Groundwater Replenishment through Aquifer Recharge with Treated Wastewater: Enhancing Water Security in Arid and Semi-Arid Regions

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EGU26 GENERAL ASSEMBLY

EGU26-12097

1. Abstract

Groundwater resources worldwide are under increasing stress, particularly in arid and semi-arid regions. Urbanization, intensive agriculture, and industrial development place heavy pressure on the fossil groundwater, resulting in depletion of major aquifers worldwide, with more severe consequences in arid regions such as Saudi Arabia. This study aims to evaluate the feasibility of Treated Wastewater (TWW) for sustainable managed aquifer recharge (MAR) in the eastern coastal region of Saudi Arabia using an experimental approach. Twelve 1D MAR experiments were conducted to assess the efficiencies of various TWW effluents for groundwater replenishment in the coastal sandy aquifer in the eastern region of Saudi Arabia. Three recharge scenarios (low, medium, and high) and two types of TWW (tertiary and secondary) were evaluated to optimize the MAR system. Clogging materials and water quality change were evaluated to determine the optimal recharge scenario. The results showed that the tertiary TWW with low recharge scenarios was the optimal case with minimal impact on groundwater quality and aquifer integrity. In contrast, the high recharge scenarios with either tertiary or secondary TWW showed a significant reduction in the hydraulic performance of aquifer materials, thus, the efficiency of the recharge system. The study found that the tertiary TWW from the eastern region of Saudi Arabia is suitable for aquifer recharge with minimal pretreatment to remove nutrients, ions, and emerging contaminants (e.g., microplastics). The study findings provide insights into effective water resource management strategies that reduce water scarcity risks and strengthen long-term water security in arid environments. Moreover, the study demonstrated that implementing MAR with TWW can reduce non-renewable groundwater withdrawals by up to 30% in eastern Saudi Arabia, mitigating aquifer depletion and ensuring a more sustainable water supply.

2. Objectives

- Evaluate the impact of TWW on aquifer hydraulic properties using laboratory column experiments.
- Determine optimal TWW recharge rates for sustainable MAR in Saudi Arabian sandy aquifer while preserving of aquifer hydraulic integrity.
- Identify the optimal TWW quality for MAR to minimize adverse impacts on groundwater quality and ensure long-term aquifer sustainability.

3. Material and methods

- Integrated field-scale and laboratory-based investigations.
- Systematic MAR experiments using a multidimensional framework.
- Long-term simulation of MAR performance
- Real-time monitoring of recharge dynamics using electrical resistivity tomography (ERT).

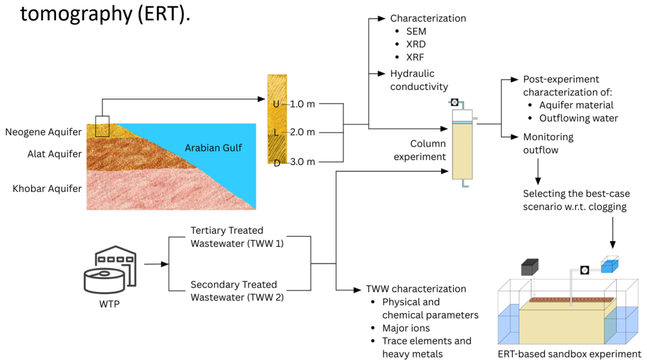

Fig. 1: Flowchart showing the integrated methodological framework applied in this study

4. Results and discussion

- GW accounts for **~ 30%** of the urban use & **> 80%** of agriculture. GW withdrawals for irrigation in the Eastern Province in 2023 were around **796.7 million m³.**
- Average GW storage depletion rate ≈ **−1.03 cm/year.**

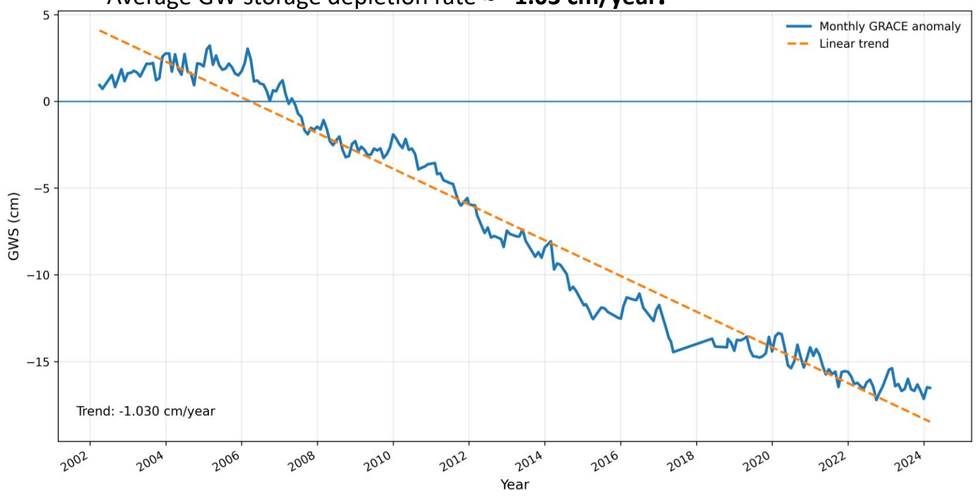

Fig. 2: GRACE-derived Groundwater storage change in heavy extracted region of Saudi Arabia for 2002-2024.

