Hydrogeology Journal
https://doi.org/10.1007/s10040-022-02552-y

ESSAY

Why do we need to care about transboundary aquifers and how do we solve their issues?

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Received: 2 March 2022 / Accepted: 26 September 2022

Abstract
As the reliance on transboundary groundwater is increasing globally, it is important to understand and address the specific issues raised by the assessment and management of transboundary aquifers (TBAs). Building on 20 years of TBA experience and through a three-pillar framework (assessment, cooperation-collaboration, shared management), the key elements to addressing TBA issues are described, including a multidisciplinary approach, identification of hotspot zones, local vs border-wide approaches, appropriate funding models, and an increased recognition of the role and value of each TBA.

Keywords Transboundary aquifers · Groundwater and society · Water-resources management · Socio-economic aspects

Introduction

Transboundary aquifers (TBAs) contain groundwater that transfers from one country to others (Wada and Heinrich 2013). As a TBA is shared across boundaries, it elevates the challenges associated with assessment and management, as additional variables come into play. Physical assessments are not enough—social, economic, political, cultural, and historical variables play an equally significant role in the assessment of the aquifer to understand its complexities (Sanchez and Eckstein 2020).

Users relying upon TBAs can suffer deleterious effects of mismanagement from other jurisdictions. The most common effect is groundwater depletion caused by the frequent pumping of water from aquifers, which is often linked to inefficient management practices. Further, overwithdrawals of surface water and/or groundwater may decrease the amount of surface water available in other jurisdictions due to surface water and groundwater connectivity. These and other transboundary issues (e.g., cultural, environmental) are common around the world: Silala TBA (Bolivia–Chile; ICJ 2022); The Mountain Aquifer (Israel–Palestine; Harpaz et al. (2001)); the Lower Colorado River Basin and Hueco Bolson TBAs (Mexico–USA; Sheng et al. (2001)); Nubian Sandstone Aquifer System (Libya–Egypt–Sudan–Chad; Hamada and Ahweejb 2020).

While disputes over surface water (rivers) abound and are well documented (The Economist 2019), conflicts over groundwater (aquifers) are less known and less documented, but looming (UNESCO 2022).

Many issues are unavoidable, but most could be addressed through a framework with assessment, cooperation, and shared management. From a global perspective, this essay addresses why we need to care about TBAs. A three-pillar framework is proposed for effective shared TBA management, the combination of the three components could help to resolve TBA issues.

Global issues

While every aquifer contains a unique set of characteristics, they also face several common issues that impact them. In many locations, particularly in arid and drought-prone regions, transboundary groundwater is a key component of water security (IAH 2021). Water security has been defined as the human capacity to ensure sustainable

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

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Published online: 03 November 2022

access to water at sufficient quantities and acceptable quality to ensure human, economic, and environmental well-being (UN-Water 2013). For groundwater, these dimensions include storage availability, supply productivity, and pollution protection. Recommendations for improving transboundary groundwater security include strengthening institutional capacity, improving data and information exchange, and involving diverse groups of stakeholders (Albrecht et al. 2017).

The main threats to groundwater security include unsustainable use, decreased recharge rates, and conflict. Determining TBA groundwater footprints can be particularly challenging as locations of hydraulic connectivity to surface waters, recharge zones, and overexploitation can span international borders (Wada and Heinrich 2013).

Both physical and anthropogenic changes to water quality and water quantity in a TBA can lead to water conflicts. Though conflicts between states over TBAs have been relatively minor compared to those over surface waters, the comparative lack of institutional capacity in the form of transboundary groundwater agreements is concerning as it could lead to significant disputes (Eckstein 2021).

State of affairs

In 2000, the International Hydrological Programme (IHP) of UNESCO and the International Association of Hydrogeologists (IAH) established the Internationally Shared Aquifer Resources Management (ISARM) initiative (UNESCO-IHP et al. 2001). Through the creation of four ISARM-networks of experts, regional strategies were proposed to assess and manage TBAs. Since then, substantial progress has been made in delineating TBAs globally (see UNESCO-IHP and UNEP 2016), leading to a global baseline of understanding for many of the world's largest TBAs.

