The Impact of Injection/Pumping Wells on the Pollution Transport in Groundwater

Walid Mohamed Abdel-Samad Khalifa
Civil Engineering Department, Faculty of Engineering, Ha'il University, Saudi Arabia | Civil Engineering Department, Faculty of Engineering, Fayoum University, Egypt
w.khalifa@uoh.edu.sa (corresponding author)

Belkacem Achour
Civil Engineering Department, Faculty of Engineering, Ha'il University, Saudi Arabia
b.achour@uoh.edu.sa

Tayyab Butt
Civil Engineering Department, Faculty of Engineering, Ha'il University, Saudi Arabia
ta.butt@uoh.edu.sa

Cirrus Mirza
Civil Engineering Department, Faculty of Engineering, Ha'il University, Saudi Arabia
cy.Mirza@uoh.edu.sa

Heba Salah
Khatib & Alami, Egypt
hipamh@gmail.com

Sherif El-Didy
Department of Irrigation and Hydraulics, Faculty of Engineering, Cairo University, Egypt
smadidy@hotmail.com

Received: 30 September 2023 | Revised: 13 October 2023and 5 November 2023 | Accepted: 7 November 2023

 DOI: https://doi.org/10.48084/etasr.6458

ABSTRACT

The natural quality of groundwater tends to be degraded by industry, agriculture, and wastewaters. There are several alternatives to prevent migration and the spread of pollution in groundwater. Some alternatives are physical such as grouting, or slurry walls. Others could be hydrodynamic containment by injection or pumping wells. Injection wells are used to confine a pollutant in place or dilute its concentration by injecting clean water into the aquifer. Pumping wells are used to discharge the pollutant out of the groundwater reservoir or act as interceptors. In this research, the hydraulic characteristics and behavior of the hydrodynamic methods are investigated by using numerical simulation. In this investigation, the numerical model MT3D has been integrally used with the flow model MODFLOW. Injection/pumping rate, screen length and layer, and the number of wells are considered. The results have shown that increasing the rate or the number of the injection/pumping wells permits less pollution spread. Changing the screen length of the injection/pumping wells are not effective in preventing the pollution spread in the long-term. Changing the number of wells has more effect on a containment spread. Injection wells can prevent the spread of contaminants more than pumping wells.

Keywords-groundwater; pollution transport; injection wells; pumping wells; MT3D model; MODFLOW model

I. INTRODUCTION

Groundwater supply is considered a vital aspect of human wellbeing. Groundwater provides the population with water for drinking and irrigation. The sustainability of groundwater quality and management is highly challenged in this regard [1-16]. Hydrodynamic control for containing contaminants in place by injection wells or removing them from the ground by discharge wells are considered effective methods to prevent contamination spread in a hydrogeological system [17-24]. With pumping, there is always the problem of what to do with the contaminated water removed from the ground. On site treatment is required before injecting the water to the subsurface or releasing it to surface water bodies [25-26]. Injection wells could be used to dilute the groundwater pollution by the injection of clean water or as interceptors for diverting the flow direction. The number of injection or withdrawal wells and the pumping/injection rates can be minimized through the proper choice of well location and distance between wells [27-28]. This could be achieved through good understanding of the problem and implementing successful design for the controlling system in each specific site. In this paper, investigation of injection and pumping wells is performed and discussed. The numerical models MT3D and MOFDLOW are employed. Change of injection/pumping rate, depth and position of the screen, and distribution of wells around the pollution source are considered.

II. MODEL DESCRIPTION

The study is implemented by using the transport model (MT3D) through the flow model (MODFLOW). MT3D is a computer model for the two or three dimensional simulation of advection, dispersion, and chemical reactions of contaminants in groundwater flow systems [29]. A mixed Eulerian-Lagrangian approach is used by the MT3D model to solve the advective-dispersive-reactive equation. This can be done depending on the supposition that concentration changes cannot influence the flow field significantly [30]. The model uses a modular structure like that implemented in the U.S. Geological Survey (USGS) modular three-dimensional finite-difference groundwater flow model, referred to as MODFLOW [31-33]. MT3D retrieves the hydraulic heads and the various flow and sink/source terms saved by MODFLOW, combining the hydraulic boundary conditions [34-35]. The structure of MT3D can readily simulate the terms of advection, dispersion, and source or sink mixing of chemical reactions. Further, MT3D can simulate the concentration changes for one kind of contaminant considering the hydrological and chemical reactions with different kinds of boundary conditions and extrinsic sources or sinks. The MT3D model includes the chemical reactions. These reactions are controlled linearly or nonlinearly of sorption and first-order biodegradation [36]. MT3D fits the spatial discretization and boundary conditions as: (1) confined/unconfined aquifer layers, (2) sloped model layers and cell thickness within the same layer, (3) one kind of mass concentration or flow of mass through boundaries, and (4) the effects of solute transport of extrinsic sources or sinks like springs, wells, ditches, rivers, recharge, and evapotranspiration. The MT3D model, like the MODFLOW, consists of a main program and subroutines, called modules, which are grouped into a series of "packages".

