



Topical Collection: International Year of Groundwater—managing future societal and environmental challenges

Marco Petitta¹ · David Kreamer² · Ian Davey³ · Jane Dottridge⁴ · Alan MacDonald⁵ · Viviana Re⁶ · Teodóra Szócs⁷

Received: 29 November 2022 / Accepted: 21 December 2022
© The Author(s) 2023

Abstract

Groundwater's role in maintaining the well-being of the planet is increasingly acknowledged. Only recently has society recognised groundwater as a key component of the water cycle. To improve public understanding and the proper use of groundwater, the hydrogeological community must expand its efforts in groundwater assessment, management, and communication. The International Association of Hydrogeologists (IAH) intends to help achieve the United Nation's water-related Sustainable Development Goals (SDGs) by the adoption of innovative hydrogeological strategies. This essay introduces a topical collection that encapsulates IAH's 2022 'Year for Groundwater'.

Keywords Groundwater management · Decision making · Groundwater and society · Groundwater science communication · Sustainability

Introduction

Hydrogeologists know that groundwater represents the hidden part of the water cycle and has a key role in human well-being, societal development, and environmental and planetary equilibrium (Re et al. 2022). This role is corroborated by the huge quantity (about 95% of planetary liquid freshwater) and high renewable rate of groundwater stored in the subsoil and aquifers (0.35 million km³ younger than

50 years, Gleeson et al. 2016). Hydrogeologists frequently neglect to disseminate this fundamental information both inside and outside the scientific community. At the same time, groundwater is still undervalued by governments and policymakers, who consider groundwater only in case of emergency/scarcity.

UN-Water and UNESCO dedicated the 2022 World Water Day to promoting the relevance of groundwater, "making the invisible visible"; thus, 2022 was considered a "year for groundwater" as stated in the World Water Development Report (United Nations 2022). Appropriately, the International Association of Hydrogeologists (IAH) has been playing a key role in several initiatives and promotes awareness of the significance of groundwater at different levels, from local to international. To this end, the IAH Commissions and Networks contributed to a topical collection published in this issue of the official journal of IAH, *Hydrogeology Journal*. Such contributions represent an update of the knowledge and achievements in groundwater science and demonstrate the passion that IAH members hold for communicating about groundwater. IAH provides representative global guidance on hydrogeology, looking both at the transfer of knowledge to external audiences and at evaluating the next challenges and potential solutions.

During the last decade, there has been a modification of the perception of environmental values and sustainable needs, which are summarised by the Sustainable Development Goals (SDGs; United Nations 2015). Because water

This article is part of the topical collection "International Year of Groundwater".

✉ Marco Petitta
marco.petitta@uniroma1.it

- ¹ Earth Sciences Department, Sapienza University of Rome, Roma, Italy
- ² Department of Geoscience, University of Nevada, Las Vegas, NV 89154-4010, USA
- ³ International Association of Hydrogeologists, Reading, UK
- ⁴ Mott MacDonald, Cambridge, UK
- ⁵ British Geological Survey, Lyell Centre, Research Av South, Edinburgh EH14 4AP, UK
- ⁶ Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy
- ⁷ Hydrogeology Department, Supervisory Authority for Regulatory Affairs, Budapest, Hungary

plays a fundamental role in addressing all SDGs, and because groundwater is a major component of the hydrosphere, it should be included in many implementation processes previewed by the 2030 SDG agenda (specifically SDG6) with the goal to achieve universal and equitable access to safe and affordable drinking water for all. However, groundwater is often ignored in water and ecosystem management; thus, the benefits of groundwater—its availability, quality and accessibility—will not contribute to the successful achievement of the SDG goals, with negative impacts on society and the natural environment. To help incorporate groundwater more fully within the SDGs, several key actions are identified:

- Improvement in *communication* by hydrogeologists with other disciplines, policymakers and the public for “making the invisible visible” and to ensure that optimal policy and practice are based on an accurate and insightful understanding of groundwater systems
- Acceleration in the development of *new knowledge* within groundwater science, strongly interconnected with other disciplines, and driven by innovative approaches and techniques, to promote practical and sustainable solutions
- An engagement strategy, through *increased involvement of all stakeholders*, to guide the production of groundwater science that is useful, usable and accepted for guiding policy and practice (Milman and MacDonald 2020)
- To value and *integrate traditional knowledge* with the formal science of hydrogeology, thus to recognise the important role indigenous communities have in the management of groundwater resources

Hydrogeologists can contribute by expending more effort, adopting suitable tools, and facing expectations in the coming years. The application of this strategy will depend on differing economic, societal and geological conditions; technical solutions cannot be considered universal, but require flexible application depending on the local conditions, with different impacts and costs in different contexts.