Based on the most recent global inventory, there are 468 identified TBAs or aquifer systems: 106 in Africa, 135 in the Americas, 130 in Asia and Oceania, and 97 across Europe. In total, 142 countries share TBAs (IGRAC 2021). However, TBA delineations represented on maps are still only a vertical projection of the aquifer extent at the surface and the identification of a TBA differs from their assessment, which should consider the complex functioning of the system in three-dimensional (3D) space. Further, many of the newly identified TBAs have not been officially recognized by the countries sharing them.

Though TBAs greatly outnumber transboundary surface waters, the number of international agreements on transboundary groundwater are not commensurate. Depending on the classification method, barely tens of international agreements and arrangements governing specific TBAs exist, compared to over 600 international agreements governing transboundary surface waters (TFDD 2018). Groundwater-governing institutions generally have undeveloped, underdeveloped, or fragmented approaches for addressing and/or resolving problems (de Chaisemartin et al. 2017).

TBA Pillars

The global issues and situation described previously clearly point toward an urgent need to care about TBAs; these issues need to be addressed, managed, and understood differently compared to domestic aquifers. Reaching conflict-free joint governance of a TBA, towards its equitable and sustainable use, requires a three-pillar framework (Fig. 1), including—the physical assessment of the TBA, cooperation and collaboration mechanisms, and shared management.

Assessment includes the mapping and full physical assessment of the TBA, its physical boundaries, conditions, issues, and its relationship to the communities that depend upon it. Ideally, the knowledge acquired in this first pillar would be used in the decision-making process to support informed decisions at the management level in the third pillar.

To achieve this level of understanding, however, transboundary cooperation and collaboration mechanisms are required. Assessing the physical system through transboundary collaboration and stakeholder involvement is the most important milestone that eventually can create shared management strategies leading toward systemic sustainability. The pillars are built upon each other and should be understood as an iterative process with permanent feedback (Fig. 1).

Assessment

To prevent and solve issues that arise from TBA utilization, a sound scientific and technical knowledge base is needed. The most important components for physical knowledge are—space and time scales, surface-water/groundwater interactions, and monitoring. Other, non-physical variables are needed to complete a TBA assessment: social, economic, political, and cultural variables. To date, few TBAs have been fully assessed with those attributes.

Recommendations for the assessment and management of TBAs have been formulated in a few methodological guidebooks and strategies (Machard de Gramont et al. 2011; UNEP 2011). IGRAC and UNESCO-IHP (2015) proposed a methodology reflecting the results of first-hand TBA assessment experiences, encompassing a multidisciplinary approach that includes not only hydrogeology but also environmental, socio-economic, legal and institutional aspects.

Although a full aquifer-wide transboundary assessment may be essential, often transboundary impacts are limited to border regions or hotspot zones. Here, to alleviate data scarcity, financing and capacity issues, it might be useful to focus on a more detailed assessment at smaller scales (Fraser et al. 2020). However, a major challenge exists in identifying the appropriate transboundary groundwater management units, where transboundary implications are important (i.e., active groundwater flow across the international border, presence of well fields or pollution, etc.). This concept is still within its infancy and methodologies to carry out such a task are limited.

Characterizing *surface-water/groundwater interactions* is an important component of the physical assessment of TBAs, raising additional shared management and governance challenges. For example, surface waters interacting with a TBA might already be managed by a transboundary agreement that does not include groundwater. Furthermore, the extent of a TBA can greatly differ from the extent of the watershed(s) with which it interacts, suggesting that different stakeholders might be involved. *Identifying hotspot zones* and considering conjunctive management might again be a way forward.

