Transboundary Aquifers

Challenges and the way forward

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SHORT SUMMARY

Cooperation on transboundary aquifers: a key element to achieve sustainable development

The world is facing challenges related to population growth, surface water scarcity, and more importantly, to the increasing dependency on shared groundwater resources.

This book, which is a compilation of studies, representing the status of transboundary aquifers knowledge around the world, offers an attempt to depict a variety of assessments of transboundary aquifers in different regions of the world as well as some insights on policy development.

Potential **strategies and recommendations** to support the socio-economic development and the attainment of the SDGs resulting of the studies are:

- Improvement of the current state of knowledge on the assessment of transboundary aquifers
- Inclusion of stakeholders in the decision-making process
- Effective communication across users and sectors
- Joint data generation and open access to information

The **progress of collaborative mechanisms** that can support the joint development of physical assessments integrating the socio-economic and institutional conditions at a local and regional scales, seem to be driving the current and future discussions of the management towards the sustainability of transboundary groundwater resources.

23%

of the papers are presenting features related to the African countries

This book is a contribution to the "UN-Water Summit on Groundwater" the culminating event of the UN-Water campaign **"Groundwater: making the invisible visible"** that was run throughout all the year 2022.

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"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

Transboundary Aquifers

Challenges and the way forward

Editor
Rosario Sánchez
2022

Foreword

This book contains just over two dozen papers, presented at the *International Shared Aquifer Resources Management* - ISARM 2021 Conference (6-8 December 2021, Paris), that have been selected to illustrate and inform the reader of the range and scope of issues that are associated with transboundary aquifers of the world. The Conference itself was remarkably fortunate in receiving 152 papers that were presented to a very wide audience over 4 days in 18 virtual sessions. While whittling down this immense resource of knowledge and understanding of the issues was an immense task, the collection presented herein is intended to capture the most salient of the issues, such that participants of the UN-Water Summit on Groundwater (7-8 December 2022, Paris) will have to-hand the knowledge base that should enable them to garner action related visibility, not least to the transboundary water resources, but also to those who use and benefit from them, through institutions well equipped to conduct the sound governance of these resources.

The articles in the book cover almost all the key aspects – legal, socio-political, hydro-diplomatic, hydrogeological, while at the same time drawing examples from all continents and most of the climatic types. The historical perspective indicates that the topic of shared groundwater resources has been lifted from near obscurity in 2000 to almost a top priority in the global water agenda by 2022. In these two decades, the understanding of the hydrogeology of transboundary aquifer resources has made significant improvements, while at the same time identifying glaring gaps in some areas. In these two decades, too, the legal framework for international cooperation, from being a side issue in 2000, has reached significant maturity, having been a matter for several UN General Assembly Resolutions, urging governments to address their transboundary resources for peace and cooperation. The articles in the book also illustrate that while at the global scale, there are many 'declarative' statements on the urgent need for cooperative actions, the reality at the interstate level is one of hesitancy and perceived uncertainty to take direct actions, be it in setting up a formal basin commission, or a joint regulating body. The knowledge base that is illustrated through these selected articles is intended to help countries to leave behind their hesitancy and move forward towards joint actions. It is also noted, from a review of the articles, that some excellent examples of the move from hesitancy to action are underway – but they remain too few, too infrequent and too insular. Recent formal inter-country agreements on transboundary aquifer resources remain shrouded in confidentiality, which while somewhat justified to some extent, is also detrimental in the longer run, because opacity in the governance of "common goods" leads to unsustainability.

The articles in the book are intended to give the reader some serious food for thought – has the science of transboundary aquifers been made accessible to policy makers? Are the continuing negotiations on some of the world's critical aquifers, over the past three or so decades in some cases, going to come to direct action? Is the transboundary aquifers component of the Sustainable

Development Goal 6 (SDG 6) indicator 6.5.2 ("Proportion of transboundary basin area with an operational arrangement for water cooperation") likely to be achieved in more than just a handful of countries by the due date? While the book does not answer these questions directly, its contribution to the aims of the UN-Water Summit on Groundwater 2022 is clear.

However much has been done and achieved – but still a lot remains to be done.

Alfonso Rivera,
Co-chair Scientific Committee

Alice Aureli,
Chair Organising Committee

Shammy Puri,
Co-chair Scientific Committee

Acknowledgements

The Division of Water Sciences of UNESCO thanks Alfonso Rivera, Shaminder Puri, Neno Kukuric, Rosario Sánchez, Radwan Mahmoud and Marina Rubio for their contribution to the organization of the Conference ISARM 2021 and the preparation of this book.

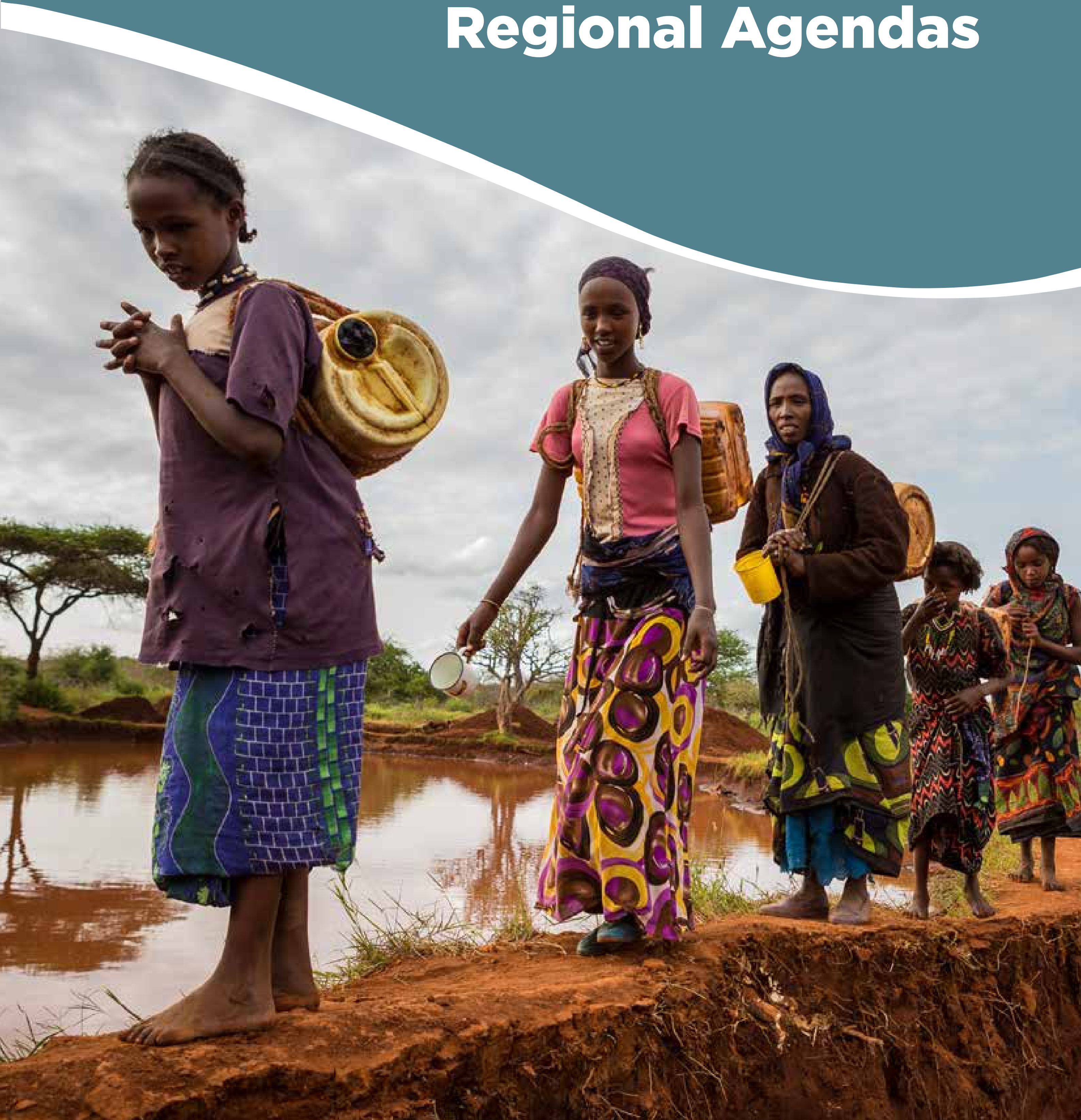
We also thank all other members of the Organizing, Technical and Scientific Committee (lists in Annex) and all the colleagues and interns of the Water Division that made the ISARM2021 Conference possible.

Table of Contents

Topic 3

TOPIC 1

TBA Contributions to Sustainable Development Goals and Regional Agendas



Introduction

by Raya Stephan

Water is at the core of sustainable development. It is critical for human needs, for socio-economic development, and healthy ecosystems. Groundwater represents the largest available source of freshwater on earth, and a lot of it is locked up in transboundary aquifers spanning the territories of two or more States. Transboundary aquifers represent a key component for reaching the objectives set in various international agendas in which freshwater is a key element. The Sustainable Development Goals include a specific goal related to water, and a target about reaching transboundary cooperation. However transboundary aquifers and their management remain critical for achieving the other targets (access to safe drinking water for all, safeguarding water quality, increasing water-use efficiency, ensuring sustainable withdrawals and supply of freshwater in water scarce regions, and protect ecosystems). This dependency increases the need for an established cooperation among the riparian States, ensuring a sound management of this resource. Furthermore, water, and moreover groundwater, represents a transversal element for achieving other goals such as ending poverty, reaching food security, healthy lives, sustaining ecosystems and others.

This section highlights several papers that describe how the topic of transboundary aquifers has impacted and contributed the Sustainable Developing Goals, specifically SDG Indicator 6.5.2. that addresses cooperation and collaboration over shared waters as a mean to assure sustainable development at domestic, regional and international scales.

TOPIC 1/Paper 1

Strengthening Cooperation on Transboundary Aquifers in the Arab Region

Ziad Khayat[1] and Carol Chouchani Cherfane[2]

Abstract

The Arab region is one of the most water scarce regions with two-thirds of its freshwater resources crossing one or more international boundary. The number of transboundary aquifers in the region outnumbers that of transboundary surface water basins. There are 42 transboundary aquifers in 21 out of 22 Arab countries which cover almost 58 per cent of the region in terms of area (UNESCWA, 2015). The dependency of Arab States on external water resources increases the need for better cooperation. This makes achieving water security especially challenging, particularly when also considering that growing demand, declining water quality and climate change are contributing to increasing water scarcity.

Water cooperation in the Arab region has traditionally focused on surface water resources, which are easier to access and understand. However, increased stresses on these resources have led to increased dependency on groundwater resources which has increased interest and political motivation to purse cooperation on transboundary aquifers. This is demonstrated by reporting on the Sustainable Development Goal (SDG) indicator related to transboundary cooperation, SDG indicator 6.5.2. As with global reporting, only few countries from the region were able to report on transboundary groundwater under the indicator, either due to limited understanding or lack of cooperation arrangements. However, reference to groundwater marginally improved during the second reporting round in the Arab region.

Strengthening cooperation on transboundary aquifers in the region requires a multifaceted approach that improves the knowledge base, develops capacities for cooperation including understanding of legal instruments and frameworks, and supports regional mechanisms to operationalize cooperative arrangements.

This paper will take stock of regional initiatives for improving transboundary aquifers cooperation along these three tracks. On the knowledge base pillar, reference will be made to the use of the ESCWA-BGR Inventory of Shared Water Resources in Western Asia and related assessments to inform dialogue. On regulatory and legal frameworks, intergovernmental initiatives will be reviewed, including those mandated by the Arab Ministerial Water Council. The operationalization of existing cooperation mechanisms such as on the Saq/Disi aquifer or the North Western Sahara Aquifer System (NWSAS) and opportunities for financing cooperation will also be examined as well as progress in regional reporting on transboundary aquifers cooperation.

The paper closes by introducing an initiative for enhancing open access to knowledge on groundwater through a regional digital knowledge platform aimed at informing cooperation through increasing understanding of transboundary groundwater resources among states and stakeholder groups.

