβάλλον

NICOSIA 2022 / ΛΕΥΚΩΣΙΑ 2022

CONFERENCE PROCEEDINGS
ΠΡΑΚΤΙΚΑ ΣΥΝΕΔΡΙΟΥ

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AN OVERVIEW OF MANAGED AQUIFER RECHARGE APPLICATIONS USING SIMULATION MODELS

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Key words: MAR, MODFLOW, simulation analysis, floods, groundwater depletion

Abstract
In arid and semi-arid regions, the groundwater resources consist of the main water supply to cover agricultural, industrial, and domestic water needs. Climate change is a main driving force that affects the hydrological cycle and leads to natural hazards such as drought and floods. Thus, managed aquifer recharge (MAR) techniques are increasingly applied to solve current and future water shortage and flood problems, as they provide integrated management solutions. Nevertheless, to evaluate the hydrogeological conditions of a basin and the impact of hazards on groundwater, the use of numerical models is essential. For this purpose, numerical models such as MODFLOW are widely used. This study provides a synoptic overview of the most recent existing studies from 2015 to 2021 of modeling approaches with MODFLOW code and MAR framework.

1 Introduction

A wide variety of reasons come across for the application of managed aquifer recharge (MAR) techniques worldwide. Indeed, climate change and the increase in water requirements in order to cover water needs indicate the importance of implementing methods to maximize water storage and manage water quality (Dillon 2005). This promising method is a crucial solution for mitigating water scarcity in arid and semi-arid regions. MAR applications involve integrated management to protect or recover surface and groundwater sources (Dillon *et al.* 2018). The application of these methods is considered necessary in areas where the natural recharge of the aquifer is not feasible, or the infiltration recovery is slow and incomplete (Daher *et al.* 2011). MAR is a complex and high-cost option, so groundwater simulation models can assess conditions before in situ application (Pliakas *et al.* 2005).
Technical management approaches with integrated strategies help alleviate multiple threats to the quality and quality conditions of aquifers (Dillon 2005). Nevertheless, it is crucial to understand which is the best MAR application according to the characteristics prevailing in each area (Aeschbach-Hertig and Gleeson 2012). Thus, methods such as numerical models are widely used to investigate the hydrogeological conditions in a basin. Water quality and quantity challenges can be approached from a developed through the knowledge that the researchers gain from previous practices (Cosgrove and Loucks 2015).
Obviously, the choice of the best modeling approach depends on the hydrogeological system conditions and the available data for processing (Zhang *et al.* 2020). MODFLOW is one of the most widely applied numerical models and is thoroughly tested. Thus, in the current literature research, a synoptic overview of the most recent existing studies from 2015 to 2021 of modeling approaches with MODFLOW code for surface water (SW) groundwater (GW) interaction giving focus on MAR is provided (Figure 1).

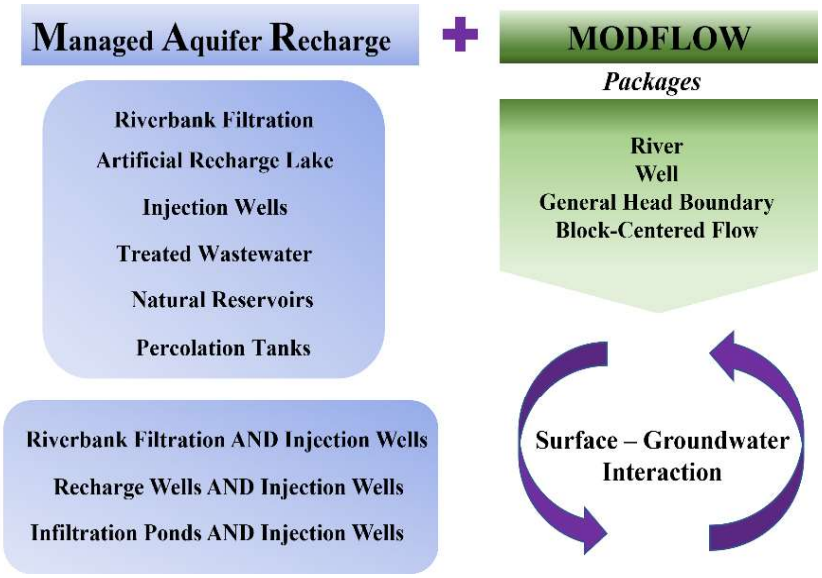

Figure 1. Summary of the research processes of MAR application with the MODFLOW model.