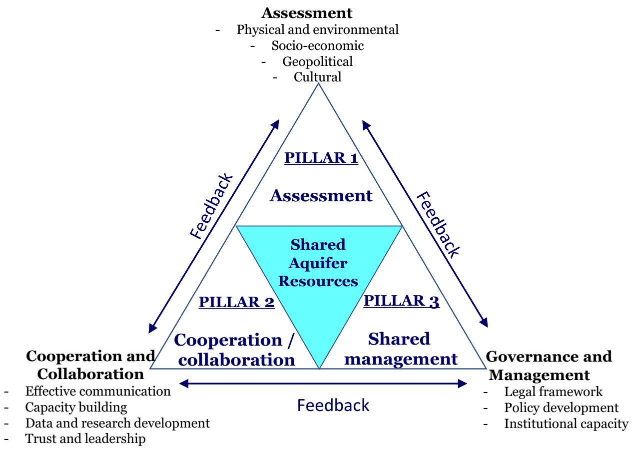

Fig. 1 A three-pillar framework for effective transboundary aquifer management

Limited knowledge of TBAs in most regions of the world poses a problem of planning and developing shared groundwater resources. A lack of adequate, long-term *groundwater monitoring* is also a common obstacle to the comprehensive assessment of TBAs.

To overcome the knowledge gaps, transboundary monitoring networks should be established based upon the priority concerns of the countries. Monitoring efforts can be harmonized around strategic action planning processes and facilitated by data exchange protocols or provisions (Tapia-Villaseñor and Megdal 2021). A great example of a cooperative framework to improve TBA knowledge is the Transboundary Aquifer Assessment Program (TAAP, Tapia-Villaseñor and Megdal 2021), which is a joint effort by the United States and Mexico to evaluate shared aquifers. Modeling can assist with prioritization efforts during the data collection and exchange phases to ensure that TBA assessments achieve their intended outcome (Atkins et al. 2021). In data-scarce environments, remote sensing data and machine learning algorithms have been utilized.

Cooperation and collaboration

International law provides tools for cooperation and collaboration to conciliate the sovereignty, rights and interests of the states sharing a TBA. Operational *agreements* and *arrangements* have the potential to enable and strengthen *cooperation* and *collaboration* (Eckstein 2021). However, the international law of TBAs is much more underdeveloped than the international law applicable to surface water (Sindico 2020). The UN Draft Articles on the Law of Transboundary Aquifers continue to be a nonbinding guidance for states (Sindico 2020) and the number of agreements and arrangements on specific TBAs is increasing very slowly.

Science-policy linkages with respect to TBAs often appear when the physical assessment has already been carried out. Agreements and arrangements are sometimes signed following these assessments, or if already existing, they are updated (e.g., the Guarani TBA and the Genevese TBA). Many lessons have been learned, one of the most important is translating the best theories to the best fit for informed decisions on shared management and overall governance.

These projects are usually externally driven and provide a necessary platform to begin cooperation between aquifer states, e.g., the Environmental Protection and Sustainable Development of the Guarani Aquifer System Project 2002–2009, or the Groundwater Resources Governance in Transboundary Aquifers (GGRETA 2021) Project 2013–2022. In brief, knowledge has been the catalyst for further cooperation and, in some cases, for full collaboration.

Contrasting with most transboundary surface-water agreements, many of the existing instruments for cooperation or collaboration on TBAs are not formal treaties. These more informal agreements or arrangements may represent a suitable option for an initial cooperative approach. Subnational entities and local communities may also use them to foster local transboundary cooperative frameworks, e.g., the 2019 Ocotepeque–Citalá Statement of Intent (El Salvador-Honduras, Sindico 2019), and local cooperation efforts on TBAs between Mexico and the United States (Sanchez and Eckstein 2020).

At any scale, *trust*, *commitment*, *leadership*, and effective *communication* strategies are key elements that build a strong and lasting collaboration mechanism that, in return, can provide a joint scientific understanding of the system under the three-pillar framework.

Shared management

The third pillar (Fig. 1) includes legal frameworks, policy development and institutional capacity. The combination of these should facilitate the preparation of shared governance and management plans between the countries.

