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EDITORIAL

Groundwater resources: challenges and future opportunities

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Ensuring the sustainability and security of groundwater resources requires identification of region-specific challenges and solutions to accommodate water needs in diverse sectors, including ecosystems. They are related to extensive variations in natural conditions (e.g. geology, geomorphology and hydrology), human interventions, and political, cultural and socio-economic realities that need to be considered in working towards sustainable development. To achieve this goal, it is important to understand social transformations and societal drivers, as well as management and governance challenges which hinder effective groundwater management and access. Unlocking the future opportunities of groundwater require to integrate the existing knowledge and emerging tools and techniques to explore the unknown resources, and device governance strategies to improve livelihoods and health, build more resilient water futures, and move towards long-term sustainable and equitable groundwater use.

Groundwater is the largest freshwater reserve for domestic, agricultural, and industrial water supply[1,2] (Fig. 1). In a changing world, it is essential to understand the many aspects that control groundwater security and sustainability[3], defined by its quantity and quality that are influenced by several different factors including geology, climate change and modifying land use, overexploitation, pollution, economics, agro-food systems, socio-economic conditions and governance[4–7].

This article summarizes the major groundwater challenges and some of the opportunities for realizing the potential of under-utilized groundwater resources, which underpins economic development and improved health outcomes, and builds resilience to natural and man-made changes.

Challenges

Groundwater is difficult to manage due to often limited understanding of the groundwater systems; uncertainties in monitoring of its status; poorly defined flow boundaries[8]; transboundary issues[9]; poor abstraction management; uncertainty in groundwater-surface water inter-connections and often a poorly defined regulatory structure[10].

The physico-chemical behaviour of groundwater are largely influenced by the hydraulic and chemical properties of the aquifers in which it is stored[11], as well as human interferences such urban and irrigation activities. Groundwater is invisible[7], its vertical and horizontal flow in porous aquifers is often extremely slow, recharge rates are uncertain, long residence times and discharge processes typically taking place over timescales of several years to millennia[12] (Fig. 1). Flow through fractured, crystalline or karstic media is highly unpredictable and influenced by bedrock geology and discontinuity pathways, as demonstrated by studies in Ivory Coast and Greece, in this collection[13,14]. For example, studies in Ivory Coast[13]demonstrated how the fracture bedrock modulates the perennial springs in the area, while karstic flow in Greece lead to groundwater enrichment with several geogenic contaminants[14]. The current reliance of global food production by irrigation through non-renewable groundwater could constitute a threat to global food security in the mid to long term[1,15].

The main stresses that lead to groundwater challenges include demographic changes, such as population growth and lifestyle changes that create the need for growth in human consumption and water use for energy and food, along with new water demand located in other areas of the globe[2,16,17].

Natural and man-made changes on hydrological regimes, including climate change[18,19], lead to modified groundwater recharge and interactions with surface water (sea, rivers, lakes, wetlands etc.)[20–22]. This can result in reduced groundwater storage, river flow, increased sea water intrusion[14]and reduced groundwater discharge

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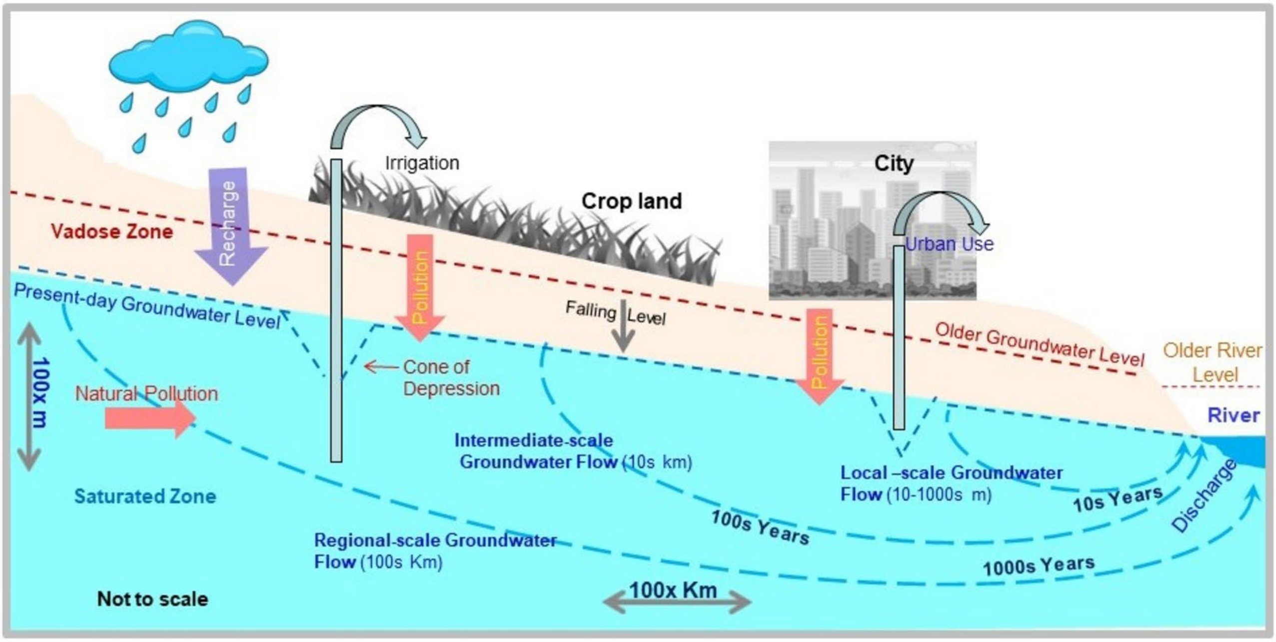