Keywords: Arab region, transboundary aquifers, cooperation

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Introduction

Arab States are among the most water scarce in the world with 18 out of 22 States falling below the renewable freshwater resources scarcity annual threshold of 1,000 cubic meters per capita and 13 States falling below the absolute water scarcity threshold of 500 cubic meters per capita per year (UNESCWA, 2019). The freshwater scarcity in the Arab region is aggravated by several factors including dependence on shared water resources, water pollution, occupation and conflict affecting people's ability to access water and sanitation services, climate change and extreme climate events, non-revenue water losses from aging water systems, intermittency, inefficient water use and growing demand associated with high population growth rates.

This has driven countries to explore more conventional and non-conventional water resources to meet their freshwater needs with groundwater being one of the most relied upon source. In fact, groundwater is the most relied on water source in at least half of the Arab States and accounts for more than 80 per cent of freshwater withdrawals in[1] Libya, Palestine and Saudi Arabia. Amid increasing water scarcity and climate change, limited renewable groundwater resources continue to be depleted, particularly by the agricultural sector and high population growth in major cities, with most countries in the region extracting groundwater at unsustainable rates.

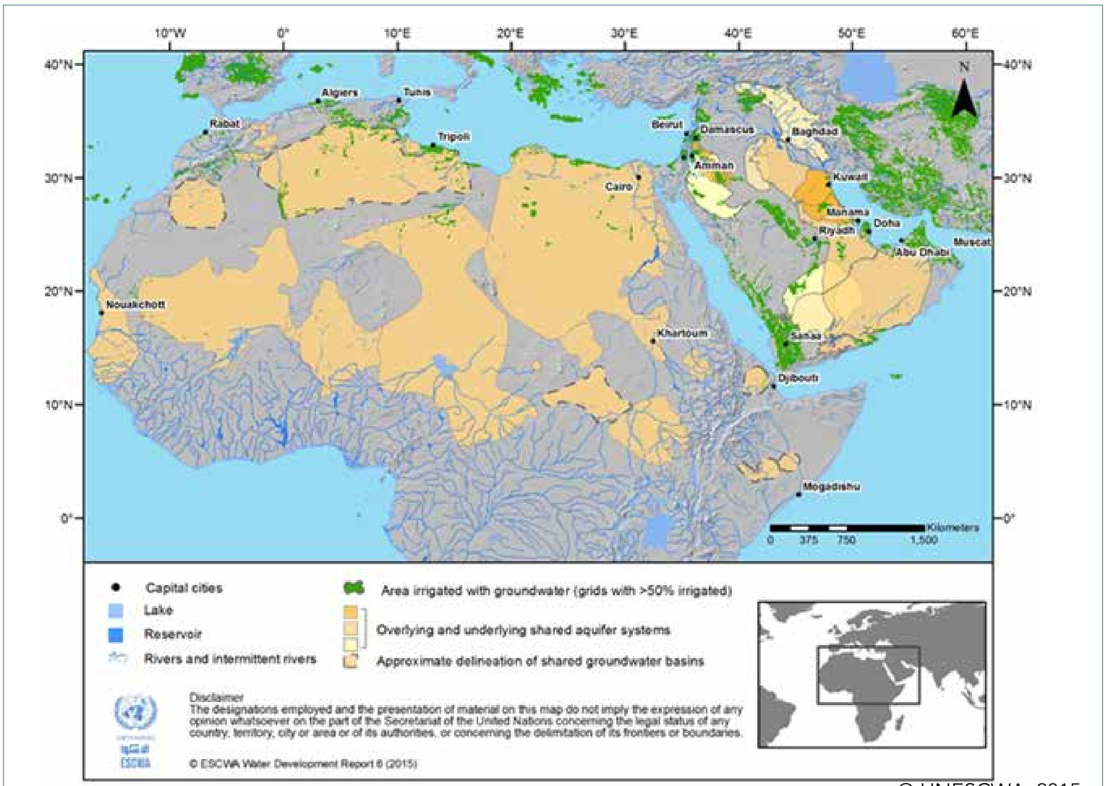
Groundwater in the region also tends to extend over large geographic areas and across political boundaries. All Arab States[2] draw upon one or more of the 42 transboundary groundwater resources (figure 1). Some of these aquifers are directly connected to surface-water hydrological systems and should be managed within the context of combined hydrological units. Other shared aquifers contain fossil groundwater reserves requiring specialized legal, policy and management frameworks that consider their non-renewable character.

Water cooperation in the Arab region has traditionally focused on surface water resources, which are easier to access and understand. However, increased stresses on groundwater resources has increased interest and political motivation to improve cooperation on transboundary aquifers as evidenced by recent cooperation arrangements such as on the Al-Saq/Al-Disi transboundary aquifer between Jordan and Saudi Arabia.

This paper examines several lead initiatives to advance cooperation on transboundary groundwater aquifers in the Arab region.

1 The original text includes Djibouti in the list, as ESCWA classification includes this country in its list of Arab States.
2 The original text was "All Arab States except for Comoros draw upon one or more of the 42..." as ESCWA classification includes Comoros in its list of Arab States".

Figure 1.
Transboundary aquifers in the Arab region



Improving Transboundary Aquifers Knowledge Base in the Arab Region

There have been several initiatives aimed at improving the understanding of transboundary aquifers in the region whether at an aquifer specific scale or at subregional to regional scales.

One such initiative is the Inventory of Shared Water Resources in Western Asia which was the first UN-led effort to comprehensively assess the state and evolution of transboundary surface and groundwater resources in the Middle East (UNESCWA & BGR, 2013).

The Inventory of Shared Water Resources in Western Asia was prepared in collaboration between the United Nations Economic and Social Commission for Western Asia (UNESCWA) and the Federal Institute for Geosciences and Natural Resources (BGR). The process was a highly collaborative effort that included representatives of UNESCWA member countries, academics and other water experts and practitioners in the Arab region and beyond.

This Inventory provided a comprehensive catalogue of transboundary surface water basins and groundwater aquifer systems in Western Asia that systematically address hydrology, hydrogeology, water resources development and use, transboundary water agreements and management efforts.

The Inventory identified and characterized transboundary aquifer systems in Western Asia, by describing basic hydrogeology and groundwater use, recharge and renewability, rock type, aquifer type, exploitability, environmental aspects, as well as agreements and cooperation projects between riparian countries.

Many of the 22 aquifer systems described in the Inventory had never been identified or considered as transboundary resources by riparian countries. In more well-known aquifers, the Inventory presented comprehensive data sets which had not been made publicly available previously. The new maps generated for the Inventory also helped to inform the dialogue by offering a modern easily accessible set of reference materials on transboundary water resources in Western Asia.

This does not mean, however, that findings and interpretations in the Inventory, published in 2013, are to be considered complete. While the Inventory is a static reference document, it aimed to inform a dynamic, multi-stakeholder process of continued analysis and assessment of transboundary water resources and transboundary cooperation governance structures.

Some of the key finding of the Inventory listed below offer ideas and pathways for further research into transboundary groundwater resources to inform cooperation on transboundary aquifers in the region.

Some key finding of the Inventory (UNESCWA & BGR, 2013):

- There are more transboundary water resources than generally assumed.
- Dialogue on transboundary groundwater resource is dominated by water quantity and allocation rather than on potential benefits derived from cooperation on its management.
- The link between groundwater and surface water is often overlooked in the management of transboundary water resources.
- Rapid water quality deterioration is largely neglected and is affecting the ability to use the transboundary groundwater.
- Transboundary groundwater resources management is hampered by lack of accurate data and if accurate data exists, it is often not shared between riparian countries.
- Large regional aquifer systems require a new thinking that identifies more manageable units where transboundary impacts can occur.
- Some transboundary groundwater aquifers have already been overexploited rendering them beyond use. Urgent cooperative dialogue and arrangements are needed to sustain the remaining transboundary groundwater resources.

Additionally, there have been several global and regional initiatives aimed at improving the state of knowledge on transboundary surface and groundwater resources in the region, but mostly focused on surface water resources. Government, academics, regional and international organizations have focused much less on transboundary groundwater resources rendering the knowledge base limited and rarely publicly available. In addition to efforts by UNESCWA other regional organizations have contributed to the knowledge base on transboundary groundwater resources. For example, the Arab Center for the Studies of Arid Lands and Dry Zones (ACSAD) published a comprehensive hydrogeological map of the Arab region in 1988 (ACSAD and UNESCO, 1988). Although the focus of this map was not transboundary water resources and currently there are joint efforts between ACSAD and ESCWA to update this map and to combine it with a groundwater online knowledge platform.

The regional knowledge base is further supported through regional and global studies and databases which include parts of the Arab region but are not focused on this specific region.

Regional Initiatives for Transboundary Water Cooperation

The Arab Ministerial Water Council (AMWC) at the League of Arab States, has shown an early interest in transboundary water resources due to their importance to the region. The interest and the focus on transboundary waters appear also as one of the elements of the Arab Water Security Strategy, which was prepared by the AMWC and approved in 2011. The Strategy covers various water-related challenges to the Arab region such as water and food security, climate change, legal frameworks, and water in occupied Arab territories. Regarding transboundary waters, the Strategy sets among its expected outcomes the establishment of "mechanisms and frameworks for cooperation between Arab States" (League of Arab states, Arab Ministerial Water Council, 2012).

Furthermore, in 2010, the AMWC adopted a resolution inviting the Center for Water Studies and Arab Water Security and UNESCWA to prepare a draft legal framework on transboundary water resources in the Arab region. The principles embodied within this framework are in line with the general principles of international water law but with some specificities of the Arab region such as protecting Arab water rights. ESCWA and other mandated organizations assisted in the preparation of the first draft which was reviewed at an intergovernmental consultative meeting in 2011. The meeting concluded with a draft in the form of a binding convention to be submitted to the AMWC. However, in 2011, the AMWC interestingly opted to limit the scope of the legal framework to transboundary groundwater only. In 2012, during its fourth session, the AMWC decided to revert to the original scope and include all waters, surface and groundwater. Revised versions of the draft framework convention were discussed during seven subsequent intergovernmental consultative meetings held between 2011 and 2016 inclusive.

The AMWC eighth session held in 2016, reached a recommendation to postpone any decision on the Arab draft framework until the conditions for its success are assured and to put in place common principles for transboundary cooperation that would serve for guidance for the Arab region. This reflected the recognition by the AMWC that there were great difficulties in reaching a common agreement on all the articles of the Arab draft framework and perhaps reaching first an agreement on common principles would be beneficial to prepare the proper conditions for stimulating new discussions on the binding draft framework.

UNESCWA as mandated by the AMWC drafted the guidance principles for Arab cooperation in the management of transboundary water resources and presented them at an intergovernmental meeting organized by UNESCWA and the League of Arab States in 2017. The scope of these guidelines covers both transboundary groundwater and surface water. The guidelines have been under discussion since then with the last intergovernmental meeting held in July 2021 without formal approval for their adoption as of yet.

Although the nearly 10-year journey of dialogue on a regional framework for transboundary cooperation and then followed by the cooperation guidelines have not resulted in tangible results in the form of formal adoption of any of these documents, it has provided Arab states with a venue for open dialogue on transboundary water issues and built the capacities of many state actors. It is worth noting that this process has also been accompanied by a variety of capacity building activities carried out by regional organizations as mandated by a standing resolution in the AMWC.

Notwithstanding a regional cooperation framework for both surface water and groundwater resources, other cooperation modalities specifically over transboundary groundwater resources are present in the Arab region. Some of these include those related to the Nubian Sandstone Aquifer System (NSAS), the North Western Sahara Aquifer System (NWSAS) and the Al-Saq/Al-Disi aquifer.

The Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System was established in 1992 by Egypt and Libya and then joined by Chad and the Sudan in the late 1990s (Salman, 2017). This joint authority has the responsibility to collect and update data, conduct studies, formulate plans and programmes for water resources development and use, implement common groundwater management policies, train technical personnel, ration the aquifer water exploitation and study the environmental aspects of water resources development. While the initiative has been in a stalemate for a while, there are recent positive signs that the situation might be changing.

The cooperation modality on the North Western Sahara Aquifer System (NWSAS) shared between Algeria, Tunisia and Libya is in the form of a consultation mechanism hosted by the Observatoire du Sahara et du Sahel. The consultation mechanism was created in 2008. The main objective of the mechanism is to offer a frame for exchange and cooperation between the three countries through generation of indicators that measure the water resources and the water demand, elaboration of management scenarios and development and the management of common monitoring systems (Machard and others, 2011).