The main challenges

Several recent and new threats are impacting groundwater storage and quality, affecting services offered to society and to the natural environment. The impact of climate change on the water cycle is rapid and already visible, via the increased occurrence of extreme events (UNESCO, UN Water 2020) and alteration of aquifer recharge (IPCC 2022). The most frequent response to climate-change pressures occurs as an increase in groundwater withdrawals (Stigter et al. 2022; this issue). The visibility to the general public, particularly of

extreme events such as droughts and floods, raises awareness of water issues, offering the possibility to underscore how groundwater is relevant to the adaptation of climate-change effects (Famiglietti 2014).

Human pressures are still affecting groundwater quality, causing pollution in highly urbanized systems, in agricultural and livestock areas, and also in less populated areas, where the limitations of remedial infrastructure and pollution prevention are a threat to groundwater resources (Mistear et al. 2022; this issue). Modern lifestyle has created a new generation of pollutants (emerging contaminants, such as pharmaceuticals, metabolites, personal care products, per- and polyfluoroalkyl substances (PFAS), micro- and nano-plastics), the occurrence of which are still underestimated due to a lack of analytical techniques and policy restrictions (Lapworth et al. 2022; this issue). At the same time, the spread of “classical” contaminants in groundwater has not stopped, due to food production requirements.

Ecological status and ecosystem services have been recognized as fundamental values, and they strongly depend on groundwater availability, defining the concept of groundwater-dependent ecosystems (Kreamer et al. 2015). Withdrawals and water-table decline can have a direct impact on ecological systems (De Graaf et al. 2019), which are quickly impacted before the water shortages can be understood by human users. This priority requires additional information resulting from the monitoring of aquifers even where no direct abstractions are active.

A widespread threat to groundwater quality is coastal marine intrusion (Stein et al. 2022; this issue), influenced by climate change (sea level rise) and increased groundwater withdrawals in coastal regions, resulting in water quality deterioration and ecosystem degradation.

The interaction of groundwater systems with surface waters (Boulton and Hancock 2006) is based on a fragile equilibrium, impacted both directly and indirectly by human pressures. The nexus between water, energy, food and ecosystems (WEFE nexus; UNESCO, EC, IWA 2021) is able to express the interdependence of these elements. Groundwater is a key element of the nexus, because its natural resilience can be considered as a self-regulatory contribution both in preserving the balance and smoothing any sudden changes.

Undoubtedly, a response to this incomplete list of challenges can be tackled by an increase in knowledge, additional surveys and data production, looking for solutions at different scales, from local cases to regional scale (Mádl-Szőnyi et al. 2022; this issue), up to synthesised worldwide information (BGR/UNESCO 2008; IGRAC 2021).

Addressing these challenges requires the direct involvement of society, at different stages and levels (Foster 2020), to promote actions for preserving groundwater quantity and quality by bottom-up and/or top-down approaches. Policy rules are an example of water governance; however, in many

societies, practice is not dictated by policy, but rather by local norms. A socio-hydrogeology approach (Re 2021) is based on local community involvement, with a direct increase of awareness of water issues by the citizens, and with mutual learning through transdisciplinarity. At a wider scale, transboundary aquifers pose a management challenge that requires international cooperation to be effectively implemented (Rivera et al. 2022; this issue).

The tools for possible solutions

How to face these and other challenges, not only to promote good management and protection of groundwater resources but also to achieve the more ambitious objectives of the SDGs, requires several robust tools. The classical hydrogeological tools (surveys, sampling, drilling, testing, analyses, conceptual models, mathematical models, etc.) remain the basic instruments for providing solutions for groundwater management. In addition, innovative tools are needed, or existing tools should be implemented in an innovative way. “Innovation” has been stated as a basic accelerator for SDGs achievement. Innovative approaches in groundwater science were discussed at the recent UN-Water Summit on Groundwater in Paris (France) in December 2022.