Fig. 1. Interaction of groundwater with natural and human systems.

to coastal zones[21,23,24], or pollution of surface water bodies[25]. For example, groundwater discharge in Oneida Lake, New York, USA led to phosphorous enrichment in the lake[25]. Further, land use change and increased urbanization cause surface sealing, decreased infiltration, conversion of recharge areas to built-up areas, deforestation, etc.[26–28];

Further, the deteriorating groundwater quality has severely jeopardized human life, mostly in the developing nations[29]. The interactions of groundwater with host rocks and sediments result in pervasive, geogenic groundwater pollution with arsenic, fluoride, radiogens, salinity etc.[29–36]that exposes millions to substantial health risks[37,38]. Studies in Chile demonstrated on geogenic magmatism and hydrothermal water lead to widespread arsenic enrichment in groundwater[36]. On the other hand, human activities on the land surface act as sources of localized and diffuse pollution. Many of these were known for several decades, where the others are regarded as emerging contaminants. These include nitrate and pesticides from agriculture and discharge of untreated wastewater, sanitation-borne pollutants, release of toxic materials and effluent by industries, healthcare facilities and municipalities[19,34,39–41], mining[36]and construction activities, household and community activities like microplastics[42]and other related domains. While many of these pollutants can be mitigated for drinking water supply[43]by nature-based or traditional/advanced technology based remediation solutions, several others, specifically the human-sourced pollutants can persist in hydrological regime for extended periods and very difficult to mitigate[33,34,40].

Future opportunities of groundwater resources

Groundwater brings the distinct advantage of being a much more widely dispersed water resource, with enormous stored volumes of mostly good quality water, which is naturally protected from many surface-sourced contaminants[44,45].

Many regions of the world have shallow under-utilized groundwater resources but have not yet been able to invest in its development, for economic, political or institutional reasons. These includes sparsely populated regions e.g. Africa[46]and islands[47]. Deeper fresh groundwater reserves offer significant opportunities for future groundwater development (Fig. 1).

During periods of droughts exacerbated by climate change, communities in water-scarce areas will increasingly depend on groundwater resources, because of its ability to buffer short terms changes and shocks. In man-made or natural disasters, such as earthquakes, landslides, flooding and industrial accidents, groundwater act as a strategic reserve. In the case of migration, and conflicts, groundwater-based drinking water wells acts as emergency supply[1,2,8,12,17].

A key aspect is improving the basic understanding of both groundwater quantity and quality at the level needed to manage aquifer resources. While, new technologies like the Gravity Recovery and Climate Experiment (GRACE) mission provide global-scale groundwater resources[48], local-scale high-resolution real-time monitoring of aquifer conditions through piezometry and other sensors may identify better response and quality of groundwater resources, as documented in this collection[49,50]. Studies in Nile delta demonstrated how such real-time piezometry coupled with other physico-chemical parameters of groundwater can used to develop numerical models of future groundwater scenarios[50]. Emerging technologies like Fiber Optics Distributed Temperature Sensing (FO-DTS) can help in developing a high resolution three-dimensional characterisation of the subsurface interaction of groundwater with sea in coastal areas[49]. Numerical, data-driven and hybrid models can be used to quantify, manage and predict future groundwater resources.