The Al-Saq/Al-Disi aquifer has a unique cooperation arrangement in the Arab region in that it is a signed formal agreement between Jordan and Saudi Arabia for the management and utilization of the groundwater in the Disi aquifer. The agreement signed in 2015 mandates the establishment of a Joint Technical Committee to hold regular meetings once every six months or as need arises. The joint technical committee is responsible for the agreement implementation including collection of data and exchange of information and analysis.

The cooperation arrangements on the Nubian sandstone aquifer and on the NWSAS are clear examples of the role that the international community can play in assisting and supporting countries to develop cooperation arrangements. Both transboundary aquifer cooperation arrangements were established through international funding in the form of projects that developed and became more formalized to sustain the results achieved. While clearly developing and sustaining transboundary water cooperation requires the political will of the concerned States, regional and international financial and technical support provides the catalyst and incentive to initiate cooperation which may develop into sustainable formalized arrangements.

It must be acknowledged that sustaining transboundary water cooperation arrangements requires dedicated financing that many countries in the region lack. This requires more innovative and integrated approach both nationally and at the transboundary level through accessing various international funds that may not always be oriented to transboundary water cooperation but may include funds for global climate and environmental conventions and agreements.

Another important factor for cooperation is the presence of dedicated national institutions or mechanisms that have the necessary capacity to properly deal with the complicated nature of transboundary groundwater systems and all the interlinkages with surface water systems.

Regional Reporting on Transboundary Aquifers Cooperation, SDG indicator 6.5.2

The second reporting exercise for SDG indicator 6.5.2 has reflected an improvement for the Arab region both in the number of countries reporting and in the quality of reports regarding the depth of details provided on the details of cooperation arrangements. SDG target 6.5 calls for the implementation of integrated water resources management at all levels, including through transboundary cooperation as appropriate by 2030. SDG Indicator 6.5.2 more specifically monitors the percentage of transboundary basin area within a country that has an operational agreement or other arrangements for water cooperation. The basin area is defined as the surface proportion of the catchment for surface water and the surface proportion of aquifer for groundwater within the country.

In the first reporting exercise, only 9 Arab countries responded to the custodians' survey on SDG indicator 6.5.2. In the second round the number of Arab countries that have reported on this indicator increased to 15 with improved overall quality of responses and with narratives for improved understanding of the cooperation arrangements.

Preliminary findings based on the first two reporting exercises show that progress on transboundary water cooperation is a long process that takes mutual understanding and exchange of information. Information on transboundary waters is either not adequately available or if available not easily accessible to advance cooperation. This is particularly true for transboundary groundwater resources where only 7 out of the 15 countries that reported provided information on transboundary groundwater resources and related cooperation agreements. Of these seven countries that reported on transboundary groundwater cooperation arrangements, Libya and Tunisia reported very high levels above 90 per cent, Algeria at 58 per cent and Jordan at nearly 15 per cent (figure 2). This is expected as all these countries are part of one form of cooperation arrangement or another.

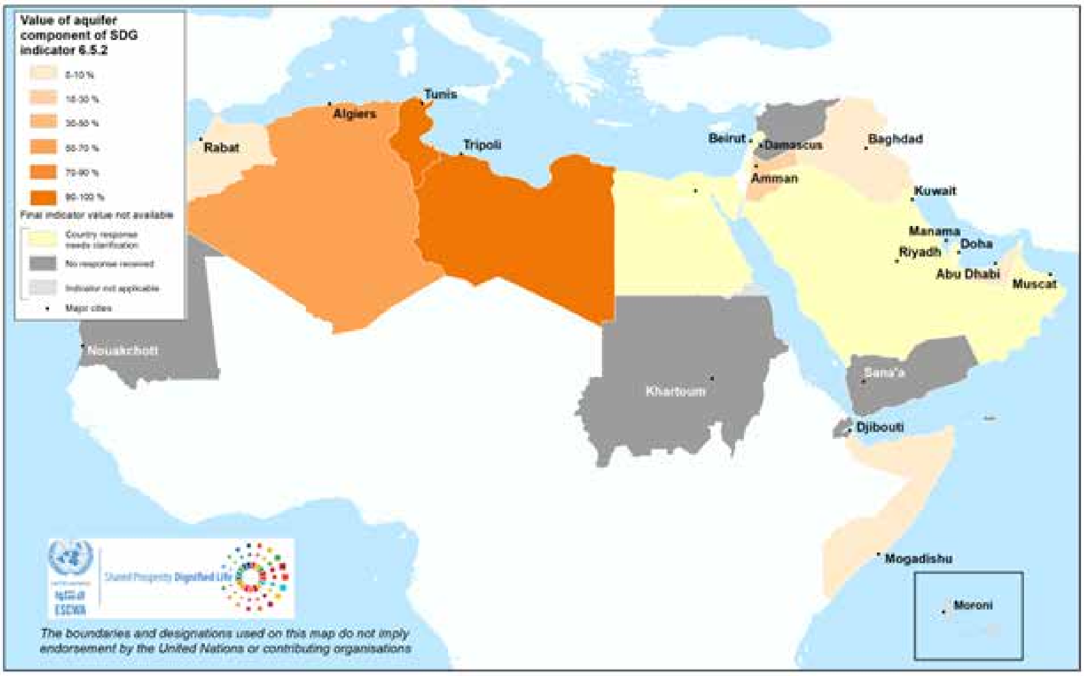
Any acceleration related to transboundary water cooperation requires an improved understanding of transboundary groundwater resources, dedicated financing, and improved access to information and monitoring, institutionalized through mandated bodies.

Arab Groundwater Digital Knowledge Platform

A clear gap for advancing transboundary groundwater cooperation as demonstrated by the Arab region responses to SDG indicator 6.5.2 and key findings of the Inventory of shared water resources is the lack of understanding of transboundary groundwater aquifers and the lack of or access to data and information. In response to these challenges, UNESCWA will be launching in collaboration with regional partners such as ACSAD and in collaboration with UNESCWA member States a dedicated Arab Groundwater Digital Knowledge Platform. The purpose of the platform is to make available and accessible data and information on groundwater resources in the Arab region building on existing resources and innovative technologies to develop and populate the platform and provide a user-friendly interface helping to inform policymaking.

This platform would complement other regional knowledge platforms and networks that ESCWA has built on climate change, integrated water resource management and the SDGs. The governance structure would include representatives of UNESCWA member States.

Figure 2.
Transboundary groundwater basin level cooperation in the Arab region, including countries that need further clarification as per 2020 SDG indicator 6.5.2



(Source: © Open street maps, Own Elaboration)

Conclusion

Strengthening cooperation on transboundary aquifers in the region requires a multifaceted approach that improves the knowledge base, develops capacities for cooperation including understanding of legal instruments and frameworks, improves access to multisource funding and supports regional mechanisms to operationalize cooperative arrangements. Building on existing initiatives of knowledge and experience exchange between Arab countries that have succeeded in establishing cooperation arrangements on transboundary aquifers will help excel strengthening cooperation.

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TOPIC 1/Paper 2

The Evolution and Success of ISARM, 2010-2020

Alfonso Rivera[1], Christina Fraser[2], Alice Aureli[3]

Abstract

The International Shared Aquifer Resources Management (ISARM) initiative was launched in 2000 at the 14th Session of the Council of the Intergovernmental Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). Ten years after, on 6-8 December 2010, UNESCO organized the first International Conference "*Transboundary Aquifers: Challenges and New Directions (ISARM2010").*

Since 2000, the ISARM initiative has facilitated projects for the identification, mapping and assessment of transboundary aquifers (TBAs). The initiative carried out regional studies designed to delineate worldwide TBAs and provided guidance for countries' cooperation on TBAs.

Within the framework of ISARM, UNESCO teamed up with donors such as the Global Environment Facility (GEF) and the Swiss Agency for Development and Cooperation (SDC), and initiated projects in different regions to support countries engaged in the development of the management and governance plans of groundwater resources contained in transboundary aquifers.

In cooperation with its main partners, in particular the International Association of Hydrogeologists (IAH), the UNESCO ISARM initiative has created a great legacy. This paper presents some of the activities and projects implemented in the framework of ISARM, such as the Transboundary Water Assessment Programme (TWAP) and the Governance of Groundwater Resources in Transboundary Aquifers (GGRETA).

Since the year 2002, ISARM has provided a framework for the substantial advancement of the legal component of the sustainable development of TBAs. UNESCO-IHP assisted the United Nations International Law Commission (UNILC) in the preparation of 19 Draft Articles on "The Law of Transboundary Aquifers" considered in several resolutions of the UNGA. This paper examines the contribution of ISARM towards the achievement of cooperation on TBAs and considers the results of the Sustainable Development Goal Indicator 6.5.2. Finally, the paper synthesizes the most important outputs and outcomes of the last 20 years of the ISARM initiative, drawing conclusions and reflections for the way forward for ISARM.

Keywords: ISARM, evolution, global, transboundary, aquifer

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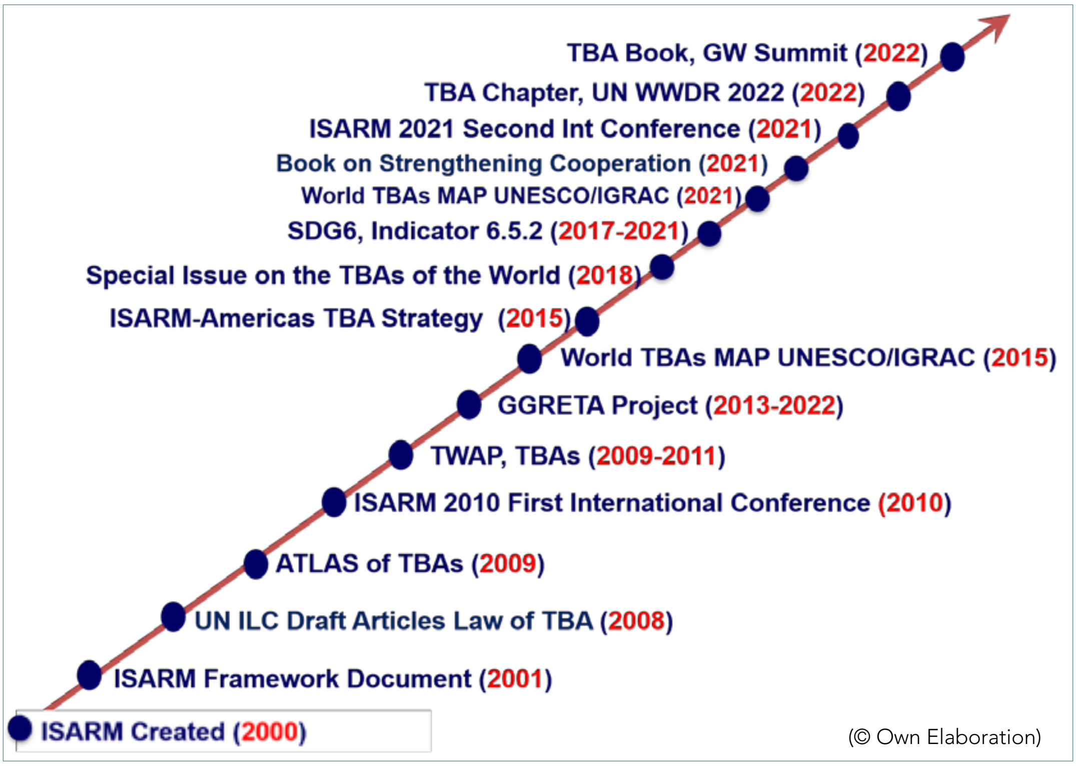
Introduction

Transboundary aquifers represent very large resources of fresh water with some individual aquifers yielding enough water to supply regions for many years (Wada and Heinrich, 2013). Globally, 153 countries share transboundary surface water and groundwater accounting for over 40% of the world's freshwater (UNESCO-UNECE second SDG 6.5.2 report 2021) and with the exclusion of most island nations, every nation on Earth is linked hydrologically to its neighbors. However, while the transboundary nature and the knowledge of international rivers and lakes have advanced substantially, the knowledge and the management of transboundary aquifers is lagging behind (Eckstein and Sindico, 2014).