The hydraulic heads and fluxes at each time step are solved by the MODFLOW model and used by MT3D model. Prior to entering the stress period loop, the program executes three procedures. First, the simulation problem is defined by identifying the model size and the number of stress periods, and specifying the various transport options to be used in the simulation. Computer memory is allocated for the data arrays whose dimensions depend on the parameters specified in the Define procedure. A second step is reading and preparing the input data which are constant within the current stress period. The transport model obtains the location, type, and flow rates of all sources and sinks simulated in the flow model. Then, a third procedure reads and processes the hydraulic heads and flow terms saved by the flow model, and the specified hydrologic boundary conditions. The transport step loop contains four procedures. The Advance procedure determines an appropriate step size for use in the current transport step. The Solve procedure solves each transport component with an explicit mixed Eulerian-Lagrangian solution scheme and calculates the mass into or out of the aquifer through each component. The Budget procedure estimates the global mass balance information and gets the printouts and saved simulation results as needed according to the control options of the user-specified output. The equation of solute transport in a porous medium is a partial differential one [37-40]:

$$\frac{\partial}{\partial X_i}(D_{ij}\frac{\partial C}{\partial X_i} - \frac{\partial}{\partial X_i}(CV_i) + \frac{q_s}{n}(C - C_s) + \sum_{k=1}^{N} R_K = \frac{\partial C}{\partial t} \quad (1)$$

$$V_i = -\frac{K_{ij}}{n}\frac{\partial h}{\partial X_i} \quad (2)$$

where i, j are the Cartesian coordinate directions, $C = C\,(x, y, t)$ is the pollutant concentration [M.L^{-3}], $V_i = V_i\,(x, y, t)$ is the seepage or average pore water velocity in the X_i [L.T^{-1}] direction, $D_{ij} = D_{ij}\,(x, y, t)$ is the dispersion coefficient tensor [L^2.T^{-1}], $n = n\left(\frac{x}{y}\right)$ is the effective porosity, $K_{ij} = K_{ij}\left(\frac{X}{Y}\right)$ is the hydraulic conductivity tensor [L.T^{-1}], q_s is the volumetric flux per unit volume representing sources (positive) and sinks (negatives) [T^{-1}], C_s is the concentration of the sources/sinks [M.L^{-3}], X_i represents the Cartesian coordinates, t is the time [T], and $\sum_{k=1}^{N} R_K$ is the adsorption and decay by chemical reaction terms [M.L^{-3}.T^{-1}]. The components of the tensor D_{ij} in a system of three-dimensional Cartesian coordinates are obtained through the transformation of coordinates formula:

$$D_{xx} = \alpha_L \frac{V_y^2}{|V|} + \alpha_T \frac{V_x^2}{|V|} + \alpha_T \frac{V_z^2}{|V|} \quad (3)$$

$$D_{yy} = \alpha_L \frac{V_y^2}{|V|} + \alpha_T \frac{V_x^2}{|V|} + \alpha_T \frac{V_z^2}{|V|} \quad (4)$$

$$D_{zz} = \alpha_L \frac{V_z^2}{|V|} + \alpha_T \frac{V_x^2}{|V|} + \alpha_T \frac{V_y^2}{|V|} \quad (5)$$

$$D_{xy} = D_{yx} = (\alpha_L - \alpha_T)\frac{V_x V_y}{|V|} \quad (6)$$

$$D_{xz} = D_{zx} = (\alpha_L - \alpha_T)\frac{V_x V_z}{|V|} \quad (7)$$

$$D_{yz} = D_{zy} = (\alpha_L - \alpha_T)\frac{V_y V_z}{|V|} \quad (8)$$

where α_L is the longitudinal dispersivity [L], α_T is the transverse dispersivity [L], and $|V| = \left(V_x^2 + V_y^2 + V_z^2\right)^2$, V_x, V_y and V_z are the components of the velocity vector along x, y and z axes.