To achieve this level of serious collaboration, however, these components should be tied to aquifer knowledge (assessment) and some cooperation mechanism. Assessing the physical system under an umbrella of collaboration and stakeholder involvement at the transboundary level is the most important milestone that eventually can drive the development of potential *shared management strategies* towards the sustainability of the system.

However, asymmetries and differences in the technological-economic capacities of neighboring countries may restrain, diminish, or even prevent the development of shared groundwater management agreements.

Way forward

Although progress has been made in the assessment of TBAs, there is much work still to be done on cooperation and shared management. In addition to the solutions proposed in the previous section, relative to the technical and institutional capacity issues, the following factors have been identified as important to move forward in solving TBA issues.

- A *multidisciplinary approach* in the three-pillars process (Fig 1) is crucial, including the economic, hydro-diplomacy and legal aspects, because the physical assessment of TBAs alone is not sufficient to support the sustainable management of the shared resources.
- *Funding model*: the limited existing agreements for TBAs are often born from external projects funded through global financing agencies, which provide the platform and technical

baseline to begin cooperation between aquifer states. However, this model is unsustainable and financing is not always driven towards areas of greatest need.

- Countries need to take ownership of their own TBAs and fund these activities themselves—TBAs need to be higher on political agendas. Countries should take ownership over the monitoring, assessment and, ultimately, *management* of their own TBA resources in cooperation with neighboring states.
- *Role and value* of TBAs: the economic and social value of a TBA should be better recognized and quantified at national government levels. Continued effort is needed to promote the key role of TBAs in supporting the 2030 Agenda for Sustainable Development.
- Key components in sustaining TBAs will be increased mechanisms of *cooperation* and *collaboration* between aquifer states or local communities. Continued communication creates meaningful interaction to cooperate and collaborate towards the same goals.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Albrecht TR, Varady RG, Zuniga-Teran AA, Gerlak AK, Staddon C (2017) Governing a shared hidden resource: a review of governance mechanisms for transboundary water security. Water Security 2:43–56. https://doi.org/10.1016/j.wasec.2017.11.002

Atkins AEP, Langarudi SP, Fernald AG (2021) Modeling as a tool for transboundary aquifer assessment prioritization. Water 13(19):2685. https://doi.org/10.3390/W13192685

De Chaisemartin M, Varady RG, Megdal SB, Conti KI, van der Gun J, Merla A, Nijsten GJ, Scheibler F (2017) Addressing the groundwater governance challenge. In: Karar E (ed) Freshwater governance for the 21st century. Springer, Cham, Switzerland, pp 205–227

Eckstein G (2021) International law for transboundary aquifers: a challenge for our times. Am J Int Law 115:201–206

Fraser CM, Kalin RM, Kanjaye M, Uka Z (2020) A methodology to identify vulnerable transboundary aquifer hotspots for multi-scale groundwater management. Water Int 45(7–8):865–883

GGRETA (Governance of Groundwater Resources in Transboundary Aquifers) (2021) Portfolio 2021 Global Programme Water. Swiss Agency for Development and Cooperation SAC, pp 40–43. https://www.shareweb.ch/site/Water/resources/Documents/GPW_Portfolio_2021.pdf. Accessed 16 Sept 2022

Hamada SM, Ahweejb, YA (2020) Evaluation of the Nubian Sandstone Aquifer System (NSAS) in Al Kufra Oasis, Southeast Libya. https://www.researchgate.net/publication/334432740_Evaluation_of_the_Nubian_Sandstone_Aquifer_System_NSAS_in_Al_Kufra_Oasis_Southeast_Libya_tqyym_alkhzan_aljwfy_alhjr_alrmly_alnwby_bwaht_alkfrt_jnwb_shrq_lybya. Accessed 16 Sept 2022

Harpaz Y, Haddad, M, Arlosoroff S (2001) Overview of the Mountain Aquifer: a shared Israeli-Palestinian resource. https://doi.org/10.1007/978-94-010-0680-4_3