Recognizing the importance of groundwater as a source of fresh water and the lack of knowledge on TBAs, the Internationally Shared Aquifer Resources Management (ISARM) initiative was launched in 2000 at the 14th Session of the Council of the Intergovernmental Hydrological Programme (IHP) of UNESCO. The initiative began studies on the scientific, socio-economic, legal, institutional, and environmental aspects of transboundary aquifers. Since its inception, ISARM has launched a number of global and regional activities designed to delineate and assess transboundary aquifer systems; it has recommended the multidisciplinary methodological approach for transboundary aquifers assessment encouraging riparian states to work cooperatively toward mutually beneficial and sustainable aquifer development. It has also been heavily involved in the development of legal frameworks for the improved governance of transboundary aquifers. Figure 1 shows the timeline of selected ISARM outputs over the past two decades.

Figure 1.
Timeline of ISARM outputs



(© Own Elaboration)

Progress of transboundary aquifer assessment, and cooperation and collaboration through hydro-diplomacy

The global legacy of UNESCO on TBAs is substantial. Many activities, including training and capacity development, have been undertaken by UNESCO over 20 years to foster cooperation.

During the last decade, ISARM expanded its scope of works and on international reach. In the framework of the initiative, important regional networks were created, and regional inventories refined. In addition, a number of TBA-focused projects contributed to fostering cooperation and facilitating the establishment of cooperative mechanisms. Table 1 shows the numbers of transboundary aquifers that ISARM initiative has identified per region and the related current number of cooperation agreements.

Table 1.
Main ISARM findings of TBA Global perspectives as per 2018 (after Rivera and Candela, 2018)

Region	Transboundary Aquifers	Agreements
Africa	72 TBA identified A few TBA adequately studied and assessed	2 political agreements International scientific arrangements
Americas	74 TBA identified 40% of TBAs mapped	1 political agreement Many scientific arrangements
Asia	129 TBA identified A few mapped	1 political agreement Some scientific arrangements
Europe	226 groundwater bodies identified under the Water Framework Directive	2 political agreements Many scientific arrangements

ISARM-inspired UN Draft Articles

One of the main achievements of ISARM is the contribution provided to the United Nations International Law Commission (UNILC). In 2002, the UNILC included the topic of shared natural resources in its work program, covering transboundary groundwater. In 2008, 19 Draft Articles on "The Law of Transboundary Aquifers" were annexed to a UN General Assembly resolution and referenced in several subsequent UNGA resolutions.UNESCO-IHP and IAH provided the UNILC Special Rapporteur, Ambassador Chusei Yamada, with scientific and technical support and organized a large experts group composed of international experts from different regions of the world and from several international and national institutions. Key influences on the articles include ensuring that focus was given to the aquifer and not just groundwater and highlighting the importance of considering the geological and hydrogeological characteristics of aquifers as a starting point of their study.

The Drat Articles are currently the only international instrument attentive to the hydrogeological aspects of transboundary aquifers and the groundwater they contain in storage. The articles include recommendations to consider the recharge and discharge zones of recharging aquifers, to evaluate the aquifers' important role in sustaining the environment and dependent ecosystems, and to give priority to the use of the groundwater for human needs.

The Draft Articles deliberate on the difficulties when entering into negotiations when one of the riparian countries is less advanced economically and owns less capacity and knowledge. The articles also appreciate the long-term benefits of cooperation on transboundary aquifers (Burchi, 2018). They are not legally binding, instead they are intended to provide technical guidance for countries who wish to utilize them in entering into cooperation for the study of their aquifers and the development and negotiation of agreements. Since 2008, the Draft Articles inspired and are mentioned in the Guarani Aquifer Agreement, and the Iullemeden, Taoudeni/Tanezrouft Aquifer Systems (ITAS) Memorandum of Understanding (Burchi, 2018).

The development of the Draft Articles has also led to scientists further investigating the transboundary nature of TBAs, and the complexity of the assessment, analysis, and management of these systems. The Draft Articles seem to have also triggered a paradigm shift in the way TBAs are perceived, with research developing new technical terms and vocabulary e.g., *transboundariness*, *TBA-hydro-diplomacy*, *zoning*, *hotspots* (Sanchez et al., 2018; Fraser et al., 2020). Furthermore, new definitions of TBA typologies have emerged (Rivera, 2015; Eckstein, 2017).

TWAP and Aquifer Mapping

The Transboundary Waters Assessment Programme (TWAP) was a seminal project dedicated to conducting the first global baseline assessment of transboundary water systems, funded by the Global Environment Facility (GEF). The project had 5 components: Transboundary River Basins, Transboundary Lake Basins, Large Marine Ecosystems, Open Ocean, and Transboundary Aquifers and Small Island Developing States (SIDS) Groundwater Systems. Its first phase was completed in 2011. UNESCO and the International Groundwater Resources Assessment Centre (IGRAC) were entrusted with the execution of the groundwater component. UNESCO and IGRAC assessed 199 transboundary aquifers and 43 SIDS aquifers. In order to support this process, IGRAC developed a web-based Information Management System (IMS) to host data collection, storage, processing, visualization and sharing of a variety of data and information (IGRAC and UNESCO-IHP, 2016).

The aim of the Transboundary Waters Assessment Programme was twofold: (1) to identify priority TBAs for investment purpose based on the description of current and future conditions of the main TBAs globally (primarily those with an aerial extent of >5,000 km^2, but also a few additional smaller key TBAs); (2) to bring the main issues, concerns and hotspots of these TBAs to the attention of policy makers, Official Development Assistance (ODA) providers and International Financial Institutions (IFIs), as well as to the scientific community. The methodology of the assessment focused on an indicator-based approach that was designed to capture the state and trends of the world's groundwater resources. 20 indicators were used, 10 of which were deemed core essential indicators. Moreover, a questionnaire was sent out to the UNESCO network and to over 200 national experts, and regional expert group were established in order to collect indicator data alongside other information, such as aquifer delineation. In addition, a WaterGap model was developed to identify the current and likely future state (2030 and 2050) of TBAs that exceeded 20,000 km^2 by assessing some of the above-mentioned indicators (e.g., future recharge, future withdrawals). The TWAP project increased understanding of TBAs internationally and has significantly contributed to the improvement of TBA assessment and delineation. Key outcomes and insights of TWAP include:

1. The identification of new TBAs and improved delineation of others;
2. The recognition that most of the large TBAs are located outside regions affected by high levels of groundwater stress and show very low levels of depletion. Combined with high residence times, these TBAs can add a valuable resource for water development and climate change mitigation;
3. Hotspots of high human dependence, low renewability and high extraction/recharge rations are actually fairly limited and even in the worst-case scenario models, very high-risk hotspot areas are only expected to increase from 20 to 58;
4. Governance and institutional frameworks are extremely limited for TBAs, the only exception being 6 cases of which 2 are in Africa;
5. There is a severe lack of knowledge and modern data available for groundwater and TBAs in particular. Modelling in these situations becomes essential;
6. TWAP established the first Global Inventory of Transboundary Aquifers that is hosted publicly on a dedicated TWAP Groundwater Information System;
7. Finally, TWAP produced a standardized set of data collection and TBA assessment methodologies, which are now being applied in other TBA studies across the globe (UNESCO-IHP, 2017).

Projects like the TWAP have significantly improved the global understanding on TBAs. IGRAC regularly published the outcomes of all available TBAs mapping and delineation improvement facilitated through projects like TWAP. Maps from 2009, 2012, 2015 show the information available at that time on the occurrence and extent of transboundary aquifers worldwide. The most recent map, published in 2021 illustrated 468 TBAs (IGRAC, 2021) covering almost every nation state. Data from the TBA map is also accessible online through IGRACs Global Groundwater Information System (GGIS), which is a valuable tool for stakeholders who wish to access GIS data for further TBA understanding and assessment (IGRAC and UNESCO-IHP, 2015).

GGRETA

The project *Governance of Groundwater Resources in Transboundary Aquifers* (GGRETA) was designed to enhance cooperation on water security, prevent transboundary and water-use conflicts, and improve overall environmental sustainability (UNESCO, 2016a). It is an integral component of UNESCO's Internationally Shared Aquifer Resource Management initiative.

GGRETA was launched in 2013 with three phases: the first phase ran from 2013 to 2016; the second from 2016 to 2019; and the third phase from 2020 to 2022. During the first phase, in-depth scientific assessments were conducted in three selected case studies: the Esquipulas-Ocotepeque-Citalá (Trifinio) Aquifer in El Salvador, Guatemala and Honduras; the Stampriet-Kalahari / Karoo Aquifer in Namibia, Botswana and South Africa; and the Pretashkent Aquifer in Kazakhstan and Uzbekistan.

The second phase of the project focused on governance and the development of frameworks, tools and guidance to enhance transboundary dialogue and discussion, as well as to further develop established capacity building, hydro-diplomacy and gender initiatives.

In the Southern Africa region, GGRETA Phase 2 saw the development of a Multi-Country Cooperation Mechanism (MCCM), a unique governance approach agreed to by the Governments of Botswana, Namibia and South Africa to consolidate the achieved technical results of the GGRETA program for the

Stampriet Transboundary Aquifer (UNESCO, 2016; Ross, 2015; Haasbroek, 2018). The main purpose of the MCCM is to ensure the continued joint collection and exchange of data and information among the STAS countries to feed the STATS Information Management System. It is also hoped that long term, the MCCM will provide joint strategic assessment and advice to STAS countries on management issues relating to the STAS groundwater resources (UNESCO, 2016; Ross, 2015; Haasbroek, 2018).

In 2017, the decision was also made to nest the MCCM in ORASECOM's Ground Water Hydrology Committee (GWHC), the first operational governance mechanism to be nested in a river basin organization and the first instance of institutionalizing cooperation over a TBA in Southern Africa (UNESCO, 2016). This is of particularly significance within the 2030 Agenda as it provides the first cooperative arrangement since the adoption of the Sustainable Development Goals alongside an in-practice example of a full IWRM approach to transboundary aquifer management (UNESCO, 2016; Ross, 2015; Haasbroek, 2018).

Phase 3 was officially launched in January 2020 and will be implemented from 2020 to 2022 through four inter-linked components (GGRETA, 2021):

1. Establishment of institutional and technical capacity on groundwater governance in river basins organizations, regional communities, and selected aquifer systems in Africa.
2. Consolidation of regional cooperation through investments on aquifer commissions, partnerships, and networks, aiming at setting the base for transboundary aquifer regional strategies (with a special focus on Africa).
3. Development of evidence-based and decision-making capacity on transboundary groundwater resources quality protection and monitoring.

In the Central America region, technical studies undertaken at the end of Phase 1 in El Salvador, Guatemala and Honduras demonstrated that the aquifer system, which was originally believed to underly the three countries, was in fact two separate aquifers: the Esquipulas aquifer, which underlies Guatemala only, and the Ocotepeque-Citala Aquifer, which underlies the contiguous territory of El Salvador and Honduras). Thus, only the latter was deemed to be a transboundary aquifer that could be considered in subsequent phases. A letter of intent was signed by El Salvador and Honduras in 2019;[2] it is not legally-binding but includes references to surface water, as well as women and indigenous participation in a possible future bi-lateral mechanism.

Role of ISARM within the SDG 6.5.2

In 2015, the 2030 Agenda for Sustainable Development was adopted by all United Nations Member states. Superseding and building upon the Millennium Development Goals era, the Sustainable Development agenda is built around 17 global goals that are designed to reflect current global challenges within the 3 pillars of sustainable development: economic, society and environmental. ISARM principles have contributed to the SDG targets.

To track and measure the progress of SDG 6, Target 6.5, UN member nations are asked to report on two separate indicators: 6.5.1

(the degree of integrated water resources management implementation) and, 6.5.2 (the proportion of transboundary basin area with an operational arrangement for water cooperation). UNESCO led the development of a methodology to calculate indicator 6.5.2 alongside co-custodians for the indicator, UNECE. The methodology calls for the calculation of the proportion of a transboundary basin/aquifer area with an operational arrangement for water cooperation within a state (UN Water, 2020a).

In the second reporting cycle for the indicator in 2020, 129 out of 153 countries sharing transboundary waters responded to the invitation to report on SDG indicator 6.5.2 progress. For the 101 countries where an indicator value could be calculated, 24 reported that operational arrangements covered all of their transboundary basins. The global average of the indicator value in 2017 and 2020 is almost the same, i.e. 58 per cent in 2020 compared with 59 per cent in 2017 (UNECE and UNESCO, 2021).