III. THE HYPOTHETICAL ZONE OF STUDY

The hypothetical zone of study is square in shape with dimensions 800 m by 800 m. It has been divided into a grid of 10,000 cells (100×100). The studied region covers a phreatic aquifer with a total depth of 30 m. The aquifer is assumed to have four layers. The thickness of the layers in the downward direction is 5, 5, 10, and 10 m. Thus, the total number of cells in the simulated problem amounts to 40,000. Each layer is homogeneous and isotropic with a hydraulic conductivity of 10 m/day and porosity 0.3. Dispersivity is taken as 500 m without considering sorption and decay. Groundwater flow takes place from the left to the right boundaries under the effect of the specified head boundaries with values of 29 and 26 m. A pollution source is assumed in the aquifer at the intersection cell of row 41 and column 24. The source has a concentration of 300 PPM. Figure 1 represents a plan view and a longitudinal section A-A showing the corresponding equipotential heads and velocity vectors. The flow is going from the west to the east.

(a)

(b)

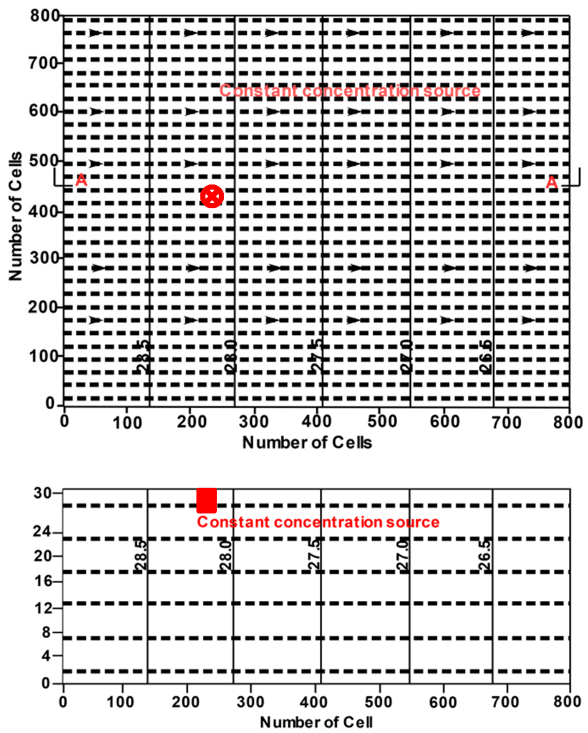

Fig. 1. (a) Equipotential lines and velocity vectors of the study zone, (b) a cross section A-A showing the equipotential lines with the velocity.

IV. INJECTION WELLS

Injection wells have been studied considering the effect of injection rate, screen length, and number of wells on a contaminant spread.

A. Injection Rate

Four injection wells around the pollution source feeding clean water into the groundwater reservoir are assumed. The wells' screen is fully penetrating the four layers of the aquifer. The injection rate is taken as 600 m^3/day from each well. The resulting equipotential lines and the concentration lines are presented in Figure 2. It is shown that the pollution spread is contained in a limited zone between the wells due to the clean water injected by the four surrounding wells. The diameter of the spread circle is about 100 m. When the injection rate is reduced to 300 m^3/day, more spread of the pollution takes place in the aquifer, as shown in Figure 3. The diameter of the resulting spread zone around the pollution source increases to about 300m.

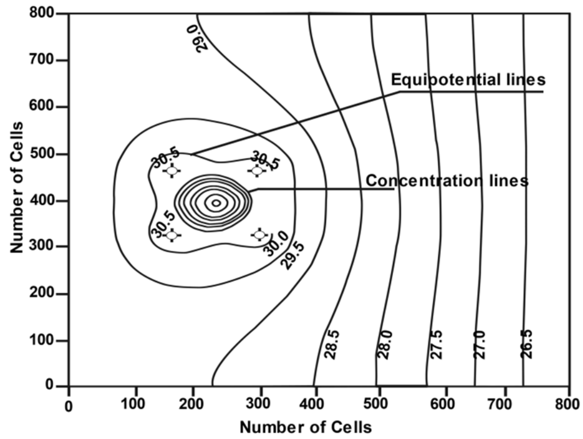

Fig. 2. Plan view of the concentration lines when having four injection wells of clean water with a rate of 600 m^3/day.

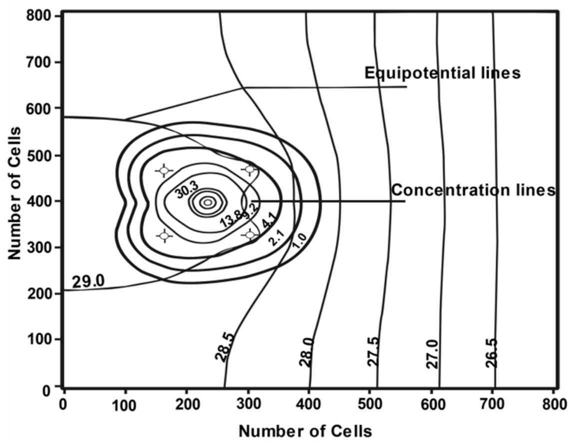

Fig. 3. Plan view of concentration lines when having four injection wells of clean water with a rate of 300 m^3/day.