References

1. Scanlon, B. R. et al. Global water resources and the role of groundwater in a resilient water future. *Nat. Rev. Earth Environ.* **4**, 87–101 (2023).
2. Mukherjee, A. et al. *Global Groundwater: Source, Scarcity, Sustainability, Security, and Solutions* (Elsevier, 2020).
3. Mukherjee, A. & Dash, A. A. Chapter 1—Water matters: The thirst, the demand, and the society. In *Water Matters* (ed. Mukherjee, A.) 3–11 (Elsevier, 2024). https://doi.org/10.1016/B978-0-443-15537-6.00001-X.
4. Jasechko, S. et al. Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. *Nat. Geosci.* **10**, 425–429 (2017).
5. Margat, J. & van der Gun, J. *Groundwater Around the World: A Geographic Synopsis* (CRC Press, 2013).
6. Aeschbach-Hertig, W. & Gleeson, T. Regional strategies for the accelerating global problem of groundwater depletion. *Nat. Geosci.* **5**, 853–861 (2012).
7. UN. Groundwater, making the invisible visible | UN World Water Development Report 2022. https://www.unesco.org/reports/wwdr/2022/en (2022).
8. Guppy, L., Uyttendaele, P., Villholth, K. G. & Smakhtin, V. U. *Groundwater and Sustainable Development Goals: Analysis of Interlinkages* (2018).
9. Aureli, A. & Puri, S. Transboundary aquifers: A global program to assess, evaluate, and develop policy. *Groundwater* https://doi.org/10.1111/j.1745-6584.2005.00100.x (2005).
10. Mukherjee, A. Water Matters: Achieving the Sustainable Development Goals. In *Water Matters* (ed. Mukherjee, A.) i–iii (Elsevier, 2024). https://doi.org/10.1016/B978-0-443-15537-6.00027-6.
11. Villholth, K. G. Groundwater assessment and management: Implications and opportunities of globalization. *Hydrogeol. J.* **14**, 330–339 (2006).
12. Alley, W. Flow and storage in groundwater systems. *Science* **296**, 1985 (2002).
13. Kouassi, K. Identifying the origin of springs in weathered-fractured crystalline aquifers using a hydrogeophysical approach. *Sci. Rep.* **14**, 12977 (2024).
14. Li Vigni, L. et al. Hellenic karst waters: Geogenic and anthropogenic processes affecting their geochemistry and quality. *Sci. Rep.* **13**, 11191 (2023).
15. Giordano, M. & Villholth, K. G. *The Agricultural Groundwater Revolution: Opportunities and Threats to Development* (CABI, 2007).
16. Shah, T., et al. Groundwater: A global assessment of scale and significance. In *Water for Food Water for Life* 395–424. (Routledge, 2013). https://doi.org/10.4324/9781849773799-15
17. Famiglietti, J. S. The global groundwater crisis. *Nat. Clim. Change* **4**, 945–948 (2014).
18. Taylor, R. G. et al. Ground water and climate change. *Nat. Clim. Change* **3**, 322–329 (2013).
19. Ascott, M., Gooddy, D. & Mulcahy, A. *Analysis of Climate Variability and Change in Observational Groundwater Quality Data.* https://nora.nerc.ac.uk/id/eprint/535818/ (2023).
20. Mukherjee, A. Contesting with the Ganges Water Machine in South Asia: Theory versus reality. *ACS ES&T Water* **3**, 626–628 (2023).
21. Mukherjee, A., Bhanja, S. N. & Wada, Y. Groundwater depletion causing reduction of baseflow triggering Ganges river summer drying. *Sci. Rep.* **8**, 12049 (2018).
22. Dulai, H. Editorial: Submarine groundwater discharge: Impacts on coastal ecosystem by hidden water and dissolved materials. *Front. Environ. Sci.* **8**, 629509 (2021).
23. Das, P. et al. Quantifying the dynamics of sub-daily to seasonal hydrological interactions of Ganges river with groundwater in a densely populated city: Implications to vulnerability of drinking water sources. *J. Environ. Manag.* **288**, 112384 (2021).
24. Barlow, P. *Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow* (U.S. Geological Survey, 2012).
25. Lisboa, M. S., Schneider, R. L., Rudstam, L. G. & Walter, M. T. Groundwater inputs could be a significant but often overlooked source of phosphorus in lake ecosystems. *Sci. Rep.* **14**, 16269 (2024).
26. Foster, S. & Skinner, A. Groundwater protection: The science and practice of land surface Zoning. *Hydrol. Sci. J.* **225**, 471–482 (1995).
27. Foster, S., Chilton, J., Nijsten, G.-J. & Richts, A. Groundwater—A global focus on the 'local resource'. *Curr. Opin. Environ. Sustain.* **5**, 685–695 (2013).
28. Guo, Z., Wang, S. D., Cheng, M. M. & Shu, Y. Assess the effect of different degrees of urbanization on land surface temperature using remote sensing images. *Procedia Environ. Sci.* **13**, 935–942 (2012).
29. Mukherjee, A. et al. Arsenic and other geogenic contaminants in global groundwater. *Nat. Rev. Earth Environ.* **5**, 312–328 (2024).
30. Edmunds, W. M. & Smedley, P. L. Groundwater geochemistry and health: An overview. *Geol. Soc. Lond. Spec. Publ.* **113**, 91–105 (1996).
31. Sarkar, S., Das, K. & Mukherjee, A. Groundwater salinity across india: predicting occurrences and controls by field-observations and machine learning modeling. *Environ. Sci. Technol.* **58**, 3953–3965 (2024).
32. Coyte, R. M., Singh, A., Furst, K. E., Mitch, W. A. & Vengosh, A. Co-occurrence of geogenic and anthropogenic contaminants in groundwater from Rajasthan, India. *Sci. Total Environ.* **688**, 1216–1227 (2019).
33. Lapworth, D. et al. Groundwater quality: Global challenges, emerging threats and novel approaches. *Hydrogeol. J.* **31**, 1–4 (2022).
34. Lapworth, D. J. et al. Deep urban groundwater vulnerability in India revealed through the use of emerging organic contaminants and residence time tracers. *Environ. Pollut.* **240**, 938–949 (2018).
35. Lapworth, D. J., Boving, T. B., Kreamer, D. K., Kebede, S. & Smedley, P. L. Groundwater quality: Global threats, opportunities and realising the potential of groundwater. *Sci. Total Environ.* **811**, 152471 (2022).
36. Alam, M. A., Mukherjee, A., Bhattacharya, P. & Bundschuh, J. An appraisal of the principal concerns and controlling factors for Arsenic contamination in Chile. *Sci. Rep.* **13**, 11168 (2023).
37. Mukherjee, A. et al. Occurrence, predictors and hazards of elevated groundwater arsenic across India through field observations and regional-scale AI-based modeling. *Sci. Total Environ.* **759**, 143511 (2021).
38. Podgorski, J. & Berg, M. Global threat of arsenic in groundwater. *Science* **368**, 845–850 (2020).
39. Mukherjee, A. Impact of sanitation and socio-economy on groundwater fecal pollution and human health towards achieving sustainable development goals across India from ground-observations and satellite-derived nightlight. *Sci. Rep.* **9**, 15193 (2019).
40. Mukhopadhyay, A., Duttagupta, S. & Mukherjee, A. Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes and remediation. *J. Environ. Chem. Eng.* **10**, 107560 (2022).
41. Duttagupta, S., Mukherjee, A., Bhattacharya, A. & Bhattacharya, J. Wide exposure of persistent organic pollutants (PoPs) in natural waters and sediments of the densely populated Western Bengal basin, India. *Sci. Total Environ.* **717**, 137187 (2020).
42. Dey, U. et al. Microplastics in groundwater: An overview of source, distribution, mobility constraints and potential health impacts during the anthropocene. *Groundw. Sustain. Dev.* **23**, 101036 (2023).