However, when looking at transboundary aquifers specifically, the coverage is 42%, even lower than the overall indicator. Very few countries reported that all of their transboundary aquifers are covered by operational arrangements, and only 8 transboundary aquifer-specific arrangements are reported to be in place (UNECE and UNESCO, 2021).

The results from the 2020 SDG 6.5.2 indicator progress report highlight that a consorted effort must be made to accelerate the achievement of target 6.5. Currently, predicted uptake of transboundary aquifer arrangements is low and therefore many countries are not expected to meet the target by 2030 (UN and UNESCO, 2018). In 2020, the Sustainable Development Goal 6 Global Acceleration Framework was launched, an initiative that aims to deliver fast results at an increased scale for SDG 6 and its corresponding targets (UN-Water, 2020c). The Acceleration Framework will be driven through 5 accelerators: optimized financing, improved data and information, capacity development, innovation, and governance (UN-Water, 2020b). Within the context of transboundary aquifer cooperation this will need to include increased financing for transboundary aquifer projects, further aquifer delineation and assessment, initiatives for cross border data sharing and harmonization, better monitoring practices, increased capacity, and the drive to push transboundary aquifer cooperation further up national political agendas.

Summary, challenges and the way forward

After two decades of ISARM, the initiative continues and will continue to inspire countries to make progress on transboundary aquifer characterization assessment and modelling, transboundary aquifer governance and shared management, and engaging nations to share TBAs; the UN Draft Articles could be used as guidance.

However, lack of investments and capacity impede many countries to fully assess and perfect their knowledge of these systems. The lack of knowledge creates an obstacle for countries to engage in negotiations and prevent them from entering in cooperation programmes. The role of the UN system is crucial in supporting countries to acquire the baseline scientific knowledge to enter into cooperation. The UNGA resolutions welcome the role played by the UNESCO Intergovernmental Hydrological Programme through the ISARM initiative; they recommended that UNESCO continue providing support to countries wishing to begin studying and cooperating on their transboundary aquifers.

Several new studies need to be undertaken in relation to issues of time-scale and space-scale factors, which are still misunderstood. Transboundary agreements and arrangements are still rare, and investments are needed in many regions to create new projects and support countries in undertaking adequate studies.

At the global scale, it is recommended to assess the baseline scientific knowledge on each TBA to support cooperation agreements and provide the basis for more elaborate legal and management instruments.

Major efforts are required to sustain shared management of transboundary aquifers against global issues: climate change, surface water/groundwater interactions, water footprint, water security, transboundary effects and conflict resolution. Trust building achieved via scientific cooperation and the continued dialogue among two or more nations sharing the same aquifer is essential to establish meaningful collaboration towards shared goals.

ISARM has made a major contribution to the assessment and governance of the transboundary aquifers of the world, as well as to the sustainable management of resources with increasingly strategic importance in the face of climate variability.

In launching this initiative 20 years ago, UNESCO and the IAH have established a firm foundation for a challenging but urgent global action.

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TOPIC 1/Paper 3

Local-Regional Governance Approaches for more Effective TBA Management

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Abstract

Worldwide countries face challenges to restore and preserve water resources in accordance with UN Sustainable Development Goal (SDG) 6. These challenges relate to the ecological, hydrological and hydrogeological domain, societal and policy context, and the role of legal frameworks. Transboundary aquifers (TBAs) and dependent ecosystems present yet another challenge in attaining SDG 6 due to issues related to a lack of coherence of legal and policy frameworks between neighbouring countries.

In Europe, the Water Framework Directive (WFD, 2000/60/EC) offers an overarching framework to secure Europe's waters for future generations. As it uses a river basin approach, it holds a strong potential for effective transboundary management. The requirements set in the WFD regarding international cooperation show a strong resemblance to the target set for transboundary water management in SDG 6.

Although the European Commission flagged the WFD as effective in terms of cooperation (2019), water quality improvement seems to have been impeded to date. The studies conducted so far often focus on effectiveness at the scale of river basins. Here, we have studied how governance approaches at the local-regional level support the attainment of water quality ambitions, using scientific literature and empirical material on water quality governance approaches in the Netherlands.

Because of the hydrogeological nature of the Netherlands, substantial parts of the country's aquifers are transboundary. Several of the cases studied are directly influenced by transboundary challenges. In general, our analysis identifies five areas for improvement of water quality governance approaches that are relevant and should be considered in the context of transboundary aquifers.

These areas for improvement affect policy responses to drivers, pressures and the state of river basins and related aquifers. This means that the linkages between governance approaches, water system characteristics and the driving forces from other sectors that lead to water quality improvement are much more complex than described in the literature so far and require a joint approach from different sectors and knowledge domains, e.g. hydrology, ecology, law, sociology and economy.

Keywords: governance conditions; connectivity; social-legal ecology.

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Introduction

What is needed to restore and preserve healthy and sustainable freshwater transboundary aquifers (TBAs) and related ecosystems in accordance with UN SDG 6 (UN 2018)? Overexploitation of groundwater aquifers and pollution caused by industry and land use are the main areas of concern regarding these ambitions.

With 468 transboundary aquifers identified worldwide, countries on all continents face the challenge of meeting this objective in the transboundary context (IGRAC 2021, Sindico 2016). Integrated Water Resources Management (IWRM) could be considered as the means to do so, as IWRM calls for integration between water resources management and the management of other environmental and social-economic activities that may have an impact on water resources.

In its report on the progress made on SDG 6, the UN noted the complexity of the implementation of IWRM, with limited progress so far and great variations between countries regardless of their economic status (UN 2018). Moreover, it remains unclear what conditions IWRM needs to meet to contribute to water quality improvement. In this paper, we aim to contribute to this knowledge gap by analysing governance approaches at the local-regional level in the Netherlands (Europe) and possible implications for the transboundary context. Governance conditions cover both technical, legal and social-economic aspects, e.g. understanding of the water system, stakeholder involvement and trade-offs, institutional settings and legal frameworks (Wuijts, 2020).

European context

In the European context, the challenges to achieving SDG 6 can be identified in 226 transboundary 'groundwater bodies' (IGRAC and UNESCO-IHP 2015). A groundwater body is defined as a distinct volume of groundwater within an aquifer or aquifers under the EU Water Framework Directive (2000/60/EC, WFD, Article 2).

The WFD and related Directives, such as the Groundwater Directive (2006/118/EC), the Nitrates Directive (91/676/EEC) and the Habitat Directive (92/43/EEC), offer an overarching framework to secure Europe's waters for future generations. The WFD's objectives could be regarded as an obligation of results (see e.g. ECJ C-559/19). As it uses a river basin approach, it holds a strong potential for effective transboundary management in line with SDG 6.

With the WFD, Europe has also introduced governance as a means to attain WFD objectives. Governance approaches, with the involvement of multiple actors at multiple levels, are often considered more effective in dealing with complex water quality challenges than conventional legal frameworks with top-down central steering mechanisms (Howarth 2017). Governance approaches could be considered a follow up to IWRM, including the process of setting objectives (Wuijts, 2020).

The WFD has been effective in encouraging cooperation and setting up governance approaches (EC 2019), yet the achievement of its objectives has been significantly delayed. Good chemical status has been reported for only 74% of the EU's groundwater bodies and 40% of surface water bodies (EC, 2019). Several

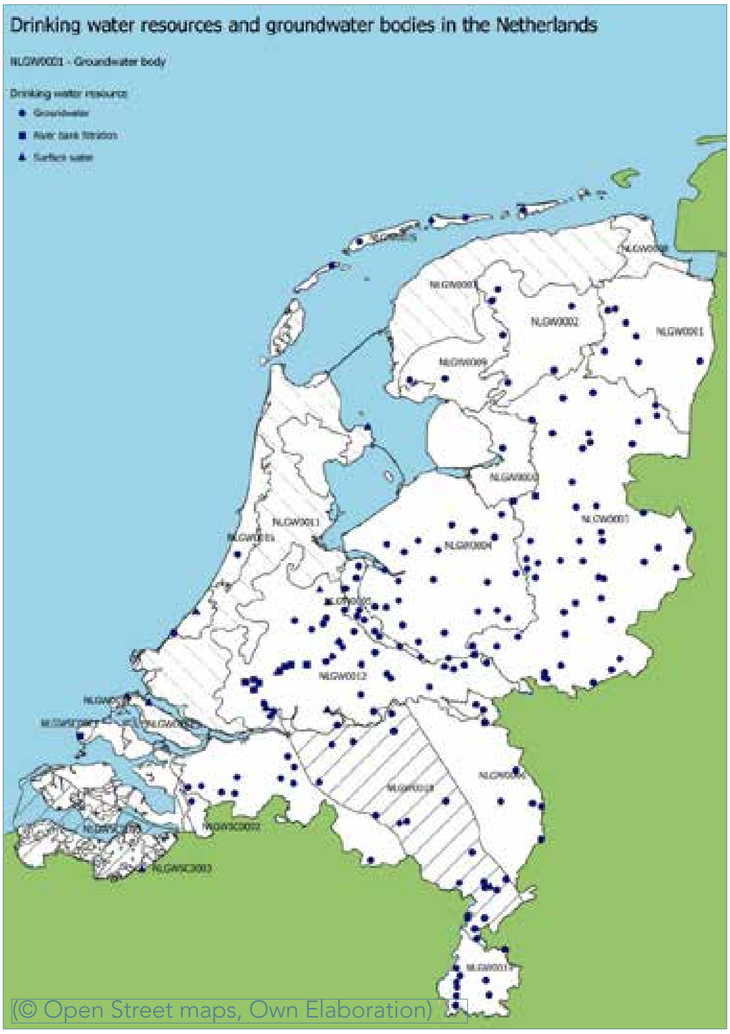
Member States report significant problems with the quantitative status of groundwater bodies due to overexploitation.

Water quality management in the Netherlands

The challenges to achieving WFD ambitions also manifest themselves in the Netherlands. Half of all drinking water resources and 40 to 70% of regional surface waters are at risk of not meeting WFD objectives by 2027 (Van Gaalen, Osté and Van Boekel 2020), due to agricultural and industrial pressures on surface water and groundwater.

The country encompasses the delta of four international river basins: Meuse, Scheldt, Rhine and Ems. The groundwater bodies in this region are part of transboundary aquifers. For drinking water resources, smaller, transboundary catchment areas have been identified (Figure 1). These catchments also have groundwater interactions with smaller regional brooks.

Figure 1.
Groundwater bodies and drinking water resources in the Netherlands



(© Open Street maps, Own Elaboration)

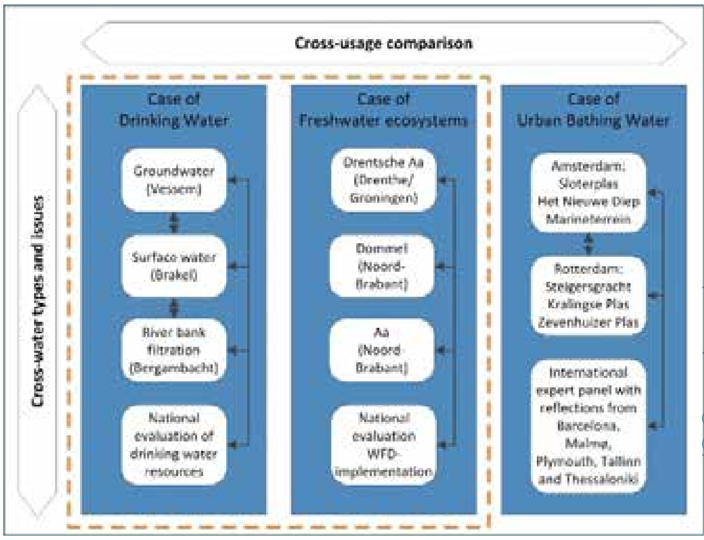
Methods

For this study, a systematic literature review was carried out regarding the effectiveness of governance approaches. The results were used to identify knowledge gaps and to develop the focal points of the empirical research.