B. Screen Well Depth

The case of having wells with an injection rate of 300 m^3/day has been repeated with a screen length of only 10 m penetrating the lowest layer of the aquifer. Figure 4 shows the results in the form of equi-concentration lines of the pollutant, in the first layer. A slight increase in the concentration can be noticed when comparing the results with the ones shown in Figure 3. This slight increase is related to having the injection screen away in the fourth layer.

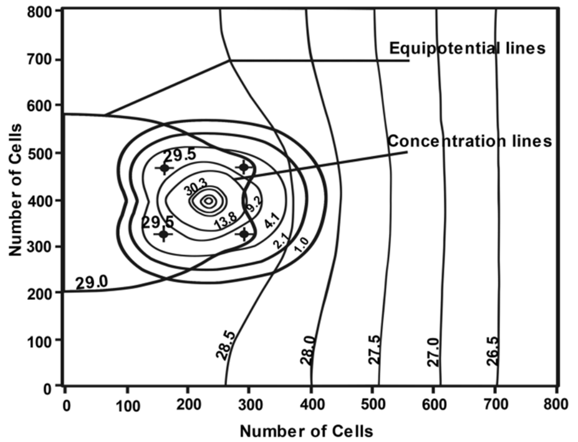

Fig. 4. Plan view of concentration lines when having four injection wells of clean water with a rate of 300 m^3/day and screen in the lower 10 m of the well.

C. Well Number

When the number of the injection wells was reduced to two upstream, more pollution spread took place downstream the contaminant source as shown in Figure 5. The increase of the pollution zone is noticed when it is compared with the corresponding one in Figure 3 that has the same conditions but with four injection wells.

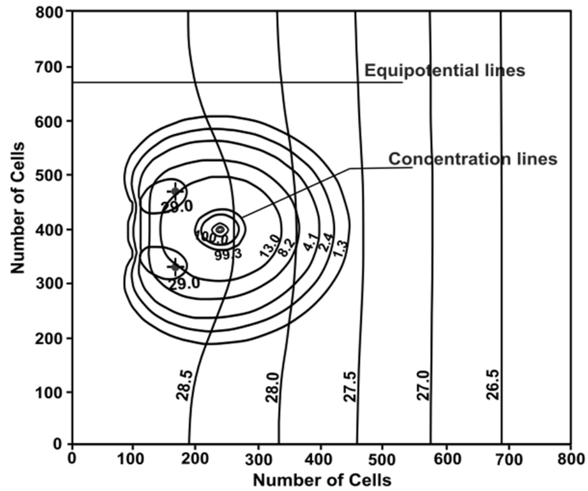

Fig. 5. Plan view of concentration lines when having two injection wells of clean water with a rate of 300 m^3/day.

V. PUMPING WELLS AS INTERCEPTORS

Investigation of hydraulics of contaminant withdrawal by pumping wells as interceptors is performed and discussed in this section. The studied hydraulic characteristics include pumping rate, depth, and number of wells.

A. Pumping Rate

Four pumping wells are assumed around the pollution source to keep the contaminant in place and prevent its spread through the aquifer. The wells are assumed to have screens which fully penetrate the aquifer with a pumping rate of 600 m^3/day. The resulting equipotential lines and the equi-concentration lines in PPM are presented in Figure 6. It is shown that the polluted zone is contained between the four wells. When the pumping rate is reduced to 300 m^3/day, the wells are not capable anymore of preventing the spread of the pollution zone which has extended outside the wells, as shown in Figure 7. A similar result was found but when increasing the time transport for reducing the pumping rate in [41].

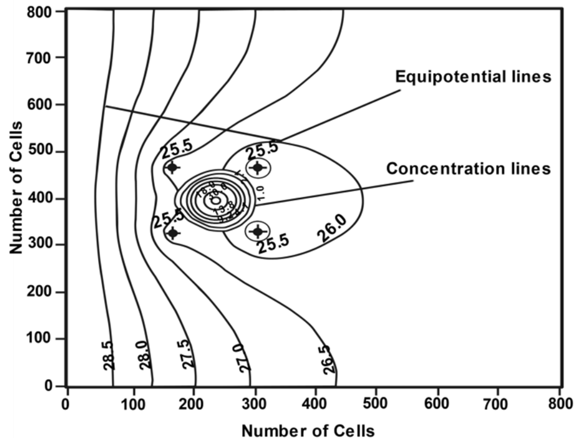

Fig. 6. Plan view of concentration lines when having four pumping wells with a rate of 600 m^3/day.