2 Literature overview

The implementation of MAR provides an important solution for the improvement of water quality and quantity conditions worldwide. Different kinds of MAR structures have been applied worldwide depending on water quality, geology, hydrogeology, morphology, soil texture, water demands, and local financial resources (Bouwer 2002). Moreover, the simulation models can be used for the optimization of system design and operation as well as for economic analyses. Optimal model selection requires consideration of water demand, system inputs and outputs, and the future availability of SW and GW infrastructures. Additionally, a combination of decision-making and simulation models such as MODFLOW and clustering techniques can improve the determination technique for the selection of the best location for the MAR application (Javadi *et al.* 2021).

2.1 Riverbank filtration (RBF)

Riverbank filtration (RBF) describes a natural process where SW infiltration is induced through nearby GW extraction (Umar *et al.* 2017). Wang *et al.* (2015) used the MODFLOW model and its River package to investigate the stream aquifer interaction under forced filtration and steady-state flow assumptions at the riverbank filtration site near the Kuybyshev Reservoir, Russia. The Reservoir was formed by damming the flow of the middle Volga River. The authors tried to design and optimize a monitoring network to determine the key hydraulic parameters at riverbank well fields. Henzler *et al.* (2016) investigated the protection of bank filtration (BF) from micropollutants in Berlin, Germany. The MODFLOW and MT3DMS codes were applied to analyze flow and heat transport to understand the redox conditions which can cause implications to BF quality. The same methodology is also applied by Hamann *et al.* (2016) in the Rhine River in the Netherlands. The authors evaluated the organic micropollutants during the RBF technique by applying multiple compounds at a temporal scale of several years from 1999 to 2013. In the next years, Rossetto *et al.* (2020) applied a multidisciplinary approach entailing hydrodynamics, hydrochemical, and numerical modeling methods to investigate the interaction of Serchio River (Lucca, Italy) with sandy-gravelly aquifer due to the building of the RBF infrastructures along the river. The authors used FREEWAT software based on MODFLOW-2005 code following different scenarios of weirs in operation and aquifer exploitation values to enrich the GW recharge.

2.2 Artificial Recharge Lake (ARL)

Joodavi *et al.* (2020) applied FREEWAT software based on MODFLOW-2005 code to investigate the interaction of an ARL with the alluvial aquifer in Razavi Khorasan province in Iran. In this research, the reservoir infrastructures with relevant leakage losses to the aquifer and flood flows were investigated to exploit the water banking capacity in the aquifer as a managed aquifer recharge scheme. The results reveal that the aquifer, under MAR operations, may get reliable amounts of water supply.

2.3 Recharge wells/ Injection wells

The method of recharge wells provides support for water supply to meet demand growth using rainwater or recycled water. De Filippis *et al.* (2019) focused on the protection of deep karst coastal aquifer in Salento Peninsula, Italy. The authors estimate the improvement of the quantitative status of GW with the application of injection wells under the simulation of GW dynamics with the MODFLOW-2005 model and its i) Recharge, ii) Well, and iii) General Head Boundary (GHB) packages. Finally, this work demonstrates that simple and inexpensive tools may be applied to create a methodology to be aware of the hydrogeological conditions in an area.

2.4 Treated wastewater (TWW)

El-Rawy *et al.* (2016) applied management scenarios in the Zarqa River Basin (Jordan) using the MODFLOW-2005 model and treated wastewater technique at poorly karstified limestone aquifer for copulative use of SW and GW during drought periods. In the same year, Eshtawi *et al.* (2016) linked SWAT, MODFLOW-2005 and MT3DMS models to investigate the quality (NO_3 and Cl transport simulation) and quantity of SW-GW interactions in the urban and coastal area of the Gaza Strip, Palestine. The research is divided into i) desalination, ii) stormwater harvesting and iii) treated wastewater (TWW) reuse forecast scenarios. The results revealed that the use of combined infiltration basins for TWW and harvested stormwater from drainage basins in the study area could achieve higher qualitative and quantitative improvement of water.