The cases focused on different water usages (drinking water, freshwater ecology and bathing water), but all under the regulatory framework of the WFD. Cases comprised both surface water bodies and groundwater bodies, 6 of which encompass transboundary aspects (Figure 2) (Wuijts 2020).

Cases were studied by means of interviews, water quality data and both scientific and grey literature, and the research results were reflected on in the national and international context. To avoid any bias in the results caused by differences in the mode of implementation, the empirical research was restricted to the Netherlands.

Figure 2.
Case study design (Wuijts 2020). In orange: cases presented in this paper



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Results

Literature review

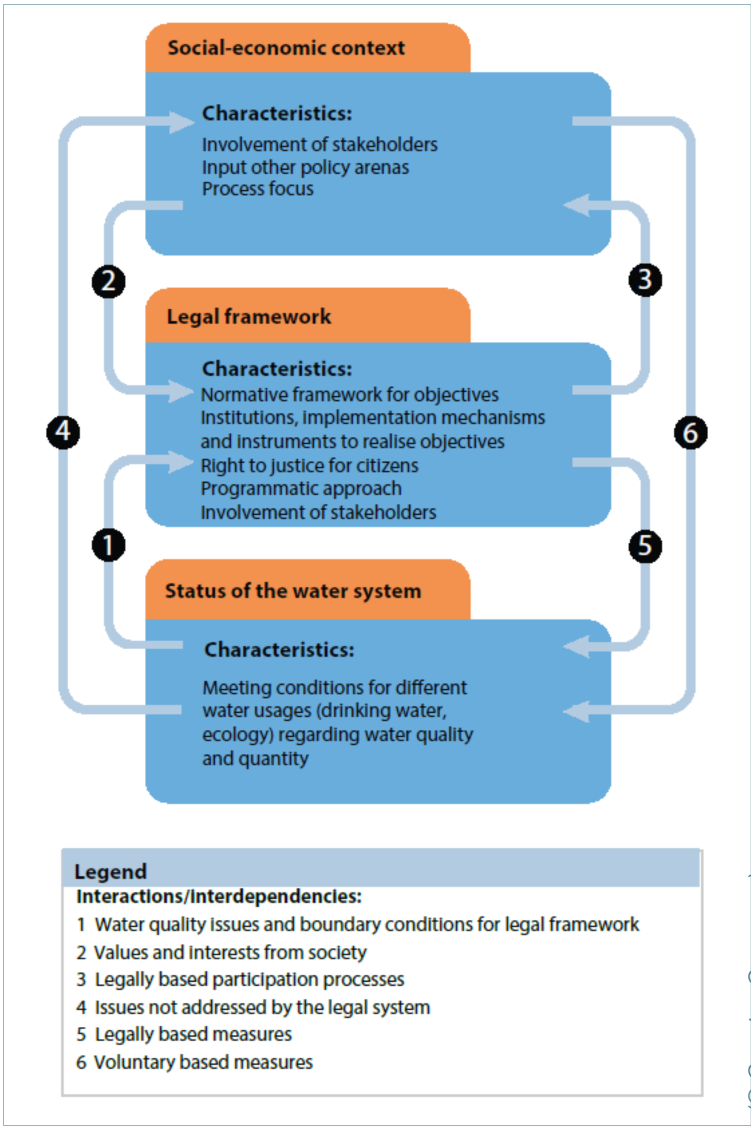
The literature review showed that perspectives on effectiveness may differ between scholars from the social-economic, legal and ecological-hydrogeological knowledge domains (Wuijts, Driessen and Van Rijswick 2018). These differences and the interdependencies between knowledge domains should be considered in a governance approach (Figure 3).

Examples from the Netherlands showed that the absence of input from the social-economic context and legal framework, can result in the stagnation of water quality improvement. For instance, if other, conflicting priorities are set in the societal debate, such as regarding the use of pesticides in agricultural practices, this may influence the achievement of water quality ambitions. In practice, this information on possible trade-offs for water quality ambitions is often not included in decision-making.

Research to date has often been set up from a specific knowledge domain, with the exception of the field of social-ecology. However, the role of the legal domain and its interactions with other knowledge domains should also be considered, for instance in terms of the identification of pressures on water quality, the complex groundwater response, and how to anchor them in legal frameworks.

The literature review also revealed that the scientific debate focuses on policy preparation and design, but much less on implementation. This could explain the weak understanding of how governance approaches are linked to water quality improvement and what could be done to increase effectiveness of governance approaches.

Figure 3.
Perspectives on effectiveness and the interactions between knowledge domains (Wuijts et al., 2018)



Case studies

The cases studied show that the interlinkages between governance approaches and water quality improvement are much more complex than has been described in the scientific literature.

The case of drinking water resources showed that governance approaches are often not designed with the characteristics of the water system and drivers of water quality in mind, but rather follow existing relationships and structures. This means that parties that have to act on drinking water objectives may not be aware of or feel the need to do so. This is especially the case for emerging contaminants not yet covered by legal standards.

In the transboundary context, protection zones are often delineated by national borders rather than hydrogeological zones. Recent initiatives to overcome this gap were often incident-driven, e.g. based on the risks for groundwater quality posed by the development of underground storage of chemical and nuclear waste and illegal manure dumps. In these cases, the incidents prompted the actors involved to meet and discuss strategies to reduce current and future risks.

The case of freshwater ecosystems showed that healthy freshwater ecosystems have hydrological, morphological and physical-chemical needs, each of which require specific governance conditions. For instance, it is possible to adopt policies at a more local level to address the groundwater dependency of an ecosystem, but upstream spills need to be addressed in a river basin context and require cooperation with other authorities within other policy and regulatory frameworks. This means that objectives need to be specific enough to identify the governance conditions needed and need to include the institutional settings of the diverse governance levels of the countries involved.

Discussion and conclusions

The complex relationship between governance and water quality improvement may explain the challenges experienced in policy practice. Choices made in the governance approach (who to involve and at what level, availability and use of instruments, measures, and monitoring) influence the water quality improvement that can be achieved. In the transboundary context, this plays an even stronger role, since it has been found that countries apply different modes of implementation (Voulvoulis, Arpon and Giakoumis 2017).

Governance conditions needed to improve water quality include engaging actors at relevant hydrological scales and at the appropriate level and creating connectivity between the different institutional levels involved. Local authorities should be able to list issues that cannot be resolved at the local level (e.g. emerging contaminants) and have them aligned to policy development on these issues at national and transboundary level, especially in countries with a high level of decentralisation (principle of subsidiarity), in addition to the subsidiarity principle that is leading in EU environmental law.

Furthermore, objectives may create different demands for governance conditions, e.g. regarding the scale, the actors to be involved at the various levels and the coherence and consistency of the legal and policy frameworks in place. This may require opening up governance approaches beyond the jurisdiction of water authorities but could contribute substantially to achieving WFD objectives. Further guidance, also on a European level, could support this development.

As the achievement of water quality ambitions takes place in the context of other social and economic activities, tailored information on the value of water to society and its vulnerability should be brought into the societal debate more explicitly at different levels and scales to get sufficient societal commitment and adapt policy interventions in response to monitoring of results.

Discussions on transitions in agriculture, SDGs, urban and industrial development should be fed with this information on water quality, its challenges, and its usages. This is necessary not only to prevent deterioration, but also to set shared objectives and to achieve co-benefits.

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Conclusions

by Raya Stephan

The ISARM Conference has continuously recognized transboundary aquifers as an important component for the achievements of the Sustainable Development Goals, not only target 6.5.2 related to transboundary cooperation, but also under SDG 6 and other water related goals.

The contribution and support of the ISARM program towards the realization of the SDGs and other global agendas, such as the Climate Change framework or the human rights through its results and achievements, is widely acknowledged. The program has initiated global awareness on the importance of TBAs through its regional developments on the five continents. Over the last two decades the program is inspiring countries to make progress on TBAs characterization, assessment, modelling and to develop TBAs governance and shared management. Progress in legal issues is notable with the development of regional initiatives for promoting the establishment of the legal/institutional frameworks for TBA cooperation under the guidance of the Draft Articles on the Law of Transboundary Aquifers.

Despite all these efforts, the world is not on track to achieve the SDGs, including the specific target on cooperation (6.52). Progress on institutionalizing cooperation for TBAs still faces important challenges that were raised during the Conference, they are summarized below:

Lack of knowledge: There is no need to stress again here on the importance of knowing the resource for managing an aquifer. Data from the ground is needed to adopt and implement policies. However, this task becomes more complicated when an aquifer falls under the territory of more than one country. Its proper management requires a comprehensive knowledge of the complete aquifer. This implies not only collecting more data, and more analysis, but also sharing and exchanging the data between the concerned countries as a first step, and then harmonizing the data so the countries adopt one system agreeable by the sharing countries.

Lack of capacities: Capacities are needed to collect and analyze the data and make it available for policy makers. Capacities are important to support and sustain the data collection and the development of knowledge. It is also needed to ensure the reporting exercise under the SDGs.

Financing: Funding is important to support countries in their efforts of data collection and developing knowledge. There is no required scale for funding. It can be at a small scale and still contribute to foster data. It is also fundamental for establishing and sustaining institutional setups and it must be streamlined with the institutional and regulatory frameworks of the sharing countries.

Technical and engineering solutions are available and can contribute to building cooperation. However, they need to be based on enough data and science as well as on a common understanding which is often missing, and cannot be reached without the exchange of data, information, science, capacities, and financing mechanisms. Additionally, without strong governance schemes, these solutions cannot last and might not be sustainable. **Governance is key.**

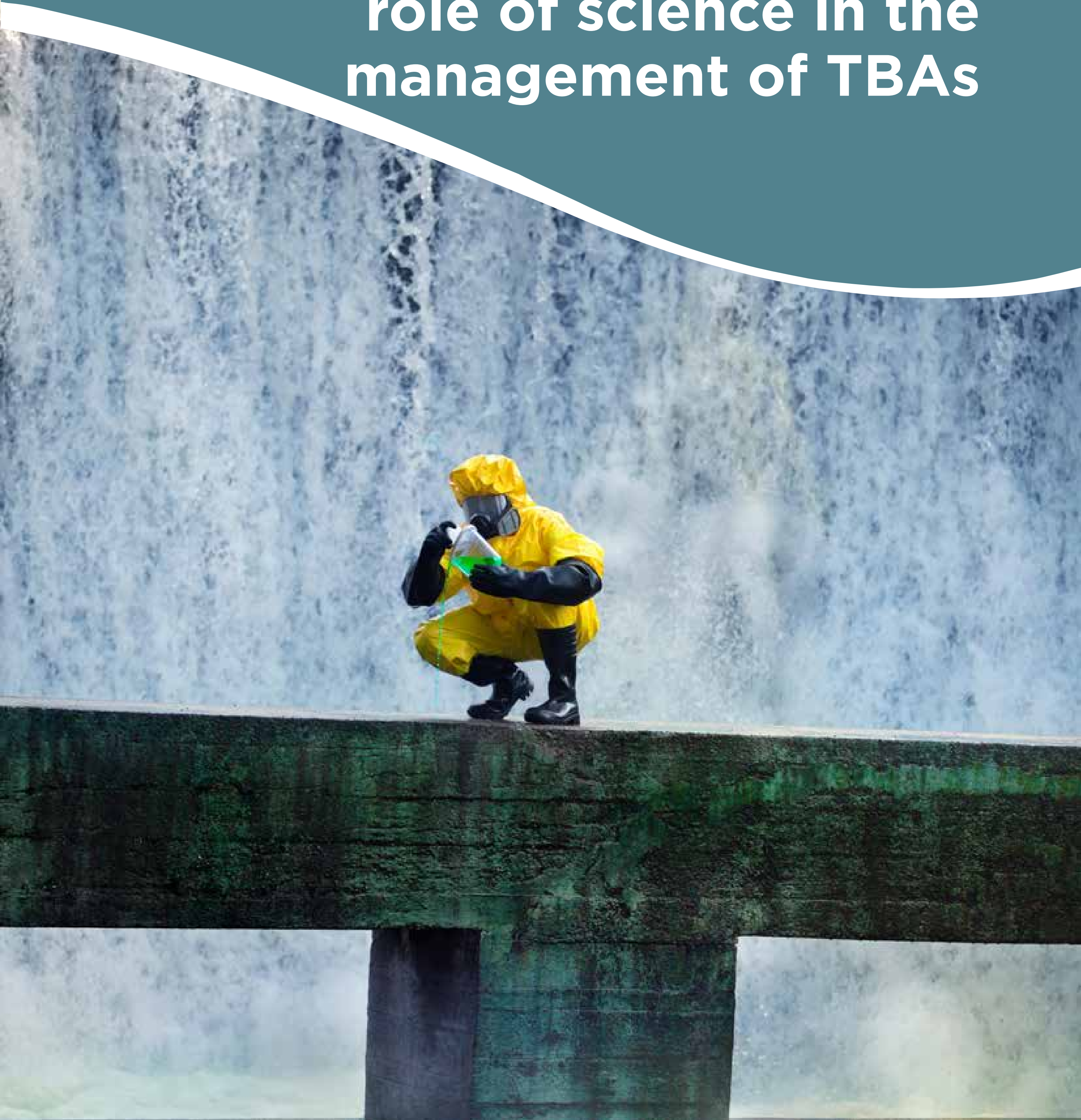
International water law, and the related global instruments, the UN Convention on the law of non-navigational uses of international watercourses (1997), the Convention on the protection and uses of transboundary watercourses and international lakes (1992) and the Draft Articles on the Law of Transboundary aquifers (2008) represent important tools for accelerating cooperation on TBAs and achieving the SDGs. Regional frameworks such as the SADC Revised Protocol on Shared Watercourses also play a significant role.