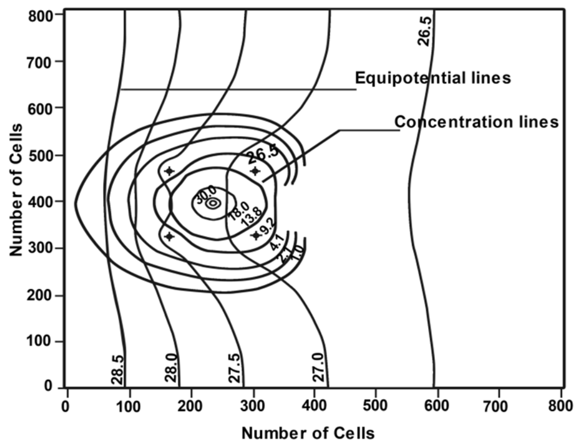

Fig. 7. Plan view of concentration lines when having four pumping wells with a rate of 300 m^3/day.

B. Screen Well Depth

The case of having wells with a pumping rate of 300 m^3/day was repeated with a screen length of 10 m that penetrates only the lower part of the aquifer. The corresponding concentration in the first layer is shown in Figure 8 showing more pollution compared with the results of the fully penetrating wells shown in Figure 7. This takes place in the first layer because the discharging screen is far in the lowest (fourth) layer.

C. Well Number

The number of discharging wells is reduced to two downstream as in Figure 9 and then to one as in Figure 10. The results show an increase in the pollution spread in comparison with the results shown in Figure 7.

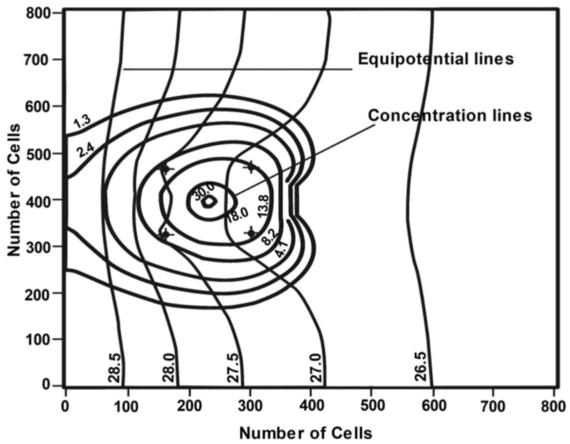

Fig. 8. Plan view of concentration lines when having four pumping wells with a rate of 300 m^3/day and screen in the lower 10 m of the well.

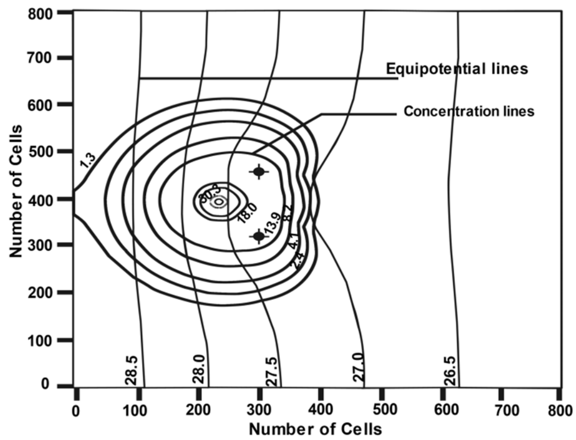

Fig. 9. Plan view of concentration lines when having two downstream pumping wells with a rate of 300 m^3/day.

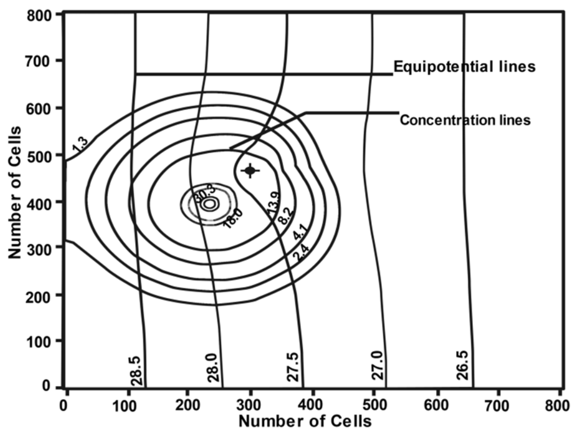

Fig. 10. Plan view of concentration lines when having one downstream pumping well with a rate of 300 m^3/day.