Innovations, to move beyond research into implementation, can be both technical and nontechnical. Successful innovations can be effectively translated into operational management and ultimately deliver governance outcomes. Innovation implies actions and priorities relevant to the local context. Although aquifers occur on regional to international scales, groundwater is developed and used at the local, sometimes even household, scale, in a more local and personal dimension. Optimization of sustainable groundwater use and ensuring continued good quality is, therefore, not only a question of applying the latest advances in technology, but also requires the active engagement of the user community.

General areas of innovation in groundwater resources include: (1) technological innovation and discoveries, (2) conceptual advancement such as improvements in problem-solving, policy actions, and regulatory controls, (3) upgrading educational approaches for students, professionals and young people, and (4) communication and social innovation.

The field of *technical innovation* is rapidly growing, benefiting international collaboration, interdisciplinary research, digital solutions, and the involvement of end-users. The latter is crucial to ensure the applicability of the technology to a variety of socio-economic and cultural backgrounds. Significant improvements have been observed in monitoring by using remote sensing techniques (Rodell et al. 2018), which have revolutionised the ability to identify decadal changes in groundwater storage.

The widespread adoption of pressure transducers linked to telemetry has given managers groundwater data at their fingertips, enabling near-real-time and online monitoring (Martinsen et al. 2022). Fibre-optic water temperature loggers have helped understand heat flow (Ruba et al. 2021), and the emerging technologies of quantum gravity sensors (Shearan et al. 2022) enable the monitoring of groundwater-storage changes at the field and catchment scale. At the single well scale, the Smart Handpumps initiative has reduced the time required for fixing a broken pump (Gamble et al. 2017), while solar-powered groundwater pumping (Closas and Rap 2017) rapidly gained popularity via a more affordable second generation of solar panels. Rapid tests for microbial contamination in drinking water can return instantaneous results for screening high-risk supplies (Sorensen et al. 2021). Managed aquifer recharge (Dillon et al. 2019) is also providing the ability to reuse appropriately treated urban stormwater, sewage and other waste waters to increase groundwater storage (Zheng et al. 2022; this issue).

In terms of *conceptual innovation*, water governance requires complex groundwater science to be simplified, while retaining the key elements, so that it can be understood by external actors. Regulatory agency actions and guidance, adopting innovative strategies for monitoring, control, and planning groundwater usage, give decision-makers the possibility to realize implementation strategies (European Commission 2008). Innovative inputs are frequently offered by agencies, academia and professional associations, producing new concepts and frameworks that can provide novel opportunities. Technical tools, such as mathematical models for groundwater flow and transport, as well as decision support tools, can be adopted by planners at city, regional and national scales. Policies and regulations posed by authorities can be an efficient way to regulate withdrawals, wastewater releases, water management and groundwater protection. Public consultations enhance the involvement of stakeholders in the policy process.

Communication and social innovation are essential to reduce the risk associated with any top-down action. Adopting a bottom-up process requires additional effort, putting people at the centre by involving local communities or even individual family members. The socio-hydrogeology network (Re 2021), operating at the interface between society and groundwater, has the goal of promoting the integration of social sciences into hydrogeology and including local perspectives by developing concepts on how inter- and transdisciplinary cooperation and research can be carried out.

Communication and dissemination actions include several tools: (1) the direct application of groundwater science to pressing challenges, as described in the IAH Strategic Overview Series (IAH 2022a); (2) the engagement of water end-users, well owners and civil society to help unveil the invisible connections between people and groundwater; (3) simple but effective tools represented by local radio programmes (e.g., IGRAC 2022), television documentaries, news

media reporting and interviews with scientists and policymakers, which can be flanked by social media engagement and podcasts.