Cooperation on TBAs is important beyond the management of the water resource itself or for achieving SDG6. It is important for achieving other SDGs (ending poverty, reaching food security, access to water, economic growth, protection of ecosystems) and for adapting to Climate Change. It is also fundamental for the realization of the human right to safe drinking water and sanitation, which is at the core of the realization of all human rights (UN GA Resolution A/RES/64/292).

Despite these challenges and difficulties, it is possible to conclude on a positive note. The work on target 6.5.2 has boosted the interest and the awareness within the countries for the need of initiating and reaching a common knowledge and understanding of transboundary aquifers and their joint management.

TOPIC 2

The Science - Policy Interface of Transboundary Aquifers (TBAs): The role of science in the management of TBAs



Introduction

by Karen G. Villholth

At the 2020 session of the United Nations High-level Political Forum, ministers made a collective commitment to *"strengthen the science-policy interface through evidence-based policymaking, support for research and development, harnessing science, technology and innovation, and leveraging technologies to promote inclusive digital economy and promote resilience across sectors."* Groundwater, and indeed transboundary aquifers, are becoming increasingly important globally as a critical component of achieving the sustainable development goals (SDGs). Groundwater provides water for households, for agriculture, industries and important ecosystems, and the reliance becomes the more critical as populations grow, welfare increases, climate changes, and degradation of water quality in lakes and rivers continues.

Never-the-less, groundwater's role and value in countries' development targets and GDP seldom gets articulated and continues under the radar of most policy makers. This is primarily due to the hidden and common pool resource nature of groundwater, the often individual and piecemeal appropriation of the resource, and the typical time lag associated with externalities from its exploitation. This may jeopardize the sustainable use and management of groundwater resources as well as the ecosystems and ecosystem services they underpin.

Transboundary aquifers are prone to same challenges of policy dis-attention, but thanks to the efforts of ISARM and partners around the world these resources are coming under increasing scrutiny of governments, policy makers, scientists, and society at large as critical resources for sustainable joint development and management, international cooperation, and regional integration.

The complexity of such hidden, common pool, but essential and potentially contested resources, calls for science to inform policy making. Hence, the policy-science interface (SPI) of transboundary aquifers is becoming a key space to manoeuvre to achieve the best outcomes of TBA development and cooperation.

TOPIC 2/Paper 4

Using Science to Achieve Cooperation in Submarine Transboundary Aquifers

Renée Martin-Nagle[1], Aaron Micallef[2]

Abstract

Both recharging and non-recharging offshore aquifers containing vast quantities of freshened groundwater can be found in continental shelves around the globe. Given their ubiquity, some of these offshore aquifers will straddle international maritime boundaries. Accessing the freshwater in these aquifers will be costly, and therefore offshore freshwater resources will likely be utilized only when the quantity and/or quality of land-based freshwater resources are scarce. In a time of such freshwater scarcity, conflicts over transboundary deposits of a critically and vitally important resource could easily arise. Thus, an ability to define the boundaries, volumes and characteristics of offshore aquifers will reduce conflicts and support collaborative exploration and exploitation of the resources. Recent maritime expeditions have utilized specialized techniques for identifying and measuring offshore aquifers, including non-invasive seismic reflection profiling and electromagnetic surveying as well as numerical modeling and offshore boreholes. Equipped with adequate knowledge about the location and volume of offshore freshwater, nations can then determine their rights as outlined in the UN Convention on the Law of the Sea (LOSC). While LOSC is silent about governance of any transboundary resources, science can provide data to policymakers that will support informed discussions and fair resolutions regarding ownership and development of transboundary offshore freshwater resources.

Keywords: Cooperation, Offshore, Submarine

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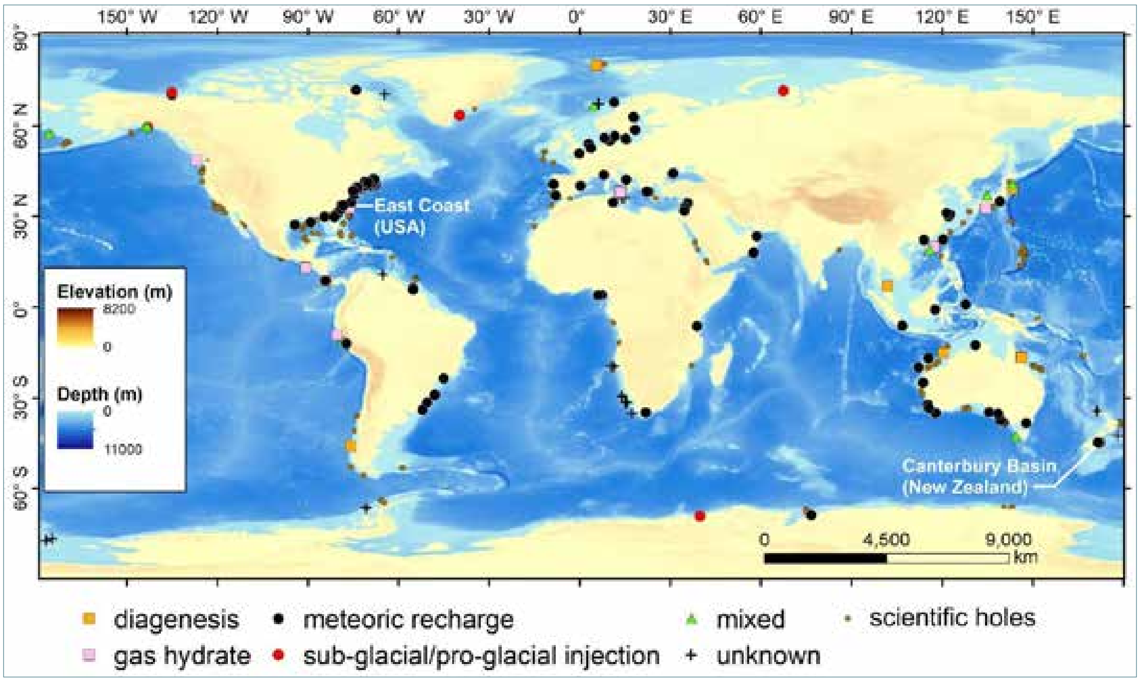
Origin and characteristics of OFG

Offshore freshened groundwater (OFG) can be defined as water that is hosted in sediments and rocks below the seafloor and that has a salinity lower than seawater (Micallef et al., 2021). First discovered during a drilling expedition off the coast of Florida in the 1960s (Kohout, 1964), OFG has now been documented in most continental margins (Figure 1) and has estimated global volume of 105 to 106 km^3.The majority of known OFG is located in passive margins, within 50 km from the coast, down to a water depth of 100 m and a sub-seafloor depth of 200 m (Micallef et al., 2021). OFG predominantly occurs as multiple bodies that are up to 1 km thick and that have mean salinities of 15 g/kgl. The hosting aquifers are primarily made of sand to clay units with porosities of 30-60%.

Figure 1.
Map of OFG records and their emplacement mechanisms



Source: Micallef et al., 2021. (© Creative Commons)

The key mechanisms responsible for emplacing freshened groundwater offshore include (1) recharge by rainfall, either historically during periods of lower sea levels or currently where onshore aquifers extend offshore, or (2) recharge via glacial basal melting resulting in sub-glacial streams and lakes (Micallef et al., 2021). Other minor sources of OFG include release of freshened water during the alteration of sediments (a process known as diagenesis) or the dissociation of gas hydrates (Hesse, 2003; Kastner & Gieskes, 1983). Geological factors controlling the distribution of OFG include a permeability contrast along the top of the OFG body, continuity/connectivity of permeable and confining strata, clinoform structures, buried palaeochannels, faults and dissolution structures (Micallef et al., 2020). Topography driven flow and salinization due to sea level rise are key hydrological factors influencing OFG distribution (Micallef et al. 2020).

The interest in OFG systems is largely driven by their potential use as unconventional sources of potable water in coastal regions. However, their study is important for a number of other reasons, such as improving the recovery in petroleum extraction, resource exploration, reconstruction of environmental changes, and regulation of global biogeochemical fluxes.

OFG exploration and characterization

Most fundamental information available on OFG has been provided by incidental discoveries during scientific and industry boreholes, especially from measurements of salinity or chlorinity (Hathaway et al., 1979). However, the spatial coverage of these boreholes is limited and biased towards hydrocarbon regions. As a result, a number of geophysical methods have been employed to detect OFG. The most powerful approach comprises an integration of seismic reflection profiling, which provides constraints on lithology, aquifer geometry and geological structures (e.g. faults, buried channels), and electromagnetic surveying, which is used to discriminate between saturated regions with saline water (less resistive) from those containing fresh groundwater (more resistive) (Micallef et al., 2021). In view of the paucity and depth limitations of offshore wells and marine geophysical data, a cost-effective method for estimating OFG volumes and emplacement is numerical modelling (Cohen et al., 2010). Since the 1980s, numerical modelling has evolved from simple, 2-D sharp interface approaches into 3-D models considering solute transport and variable density effects. The shelf off the eastern United States and the Canterbury Bight (New Zealand) provide the best examples of the application of the above methods for the investigation of OFG.

OFG exploitation

An exercise by Micallef et al. (2021) has identified Cape Town (South Africa), Melbourne and Perth (Australia) as coastal cities where OFG can potentially be used as a resource. Exploitation, however, is limited by the technological and economic feasibility of developing OFG, the wide range of potential environmental impacts (e.g. subsidence, contamination, brine disposal, habitat degradation), and the unclear legal implications. In addition, in some instances OFG can be a non-renewable resource (e.g. fossil groundwater bodies not actively recharged), and withdrawals may therefore be unsustainable (Zamrsky et al., 2022). Development of OFG must therefore be carefully and strategically planned.

Determination of rights

For centuries, customary law has recognized that nations have full sovereignty over the seas and continental shelves extending from their coastlines (Thornton, 2004). The 1982 UN Convention on the Law of the Sea (LOSC), which became effective in 1994 and currently has one hundred sixty-eight parties, codified customary law by allocating ownership of maritime natural resources. Pursuant to LOSC, nations have full sovereignty over natural resources in the water column and in the seabed for twelve nautical miles from the low tide line at the coast, an area known as the Territorial Sea. From the end of the Territorial Sea and to a point that is two hundred nautical miles from the low tide line at the coast, in an area known as the Exclusive

Economic Zone ("EEZ"), nations have exclusive sovereign rights to all natural resources in the water column and the seabed. If a nation can prove through a complex set of calculations that its continental shelf extends beyond the EEZ, then that nation can claim exclusive sovereign rights to natural resources in the seabed for up to an additional one hundred fifty nautical miles of the extended continental shelf.

Freshwater aquifers have been found in both Territorial Seas and in EEZs, but due to seawater intrusion as sea levels have risen over millennia, OFG with low salinity is not expected to be present in the extended continental shelf (Martin-Nagle, 2020). Pursuant to the LOSC, OFG will belong to the nation in whose Territorial Sea or EEZ the OFG resides.