IAH (2021) Water security and groundwater. Strategic Overview Series, IAH, Wallingford, UK. https://iah.org/wp-content/uploads/2021/08/IAH-Water-Security_Groundwater-July-2021.pdf. Accessed 16 Sept 2022

ICJ (2022) Dispute over the status and use of the waters of the Silala (Chile v. Bolivia). https://www.icj-cij.org/public/files/case-related/162/162-20220414-PRE-01-00-EN.pdf. Accessed 16 Sept 2022

IGRAC (2021) Transboundary aquifers of the world [map], 2021 edn. Scale 1: 50 000 000, IGRAC, Delft, The Netherlands

IGRAC, UNESCO-IHP (2015) Guidelines for multi-disciplinary assessment of transboundary aquifers, draft version. IGRAC, Delft, The Netherlands

Machard De Gramont H, Noël C, Olivier J, et al (2011) Toward a joint management of transboundary aquifer systems: methodological guidebook. https://www.riob.org/IMG/pdf/guide-2-savoirENG.pdf. Accessed 16 Sept 2022

Oregon State University Transboundary Freshwater Dispute Database (TFDD) (2018) International Freshwater Treaties Database. http://www.transboundarywaters.orst.edu. Accessed 16 Sept 2022

Sanchez R, Eckstein G (2020) Groundwater management in the borderlands of Mexico and Texas: the beauty of the unknown, the negligence of the present, and the way forward. Water Resour Res 56:e2019WR026068. https://doi.org/10.1029/2019WR026068

Sheng Z, Mace RE, Fahy MP (2001) The Hueco Bolson: an aquifer at the crossroads. https://www.researchgate.net/publication/275831953_The_Hueco_Bolson-An_aquifer_at_the_crossroads. Accessed 16 Sept 2022

Sindico F (2019) The Ocotepeque: Citalá statement of intent. https://www.strath.ac.uk/media/1newwebsite/departmentsubject/law/strathclydecentreforenvironmentallawandgovernance/pdf/policybriefs/SCELG_Policy_Brief_12.pdf. Accessed 16 Sept 2022

Sindico F (2020) International law and transboundary aquifers. Elgar, Cheltenhan, PA

Tapia-Villaseñor EM, Megdal SB (2021) The U.S.–Mexico Transboundary Aquifer Assessment Program as a model for transborder groundwater collaboration. Water 13(4):530. https://doi.org/10.3390/w13040530

The Economist (2019) Disputes over water will be an increasing source of international tension. The Economist, Feb 28th. https://www.economist.com/special-report/2019/02/28/disputes-over-water-will-be-an-increasing-source-of-international-tension. Accessed 16 Sept 2022

UNEP (2011) Methodology for the assessment of transboundary aquifers, lake basins, river basins, large marine ecosystems, and the open ocean. In: Jeftic L, Glennie P, Talaue-McManus L, Thornton JA (eds) Methodology for the GEF Transboundary Waters Assessment Programme. UNEP, Nairobi, Kenya, 60 pp

UNESCO (2022) UN-World Water Development Report: groundwater—making the invisible visible. https://unesdoc.unesco.org/ark:/48223/pf0000380721. Accessed 16 Sept 2022

UNESCO-IHP, FAO, UNECE, IAH (2001) Internationally shared (transboundary) aquifer resources management: a framework document. UNESCO, Paris

UNESCO-IHP, UNEP (2016) Transboundary aquifers and groundwater systems of small island developing states: status and trends. United Nations Environment Programme, Nairobi, Kenya

UN-Water (2013) Water security and the global water agenda: a UN-Water analytical brief. United Nations University, Hamilton, ON, 1 p

Wada Y, Heinrich L (2013) Assessment of transboundary aquifers of the world: vulnerability arising from human water use. Environ Res Lett 8:024003. https://doi.org/10.1088/1748-9326/8//2/024003