Finally, *educational innovation* will spread the relevance of groundwater to the wider public, particularly targeting the younger generation. Forced by the Covid-19 pandemic, widespread adoption of the Internet and online learning have enabled recent innovations in education. The availability of educational videos and archived webinars is growing every day, as are gaming approaches. The production of accessible, engaging, high-quality, educational materials, free of charge online in many languages, is supported by The Groundwater Project (Cherry et al. 2021).

Diversification of educational materials can be a powerful, yet simple innovation. The inclusion of nonwestern, traditional and indigenous knowledge contributes to an active engagement in decolonizing educational materials. This will provide a broader, more diverse, and more complete view of the knowledge spectrum that will result in the identification of efficient strategies for the long-term protection of groundwater better suited to individual local contexts.

Finally, IAH internal processes also require attention. The concerns and wider aspirations of IAH leading to 2030 are enshrined in the 2021 São Paulo-Brussels Groundwater Declaration (IAH 2022b). A strategy to improve the sustainability, equality and diversity of the organisation, by increasing membership, may include retaining members by providing benefits and good communication, education, outreach and knowledge transfer and collaboration with other organisations to promote understanding.

Conclusions

Thanks to increasing international awareness of the key role of groundwater, not only in the water cycle, but also in intersectoral and interdisciplinary issues related to human and environmental needs, hydrogeologists now have the opportunity to offer significant contributions for a better future. The approach requires the adoption of a new strategy, founded on classical hydrogeological tools and accompanied by innovative tools, that has the dual aim of communicating the relevance of groundwater and accelerating successful implementation of the SDGs. One step forward may be this topical collection, “International Year of Groundwater”, which contains seven essays on relevant topics.

A wide range of innovative solutions and approaches is already available in both the technical and nontechnical areas, and there is an urgency with respect to their financing, adoption, and implementation. Application of these innovations and new cutting-edge practices are a cost-effective way.

The current challenges for the implementation of groundbreaking actions include: (1) promoting the widespread trial,

adoption and review of novel and practical actions to maximise benefits, (2) ensuring that groundwater innovations are accessible and appropriate also for local conditions, and (3) enlisting agencies and governments to ensure a timely investment of resources to adequately support innovations and implement innovative actions.

All innovations need to be sustainable in the longer term and be accompanied/ followed by excellent communication, education/training, community involvement, and maintenance. Innovations need the opportunity to be robustly tested in practice and evaluated to build evidence of sustainable success.

Here, a specific challenge is addressed to hydrogeologists: how to transform knowledge—based on field data, practical tools and conceptual models—into transferable results that can be easily understood by the different components of society, as well as by decision-makers, stakeholders and final users. The main additional efforts of hydrogeologists must be dedicated to improving communication, dissemination and educational skills, and simplifying the complexity of hydrogeologic groundwater systems and their interaction with other earth systems and human populations. It should be not so difficult, after making the invisible visible.

Funding Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- BGR/UNESCO (2008) WHYMAP. Groundwater resources of the world. Map at scale 1: 25 000 000. BGR/UNESCO, Hannover/Paris. www.whymap.org/whymap/EN/Maps_Data/maps_data_node_en.html;jsessionid=66DD893882B11D6409B9BA3C76B2F141.2_cid292. Accessed Dec 2022
- Boulton AJ, Hancock PJ (2006) Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. *Aust J Botany* 54(2):133–144. <https://doi.org/10.1071/BT05074>
- Cherry J, Fan Y, Freeze A, Hsieh P, Kalwij I, Mackay D, Moran S, de Oliveira E, Parker B, Poeter E, Wood W, Zheng Y (2021) The