VI. IMPACT INTERRELATIONSHIP AMONG INJECTION AND PUMPING WELLS

Figure 11 shows the interrelationship of the impacts among injection and pumping wells according to the flow rate, well screen length, and well number. The base run for injection/pumping wells is indicated in blue/green colors. Figure 11 shows that the injection wells can prevent the spread of contamination more than the pumping wells. Full screen length is a good choice for decreasing the contamination for injection/pumping wells. Increasing the injection/pumping well number prevents more the contamination spread.

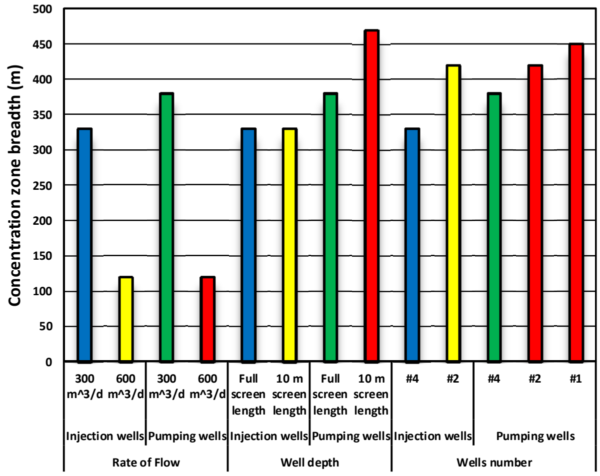

Fig. 11. Interrelationship of the impacts among injection and pumping wells.

VII. CONCLUSION

The current study helps understanding the hydraulic behavior of hydrodynamic containment of a contaminant in groundwater in order to achieve successful design of controlling systems. The main findings of the study include the following points:

- Hydrodynamic control of the pollution spread with the use of injection or pumping wells is an effective method.
- Decreasing the rate or the number of the injection/pumping wells permits more pollution spread.
- Changing the screen length of the injection well is not effective in preventing the pollution spread on the long-term.
- The effect of changing the screen length on the pollution spread is more in the case of pumping wells than in injection wells.
- Changing the number of the injection/pumping wells effects the contaminant spread.

The present investigation draws the decision makers' attention to the main factors that should be considered in the design of real applications. The injection/pumping rates as well as the number of wells should be studied well in each specific site in order to design a successful hydrodynamic system.

ACKNOWLEDGMENT

This research was funded by the Scientific Research Deanship of the University of Ha'il, Saudi Arabia through the project number RG-21168.

REFERENCES

[1] J. Mallick, C. K. Singh, M. K. AlMesfer, V. P. Singh, and M. Alsubih, "Groundwater Quality Studies in the Kingdom of Saudi Arabia: Prevalent Research and Management Dimensions," *Water*, vol. 13, no. 9, Jan. 2021, Art. no. 1266, https://doi.org/10.3390/w13091266.

[2] O. Fallatah and M. R. Khattab, "Evaluation of Groundwater Quality and Suitability for Irrigation Purposes and Human Consumption in Saudi Arabia," *Water*, vol. 15, no. 13, Jan. 2023, Art. no. 2352, https://doi.org/10.3390/w15132352.

[3] A. N. Laghari, Z. A. Siyal, D. K. Bangwar, M. A. Soomro, G. D. Walasai, and F. A. Shaikh, "Groundwater Quality Analysis for Human Consumption: A Case Study of Sukkur City, Pakistan," *Engineering, Technology & Applied Science Research*, vol. 8, no. 1, pp. 2616–2620, Feb. 2018, https://doi.org/10.48084/etasr.1768.

[4] M. A. Keerio, N. Bhatti, S. R. Samo, A. Saand, and A. A. Bhuriro, "Ground Water Quality Assessment of Daur Taluka, Shaheed Benazir Abad," *Engineering, Technology & Applied Science Research*, vol. 8, no. 2, pp. 2785–2789, Apr. 2018, https://doi.org/10.48084/etasr.1925.

[5] N. Kumar, A. A. Mahessar, S. A. Memon, K. Ansari, and A. L. Qureshi, "Impact Assessment of Groundwater Quality using WQI and Geospatial tools: A Case Study of Islamkot, Tharparkar, Pakistan," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5288–5294, Feb. 2020, https://doi.org/10.48084/etasr.3289.