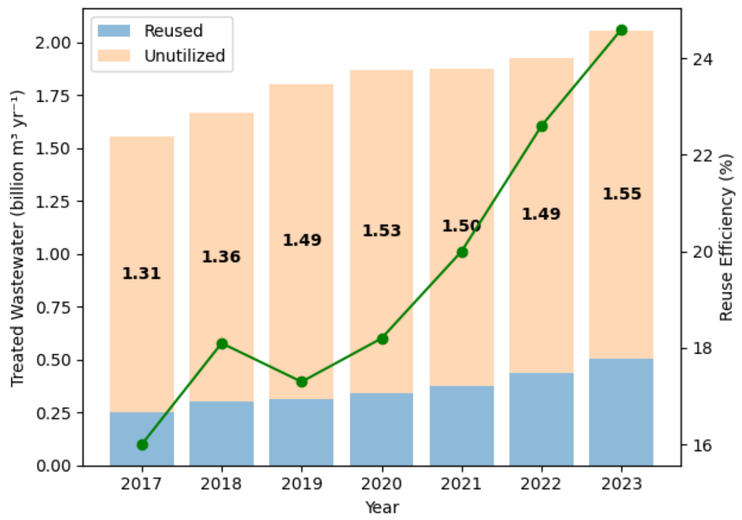

Fig. 3: Treated municipality wastewater production and reuse in Saudi Arabia for 2017-2023.

- The average annual surplus of TWW during 2023–2024 was approximately **1.6 billion m³.**

~13% ⇩ Water stress

~30% ⇩ in fossil GW withdrawals in EP

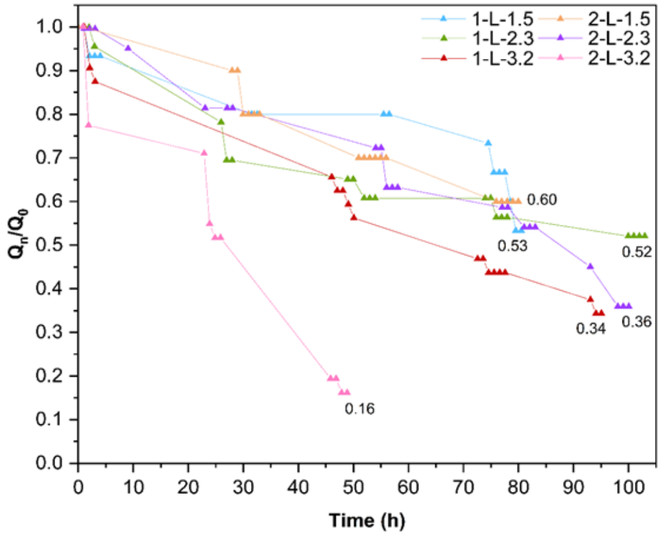

Fig. 4: Plot showing the decline in normalized outflow (Qn/Q0) during six MAR experiments using various pumping rate and wastewater effluents.

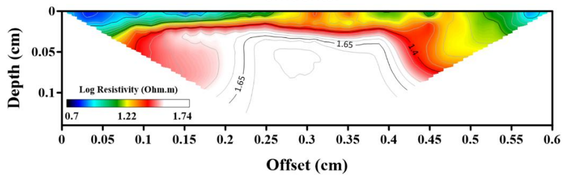

Fig. 5: ERT image showing recharge water movement during 3D MAR operation.

5. Conclusions

- High quality TWW can be used for aquifer recharge with limited impact on the aquifer integrity and groundwater quality.
- The maximum recharge efficiency achieved with high quality TWW under low recharge scenarios with limited clogging issue.
- TWW can be a sustainable source for aquifer recharge in Saudi Arabia and replenish groundwater by more than 1 billion m³/year.
- Reusing TWW for aquifer recharge has potential to reduce the pressure on the non-renewable groundwater system by 30% in the eastern coastal region of the country.
- The study concluded that the TWW should be considered as national water asset for restoring aquifer system and reducing stress on the freshwater resources.

References

- Benaafi, M., Pradipta, A., Tawabini, B., Al-Areeq, A. M., Bafaqeer, A., Humphrey, J. D., ... & Aljundi, I. H. (2024). Suitability of treated wastewater for irrigation and its impact on groundwater resources in arid coastal regions: Insights for water resources sustainability. Heliyon, 10(8).
- Alhajri, M.F., Jamil, R., Abdalla, E.M.E. et al. Status of wastewater treatment and reuse in Saudi Arabia and its forecasting for the year 2035. Appl Water Sci 15, 167 (2025). https://doi.org/10.1007/s13201-025-02484-4
- Ministry of Environment, W. and A. (2017-2023). Statistical Yearbook. Saudi Arabia.

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Acknowledgments

This study was supported by King Fahd University of Petroleum and Minerals(KFUPM). This research was funded by Interdisciplinary Research Center for Membranes and Water Security (KFUPM) [Grant no. INMW2614].

Scholarly Profile