43. Mukhopadhyay, A. et al. Chapter 7—Water pollution (SDG 6.3). In *Water Matters* (ed. Mukherjee, A.) 77–94 (Elsevier, 2024). https://doi.org/10.1016/B978-0-443-15537-6.00007-0.
44. Wada, Y. Global depletion of groundwater resources. *Geophys. Res. Lett.* https://doi.org/10.1029/2010GL044571 (2010).
45. Mukherjee, A., Fryar, A. E. & Howell, P. D. Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin, West Bengal, India. *Hydrogeol. J.* **15**, 1397–1418 (2007).
46. MacDonald, A. M. Quantitative maps of groundwater resources in Africa. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/7/2/024009 (2012).
47. Mandal, A., Gordon-Smith, D.-A.D.S. & Harris, P.-G. Chapter 8—Groundwater availability and security in the Kingston Basin, Jamaica. In *Global Groundwater* (ed. Mukherjee, A.) 97–112 (Elsevier, 2021). https://doi.org/10.1016/B978-0-12-818172-0.00008-6.
48. Rodell, M. et al. Emerging trends in global freshwater availability. *Nature* **557**, 651–659 (2018).
49. Furlanetto, D. Fiber optics passive monitoring of groundwater temperature reveals three-dimensional structures in heterogeneous aquifers. *Sci. Rep.* **14**(1), 8430 (2024).
50. Shehata, M. et al. Integrated management of groundwater quantity, physicochemical properties, and microbial quality in West Nile delta using a new MATLAB code and geographic information system mapping. *Sci. Rep.* **14**, 7762 (2024).

Author contributions

A.M. authored the manuscript with inputs from M.J., K.K. and F.P. All authors contributed to the manuscript.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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