[6] K. Praveen and L. B. Roy, "Assessment of Groundwater Quality Using Water Quality Indices: A Case Study of Paliganj Distributary, Bihar, India," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8199–8203, Feb. 2022, https://doi.org/10.48084/etasr.4696.

[7] Y. Kassem, H. Gokcekus, and T. Rizza, "Groundwater Quality Assessment Based on Water Quality Index in Northern Cyprus," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8435–8443, Apr. 2022, https://doi.org/10.48084/etasr.4790.

[8] "UN World Water Development Report 2022 'Groundwater: Making the invisible visible,'" *UN-Water*. https://www.unwater.org/news/un-world-water-development-report-2022-%E2%80%98groundwater-making-invisible-visible%E2%80%99 (accessed Nov. 13, 2023).

[9] J. van der Gun, "Groundwater resources sustainability," in *Global Groundwater*, A. Mukherjee, B. R. Scanlon, A. Aureli, S. Langan, H. Guo, and A. A. McKenzie, Eds. Amsterdam, Netherlands: Elsevier, 2021, pp. 331–345.

[10] S. E. Vero *et al.*, "Agricultural Case Studies," in *Encyclopedia of Inland Waters (Second Edition)*, T. Mehner and K. Tockner, Eds. Oxford, UK: Elsevier, 2022, pp. 68–83.

[11] C. Sanchis-Ibor, F. Molle, and M. Kuper, "Irrigation and water governance," in *Water Resources in the Mediterranean Region*, M. Zribi, L. Brocca, Y. Tramblay, and F. Molle, Eds. Amsterdam, Netherlands: Elsevier, 2020, pp. 77–106.

[12] A. Mukherjee, B. R. Scanlon, A. Aureli, S. Langan, H. Guo, and A. McKenzie, "Global groundwater: from scarcity to security through sustainability and solutions," in *Global Groundwater*, A. Mukherjee, B. R. Scanlon, A. Aureli, S. Langan, H. Guo, and A. A. McKenzie, Eds. Amsterdam, Netherlands: Elsevier, 2021, pp. 3–20.

[13] K. M. Ahmed, "Challenges of sustainable groundwater development and management in Bangladesh: vision 2050," in *Global Groundwater*, A. Mukherjee, B. R. Scanlon, A. Aureli, S. Langan, H. Guo, and A. A. McKenzie, Eds. Amsterdam, Netherlands: Elsevier, 2021, pp. 425–438.

[14] H. Ajami, "Geohydrology: Groundwater," in *Encyclopedia of Geology (Second Edition)*, D. Alderton and S. A. Elias, Eds. Oxford, UK: Academic Press, 2021, pp. 408–415.

[15] M. J. Brandt, K. M. Johnson, A. J. Elphinston, and D. D. Ratnayaka, "Groundwater Supplies," in *Twort's Water Supply (Seventh Edition)*, M. J. Brandt, K. M. Johnson, A. J. Elphinston, and D. D. Ratnayaka, Eds. Boston, MA, USA: Butterworth-Heinemann, 2017, pp. 117–158.

[16] M. Velis, K. I. Conti, and F. Biermann, "Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals," *Sustainability Science*, vol. 12, no. 6, pp. 1007–1017, Nov. 2017, https://doi.org/10.1007/s11625-017-0490-9.

[17] K. Wagner, *Remedial Action Technology For Waste Disposal Sites*. Park Ridge, NJ, USA: Noyes Np Ndc, 1983.

[18] J. W. Mercer, D. Giffin, D. C. Skipp, Dynamac Corporation, and Robert S. Kerr Environmental Research Laboratory, *Basics of pump-and-treat ground-water remediation technology*. Ada, OK, USA: Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 1990.

[19] "Technical Options for the Remediation of Contaminated Groundwater," International Atomic Energy Agency, Vienna, Austria, IAEA-TECDOC-1088, 1999.

[20] "Characterization of groundwater flow for near surface disposal facilities," International Atomic Energy Agency, Vienna, Austria, IAEA-TECDOC-1199, 2001.

[21] A. Zaporozec *et al.*, *Groundwater Contamination Inventory: A Methodological Guide*. Paris, France: Unesco, 2002.

[22] WHO, *Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources*. London, UK: World Health Organization, 2006.

[23] Z. Ahmad, A. Ashraf, G. Akhter, and I. Ahmad, "Groundwater and Contaminant Hydrology," in *Current Perspectives in Contaminant Hydrology and Water Resources Sustainability*, Rijeka, Croatia: IntechOpen, 2013, pp. 169–196.