2.5 Riverbank filtration and Injection wells

Glass *et al.* (2018) investigated the suitability of MAR applications for the protection of GW systems in Red River, Vietnam. Three scenarios with i) riverbank filtration, ii) injection wells, and iii) a combination of them were applied considering the water dynamics of the unconfined and confined aquifer of the study area using MODFLOW-NWT model. The simulation results revealed a small contribution of MAR operations to the overall water flow and storage in the study area. The current research is based on a few input simulation data thus, the authors suggest detailed hydrogeological analysis and field monitoring before MAR application to handle future rising water demands.

2.6 Natural reservoirs

Salem *et al.* (2020) evaluated the feasibility of the natural reservoir based on water resources of the floodplain through surface water storage in the Drava River floodplain, Hungary-Croatia border. The authors applied Wetspass-M and MODFLOW-NWT model and tried to analyze the restoration of natural reservoirs (abandoned paleochannels) as an economically feasible MAR technique to mitigate water shortage problems caused by drought and high water demands for tourism and irrigation needs.

2.7 Percolation tanks

Nicolas *et al.* (2019) focused on MAR in fractured crystalline rock aquifers in South India. The hydraulic conditions of saprolite upper formation and fractured granite were investigated to overcome water scarcity issues. The authors applied MODFLOW and its Block-Centered Flow (BCF2) package to examine the efficiency of the percolation basin technique. The results

showed high permeability of the saprolite/bedrock interface and high values of recharge. Moreover, the variable depth of the current interface affects the water level variations.

2.8 Infiltration ponds and Injection wells

Ronayne *et al.* (2017) applied MODFLOW code to evaluate MAR operation in order to increase the flow of the South Platte River, Colorado (USA). The main cause of this project was the protection of species under threat of extinction. The authors investigate the impact of infiltration ponds and injection wells during the wet and dry periods to solve the problem of low flow in the alluvial river. The results reveal that the recharge ponds improve the aquifer's hydraulic heads throughout the year while the augmentation of streamflow was greatest in April and May rendering the project ineffective. Thus, the duration of MAR application and analysis framework must be related to the climatic and hydrogeological characteristics of the area. Zhang *et al.* (2019) performed different combinations of infiltration ponds and injection wells scenarios in a region of West Coast, South Africa. The MODFLOW and MODPATH codes were used to evaluate the MAR techniques. The results showed that pond or basin infiltration can be used as an appropriate MAR method. However, the authors highlight the importance of a thorough analysis of the study area including water chemistry and clogging to be carried out before implementing MAR.

3 Discussion

MAR techniques are increasingly considered to solve current and future water shortage and flood problems, as they provide integrated management solutions (Ward *et al.* 2020). On the other hand, there is a need for holistic model systems integrating surface and groundwater systems in order to enhance the option of the optimal performance of intricate MAR techniques such as in-channel modifications. Thus, research techniques such as a combination of models (ex., SWAT-MODFLOW) and/or application of other frameworks, for instance, DPSIR model of intervention can provide thorough information about the basin under investigation and minimize the doubts.

In addition, climatic conditions have an important role in determining the dimensions and type of structures that need to be implemented. Indeed, the number of rainy days, mean annual rainfall as well variability of air temperature consists key factors for the optimal choice of MAR. According to the results of the current overview, the researchers use a combination of packages in MODFLOW to examine the interaction of water bodies in a basin. Nevertheless, the hydrological characteristics of a basin are affected by internal factors, for instance, anthropogenic activities (land use), vegetation cover and terrain characteristics. Thus, a high-frequency monitoring of the variability of internal and external factors can provide more reliable predictions of future simulations.

4 Conclusion

This study aims to provide a brief overview of MODFLOW simulation code in combination with applications of managed aquifer recharge (MAR) in the existing literature of the last years from 2015-2021 in order to achieve maximum performance of MAR analysis. The current work highlights the applications and analysis of MAR techniques according to the latest challenges. According to the afford mentioned, riverbank filtration and infiltration ponds and injection wells are the most applied MAR methods during this period.

5 Acknowledgment

This research project was supported financially by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "Second Call for H.F.R.I. Research Projects to support Post-

Doctoral Researchers" (Project Number: 00138, Title: Groundwater Depletion. Are Eco-friendly Energy Recharge Dams a Solution?).

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