- Groundwater Project: a global vision towards understanding the planet's water resource. Vision and Progress report. <https://gw-project.org/about/>. Accessed Dec 2022
- Closas A, Rap E (2017) Solar-based groundwater pumping for irrigation: sustainability, policies and limitations. *Energy Policy* 104:33–37. <https://doi.org/10.1016/j.enpol.2017.01.035>
- De Graaf IEM, Gleeson T, van Beek LPH, Sutanudjaja EH, Bierkens MFP (2019) Environmental flow limits to global groundwater pumping. *Nature* 574:90–94. <https://doi.org/10.1038/s41586-019-1594-4>
- Dillon P, Stuyfzand P, Grischek T, Lluria M, Pyne RDG, Jain RC, Bear J, Schwarz J, Wang W, Fernandez E, Stefan C, Pettenati M, Van der Gun J, Sprenger C, Massmann G, Scanlon BR, Xanke J, Jokela P, Zheng Y et al (2019) Sixty years of global progress in managed aquifer recharge. *Hydrogeol J* 27:1–30. <https://doi.org/10.1007/s10040-018-1841-z>
- European Commission (2008) Groundwater protection in Europe. The new groundwater directive: consolidating the EU regulatory framework. Office for Official Publications of the European Communities, Luxembourg. <https://op.europa.eu/en/publication-detail/-/publication/4f3c68f2464d-4502-9086-6fcd1be8ab01>. Accessed Dec 2022
- Famiglietti JS (2014) The global groundwater crisis. *Nat Clim Chang* 4:945–948. <https://doi.org/10.1038/nclimate2425>
- Foster S (2020) Global policy overview of groundwater in urban development: a tale of 10 cities! *Water* 12(2):456. <https://doi.org/10.3390/w12020456>
- Gamble W, Pritchard M, Swan A, Cooper N (2017) Using smart pumps to help deliver universal access to safe and affordable drinking water. *Proc Institution Civil Eng: Eng Sustainabil* 171(6):277–285. <https://doi.org/10.1680/jensu.16.00013>
- Gleeson T, Befus KM, Jasechko S, Luijendijk E, Cardenas MB (2016) The global volume and distribution of modern groundwater. *Nat Geosci* 9:161–167. <https://doi.org/10.1038/ngeo2590>
- IAH (2022a) Strategic overview series. International Association of Hydrogeologists. <https://iah.org/education/professionals/strategic-overview-series>. Accessed Dec 2022
- IAH (2022b) São Paulo-Brussels Groundwater Declaration. International Association of Hydrogeologists. <https://iah.org/news/make-a-difference-in-groundwater>. Accessed Dec 2022
- IGRAC (2021) Transboundary aquifers of the world [map]. Edition 2021. Scale 1: 50 000 000. IGRAC, Delft, The Netherlands. www.un-igrac.org/sites/default/files/resources/files/2021TBAMap_UNESCO%20Version.pdf; unesdoc.unesco.org/ark:/48223/pf0000380193. Accessed Dec 2022
- IGRAC (2022) Amplifying voices of rural communities in Tanzania to improve groundwater management. <https://www.un-igrac.org/stories/amplifying-voices-rural-communities-tanzania-improve-groundwater-management>. Accessed Dec 2022
- IPCC (2022) Climate Change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pörtner et al (eds) Cambridge University Press, Cambridge, UK, 3056 pp. <https://doi.org/10.1017/9781009325844>
- Kreamer DK, Stevens LE, Ledbetter JD (2015) Groundwater dependent ecosystems: policy challenges and technical solutions. In: Adelana S (ed) Groundwater, hydrochemistry, environmental impacts and management impacts, chap 9. Nova, New York, pp 205–230
- Lapworth D, Boving T, Brauns B, Dottridge J, Pul Hynds P, Kebede S, Kreamer D, Misstear B, Mukherjee A, Re V, Sorensen J, Ruz Vargas C (2022) Groundwater quality: global challenges, emerging threats and novel approaches. *Hydrogeol J*. <https://link.springer.com/article/10.1007/s10040-022-02542-0>. Accessed Dec 2022
- Mádl-Szőnyi J, Batelaan O, Molson J, Verweij H, Jiang X-W, Carrillo-Rivera JJ, Tóth Á (2022) Regional groundwater flow and the future of Hydrogeology: evolving concepts and communication. *Hydrogeol J*. <https://doi.org/10.1007/s10040-022-02577-3>