[24] N. Zhou, S. Lu, Y. Cai, and S. Zhao, "Site Investigation and Remediation of Sulfate-Contaminated Groundwater Using Integrated Hydraulic Capture Techniques," *Water*, vol. 14, no. 19, Jan. 2022, Art. no. 2989, https://doi.org/10.3390/w14192989.

[25] R. C. Knox, L. W. Canter, D. F. Kincannon, E. L. Stover, and C. H. Ward, "State-of-the-art of aquifer restoration. Volume 1: sections 1 through 8. Final Report, 1979-1984," Oklahoma University, Norman, OK, USA, PB-85-181071; EPA-600/2-84-182A-VOL-1, Nov. 1984.

[26] A. Casasso, T. Tosco, C. Bianco, A. Bucci, and R. Sethi, "How Can We Make Pump and Treat Systems More Energetically Sustainable?," *Water*, vol. 12, no. 1, Jan. 2020, Art. no. 67, https://doi.org/10.3390/w12010067.

[27] C. R. Guevara Morel, M. van Reeuwijk, and T. Graf, "Systematic investigation of non-Boussinesq effects in variable-density groundwater flow simulations," *Journal of Contaminant Hydrology*, vol. 183, pp. 82–98, Dec. 2015, https://doi.org/10.1016/j.jconhyd.2015.10.004.

[28] R. H. Bogan, "Problems arising from ground water contamination by sewage lagoons at Tieton, Washington," in *Proceedings of the Symposium on Ground Water Contamination*, 1961.

[29] C. Zheng and P. Wang, "MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide," US Army Corps of Engineers-Engineer Research and Development Center, Contract Report SERDP-99-1, Jan. 1999.

[30] H. Suk, "Modified Mixed Lagrangian–Eulerian Method Based on Numerical Framework of MT3DMS on Cauchy Boundary," *Groundwater*, vol. 54, no. 4, pp. 508–520, 2016, https://doi.org/10.1111/gwat.12398.

[31] M. G. McDonald and A. W. Harbaugh, *A Modular Three-dimensional Finite-difference Ground-water Flow Model*. Reston, VA, USA: U.S. Geological Survey, 1988.

[32] C. D. Langevin, J. D. Hughes, E. Banta, A. Provost, R. Niswonger, and S. Panday, "MODFLOW 6, the U.S. Geological Survey Modular Hydrologic Model." U.S. Geological Survey, 2017, https://doi.org/10.5066/F76Q1VQV.

[33] C. D. Langevin *et al.*, "MODFLOW Version 6.4.0." U.S. Geological Survey, 2022, https://doi.org/10.5066/P9FL1JCC.

[34] M. A. El Fakharany, M. Monem, and N. Mansour, "Using Modflow and MT3D Groundwater Flow and Transport Models as a Management Tool forthe Quaternary aquifer, East Nile Delta, Egypt.," *International journal of Science Commerce and Humanities*, vol. 1, pp. 219–223, Jan. 2013.

[35] V. Bedekar, E. D. Morway, C. D. Langevin, and M. J. Tonkin, "MT3D-USGS version 1: A U.S. Geological Survey release of MT3DMS updated with new and expanded transport capabilities for use with MODFLOW," U.S. Geological Survey, 6-A53, 2016, https://doi.org/10.3133/tm6A53.

[36] S. E. Serrano, "Solute transport under non-linear sorption and decay," *Water Research*, vol. 35, no. 6, pp. 1525–1533, Apr. 2001, https://doi.org/10.1016/S0043-1354(00)00390-0.

[37] J. Bear, *Dynamics of fluids in porous medium*. Amsterdam, Netherlands: Elsevier, 1972.

[38] J. Bear, *Hydraulics of groundwater*. New York, NY, USA: McGraw-Hill, 1979.

[39] C. F. Tsang, T. Buscheck, and C. Doughty, "Aquifer thermal energy storage: A numerical simulation of Auburn University Field Experiments," *Water Resources Research*, vol. 17, no. 3, pp. 647–658, 1981, https://doi.org/10.1029/WR017i003p00647.

[40] M. Th. Van Genuchten, "Analytical solutions for chemical transport with simultaneous adsorption, zero-order production and first-order decay," *Journal of Hydrology*, vol. 49, no. 3, pp. 213–233, Feb. 1981, https://doi.org/10.1016/0022-1694(81)90214-6.

[41] H. Ahmadi, F. Kilanehei, and M. Nazari-Sharabian, "Impact of Pumping Rate on Contaminant Transport in Groundwater—A Numerical Study," *Hydrology*, vol. 8, no. 3, Sep. 2021, Art. no. 103, https://doi.org/10.3390/hydrology8030103.