- Martinsen G, Bessiere H, Caballero Y, Koch J, Collados-Lara AJ, Mansour M, Sallasmaa O, Pulido-Velazquez D, Williams NH, Zaadnoordijk WJ (2022) Developing a pan-European high-resolution groundwater recharge map: combining satellite data and national survey data using machine learning. *STOTEN* 822:153464
- Milman A, MacDonald A (2020) Focus on interactions between science-policy in groundwater systems. *Env Res Letters* 15(9):090201. <https://doi.org/10.1088/1748-9326/aba100>
- Misstear B, Ruz Vargas C, Lapworth D, Ouedraogo I, Podgorski J (2022) A global perspective on assessing groundwater quality. *Hydrogeol J*. <https://link.springer.com/article/10.1007/s10040-022-02461-0>. Accessed Dec 2022
- Re V (2021) Socio-hydrogeology and geoeconomics: state of the art and future challenges. In: Abrunhosa et al (eds) Advances in geoeconomics and groundwater management: theory and practice for a sustainable development. Advances in Science, Technology and Innovation. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-030-59320-9_77
- Re V, Lilla Manzione R, Abiye TA, Mukherji A, MacDonald A (eds) (2022) Groundwater for sustainable livelihoods and equitable growth. Taylor and Francis, London, 393 pp. <https://doi.org/10.1201/9781003024101>
- Rivera A, Pétré M-A, Fraser C, Petersen-Perlman JD, Sanchez R, Movilla L, Pietsersen K. (2022) Why do we need to care about transboundary aquifers and how do we solve their issues? *Hydrogeol J*. <https://link.springer.com/article/10.1007/s10040-022-02552-y>. Accessed Dec 2022
- Rodell M, Famiglietti JS, Wiese DN, Reager JT, Beaudoin HK, Landerer FW, Lo MH (2018) Emerging trends in global freshwater availability. *Nature* 557:651–659. <https://doi.org/10.1038/s41586-018-0123-1>
- Ruba AM, Mohamed RAM, Gabrielli C, Selkerb JS, Selkerb F, Brooks SC, Ahmed T, Carroll KC (2021) Comparison of fiberoptic distributed temperature sensing and high-sensitivity sensor spatial surveying of stream temperature. *J Hydrol* 603:127015
- Shearan B, Mukhopadhyay S, Tregoning P, Legge S, Close J, Andersen MS, Rutledge H, Vervoot RW, Simmons J, Scalzo R, Francis G, Isaacs M (2022) Where is All the Water? 22nd International Symposium on Electrical Apparatus and Technologies, SIELA 2022 - Proceedings. <https://doi.org/10.1109/SIELA54794.2022.9845719>
- Sorensen JPR, Nayebare J, Carr AF, Lyness R, Campos LC, Ciric L, Goodall T, Kulabako R, Rushworth Curran CM, MacDonald AM, Owor M, Read DS, Taylor RG (2021) In-situ fluorescence spectroscopy is a more rapid and resilient indicator of faecal contamination risk in drinking water than faecal indicator organisms. *Water Res* 206:117734. <https://doi.org/10.1016/j.watres.2021.117734>
- Stein S, Shalev E, Sivan O, Yechieli Y (2022) Challenges and approaches for management of seawater intrusion in coastal aquifers. *Hydrogeol J*. <https://link.springer.com/article/10.1007/s10040-022-02575-5>. Accessed Dec 2022
- Stigter TY, Miller J, Chen J, Re V (2022) Groundwater and climate change: threats and opportunities. *Hydrogeol J*. <https://link.springer.com/article/10.1007/s10040-022-02554-w>. Accessed Dec 2022
- UNESCO, European Commission, IWA (2021) Implementing the water–energy–food–ecosystems nexus and achieving the sustainable development goals. UNESCO, Paris, pp 190. <https://doi.org/10.2760/536860>
- UNESCO, UN-Water (2020) United Nations world water development report 2020: water and climate change. UNESCO, Paris, pp 219

- United Nations (2015) Transforming our world: the 2030 agenda for sustainable development. United Nation Resolution A/RES/70/1, United Nations, New York, pp 35
- United Nations (2022) The United Nations world water development report 2022: groundwater—making the invisible visible. UNESCO, Paris, pp 225
- Zheng Y, Vanderzalm J, Hartog N, Fernández Escalante E, Catalin S (2022) The 21st century water quality challenges for managed aquifer recharge: towards a risk-based regulatory approach.

Hydrogeology J. <https://link.springer.com/article/10.1007/s10040-022-02461-0>. Accessed Dec 2022

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.