However, water-bearing geological formations do not respect political boundaries, and the ubiquity of OFG strongly suggests that a significant number of aquifer formations containing OFG will be transboundary in nature. While LOSC is clear about ownership of natural resources within the Territorial Sea and the EEZ, the treaty is silent about ownership of transboundary natural resources, and the only inference about the intention of LOSC regarding transboundary resources is a requirement in Articles 74 and 83 that delimitation of maritime boundaries be fair and equitable.

Nature and economic development abhor a vacuum In addition to freshwater resources, the continental shelves also house enormous volumes of valuable hydrocarbons in the form of both petroleum and natural gas. Nature and economic development abhor a vacuum, and nations wishing to develop shared hydrocarbon deposits needed some certainty regarding ownership that LOSC and customary law did not provide. Therefore, after a series of judicial actions before the International Court of Justice, a practical solution was found in the form of unitization, whereby nations would collaborate on exploiting transboundary hydrocarbons by jointly appointing an operator and splitting the costs of extraction according to a pre-determined proportion (Onorato, 1968). In a few years, unitization evolved into joint development agreements (JDAs) that provided for collaboration for both exploration and exploitation (Blyschak, 2013). These systems saved considerable sums of money by avoiding wasteful races to extract the resource and by funding only one operator instead of separate operators for each nation. Nations signed a series of treaties that facilitate collaborative development and, in some cases, also allocated percentages of ownership (Martin-Nagle, 2020). Some treaties addressed only hydrocarbons and others included all natural resources in their scope. Interestingly, the cooperative approach embodied in unitization and JDAs was inspired by the international water law principle of equitable and reasonable use of transboundary freshwater resources (Onorato, 1968).

Conclusion

When development of transboundary OFG begins, nations will have to determine rights and ownership of those resources. Through various techniques, science will be able to provide information regarding the geographical extent, volume, and characteristics of the freshwater repositories, but policymakers will be tasked with allocating volumes and granting access to the resource. In negotiating a cooperative arrangement, those policymakers will doubtless utilize a collaborative system that has worked effectively and efficiently in the hydrocarbon industry for decades, but they should also be cognizant of conserving the freshwater for future generations. Further, onshore groundwater pumping may impact offshore groundwater systems and vice versa, so understanding the entire hydrological system is crucial to ensuring sound onshore and offshore

Thus, the authors predict that JDAs will be the mechanism for determining rights and ownership of transboundary OFG lying under the continental shelves. Since OFG reserves are located closer to the surface of the seabed, development of these freshwater resources will be less costly than development of offshore hydrocarbons, but economic efficiency and resource preservation will doubtless still encourage collaborative action. Regardless, since OFG represents a sizable, untapped reserve of a critical resource, nations will have to weigh the timing and volume of extractions, while being mindful of the freshwater needs of future generations

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TOPIC 2/Paper 5

Reaching Groundwater Agreements on the Border Between Mexico and the United States: Science and Policy Fundamentals

Sharon B. Megdal[1], Stephen Mumme[2], Roberto Salmon[3], Rosario Sánchez[4], Elia M. Tapia-Villaseñor[5], Mary-Belle Cruz Ayala[6], and Óscar Ibañez[6]

Abstract

Groundwater is vital to the sustainability and survival of human communities in the U.S.-Mexico border region, a nearly 2000 mile-long, arid zone in North America where climate uncertainty prevails. More than 30 aquifers are known to abut or span the international boundary, supporting a border area population exceeding 15 million persons in 2020 (Figure 1). Groundwater is the sole or principal water source for more that half-a-dozen sister cities or communities ranging from one of the largest binational metropolitan zones, El Paso-Cd. Juarez, to the thriving binational metropolis of Ambos Nogales, to smaller coadjacent communities on the western land boundary and along the Rio Grande River. Unfortunately, groundwater utilization is regulated by international agreement in just one small area, the San Luis Mesa, along the southerly international boundary. That agreement, signed in 1973, noted the need for a comprehensive groundwater agreement for the border region, a goal that has eluded the two countries for nearly half a century. This paper examines the prospect of reaching additional groundwater agreements between the two countries. It first considers the institutional setting shaping binational cooperation on transboundary groundwater management. It then reviews advances in binational technical and scientific cooperation on transboundary water relevant to shared aquifers. It follows by considering how emerging diplomatic principles and practices may facilitate cooperative approaches to managing shared aquifers along the U.S.-Mexico boundary, drawing on recent experience in groundwater assessment gained from binational engagement in the Transboundary Aquifer Assessment Program. The paper concludes by identifying principles and practices that are most conducive to advancing binational collaboration on transboundary aquifer management to utilize these essential resources more sustainably.

Keywords: U.S.-Mexico, groundwater, agreement

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Figure 2.
Elements and conditions for a Binational Groundwater Agreement between the United States and Mexico

(© Own Elaboration)

Managing Groundwater Along the U.S.-Mexico Border: The Institutional Setting

Any initiative to manage the use of transboundary aquifers along the U.S.-Mexico boundary plays in a complex institutional arena. Each nation governs its aquifers differently. Mexico's subsoil resources belong to the Nation. The Executive Branch exerts its authority over national waters by way of Mexico's National Water Commission (CONAGUA), extending water rights to private and public users. In the U.S., regulatory authority over groundwater is largely vested with the states. The border states of California, Arizona, New Mexico, and Texas regulate groundwater use, often with further differentiation within the states. Federal regulations in both countries establish water quality standards for drinking and water discharges.

Transboundary aquifer management today, in the absence of binational agreements, is effectively a domestic function. There is, however, a diplomatic mechanism for crafting and administering transboundary aquifer agreements. The International Boundary and Water Commission (IBWC), established under the authority of the 1944 U.S.-Mexico Water Treaty, is charged with interpreting the treaty and resolving any disputes that may arise concerning transboundary waters. Functioning as two separate national sections, each under the authority of its respective foreign ministry, the IBWC is authorized to interpret the 1944 Treaty through the adoption of binational implementing agreements (Minutes). Though the treaty did not address shared aquifers, the IBWC's jurisdiction for settling transboundary aquifer disputes was recognized in 1973 by Minute 242, which settled a longstanding dispute over Colorado River salinity and regulated groundwater extraction on the San Luis Mesa. Minute 242's consideration of groundwater establishes the study and management of transboundary aquifers as a legitimate application of 1944 Treaty authority should the governments so desire.

Principles, practices, and possibilities for transboundary groundwater collaboration

Though there is the potential for binational groundwater management of groundwater shared by border communities large and small, the history of U.S.-Mexico collaboration on groundwater resources is not much different from what has happened in other places around the world. Transboundary aquifers represent the sole or primary source of water for many border communities worldwide. Yet only a handful of agreements for the assessment and management of shared groundwater resources exist. The 2008 Draft Articles on the Law of Transboundary Aquifers (UN Draft Articles) provide guidelines for the use of shared groundwater resources focusing on best practices for the protection, preservation, and management of transboundary aquifer systems (confined and unconfined). The principles of the UN Draft Articles followed available common practices of groundwater agreements in place and have also served as the base for the development of other agreements, such as the case of the Guaraní Aquifer Agreement shared between Argentina, Brazil, Paraguay, and Uruguay. Even though there might be different technical conceptions between the use of cooperation and collaboration in a stricter sense, for the purposes of this paper we do not make a distinction between either of them as there is not enough evidence to support this distinction from the history of cooperation/collaboration efforts between Mexico and the United States.

Common principles and practices of collaboration in transboundary groundwater management agreements around the world include of the presence of data exchange provisions, the concurrence for binational aquifer assessment, the establishment of technical advisory committees, and respect for the legal framework and jurisdictional requirements of the involved countries. All these features are present in the agreements on transboundary groundwater resources for the Guaraní Aquifer System, the Franco-Swiss Genevese Aquifer System, the Iullemeden Aquifer System, the Nubian Sandstone Aquifer System, and the Al-Saq/Al-Disi Aquifer System (Tapia-Villaseñor and Megdal, 2021).

Though no binational groundwater management agreements between the U.S. and Mexico have been signed since 1973, the scope and scale of recent efforts are encouraging and suggestive of collaborative management schemes. Apart from Minute 242, the semi-formal cooperative framework of the Transboundary Aquifer Assessment Program (TAAP), and some limited provisions related to groundwater in Minutes 304, 319, and 320, the reported efforts on binational groundwater collaboration tend to be inclined to more local, non-formal, decentralized, short-termed practices (Sanchez and Eckstein, 2020). Minute 304 recognizes a joint grant contribution program aimed at addressing border region wastewater infrastructure projects as complementary to the IBWC's mandate to resolve transboundary sanitation problems—problems that may extend to groundwater. Minute 319, on binational sharing of water shortage on the Colorado River, addresses groundwater in two ways: first, as a function of salinity control measures related to the implementation of Minute 242; and second, as a potential water augmentation resource—though no specific commitments are made. Minute 320, a general framework agreement authorizing binational cooperation on transboundary issues in the Tijuana River Basin, does not exclude consideration of transboundary groundwater problems within its scope of work should the two governments agree to do so.

The UN Draft Articles principles that are the basis of the existent international groundwater collaboration are highly relevant for formal border-wide agreements/treaties (e.g., containing a binding mechanism). However, in the case of informal cooperation efforts, local scale and decentralized practices play a significant role in defining the principles of collaboration. They seem to work more effectively at the local level where social-based interactions, community closeness, individual leaderships and institutional trust are the drivers for transboundary cooperation. Though none of these elements is officially recognized as principles of current international groundwater agreements, the success of both formal and informal cooperation instruments is highly dependable on these local-based variables (Sanchez and Eckstein, 2020).

The TAAP Cooperative Framework between the United States and Mexico, is consistent with three UN Draft Articles: Article 3 "Sovereignty of Aquifer States", Article 7, "General Obligation to Cooperate" and Article 8, "Regular Exchange of Data and Information". However, success has been uneven. For the San Pedro and Santa Cruz transboundary aquifers shared by Arizona (U.S.) and Sonora (Mexico), progress has been fostered by cultural, social, and professional bonding, some of which predated TAAP efforts. Relationships vary considerably by locality. In contrast, the level of binational engagement and cooperation of TAAP in the cases of Hueco-Bolson/Valle de Juarez (Hueco-Bolson aquifer) and Mesilla Bolson/Conejos Medanos (Mesilla aquifer) remains limited.

Because transboundary groundwater is a local resource subject to the particular and differing regulatory regimes of the relevant jurisdictions, global examples of binational cooperation can provide only limited guidance. For shared aquifers along the U.S.-Mexico border, a general framework agreement that sets the parameters for future aquifer-level, locally driven negotiations could represent the path forward in terms of groundwater management collaboration. This approach clearly recognizes that, within a framework approved by the two counties, binational groundwater management must also consider domestic and local priorities for evaluating, assessing, and managing shared groundwater sustainably. A "parallel driveway" is needed, where informal local efforts are consistent with the official elements of the framework agreement. Clearly, the success of the binational collaboration is strongly linked to local social, cultural, and resource conditions, but, at the same time, the cooperation needs to be supported by mature, systemic, long-term institutional commitment.

The path forward

This complex of principles, agreements and practices affecting binational cooperation on shared groundwaters over the past 30 years holds promise for facilitating further cooperation on transboundary groundwater. Reaching a comprehensive agreement as envisioned in Minute 242, however, may be feasible but only in the form of a general framework agreement that sets the parameters for future negotiations addressing challenges on in specific transboundary aquifers along the international boundary. Such a framework agreement must accommodate the hydrological, economic, and political complexity of the circumstances affecting stakeholders sharing these aquifers.

If IBWC's experience is any guide, which we believe it is, several conditions must be met if such a framework agreement is to be had (See Figure 2). Both countries must agree on a factual set of baseline conditions and a clear set of objectives to guide diplomatic discussions that are accepted by all major stakeholders, governmental and non-governmental. The negotiation goals and objectives should be embraced as beneficial to interests/stakeholders in both countries. The scope and the general purport of the framework agreement should be accepted at the start. The terms of reference should aim at a framework that allows sufficient latitude for substantive subsidiary talks to occur addressing issues in discrete aquifers along the boundary.

As discussions that will lead to negotiations commence, it is essential to identify needs, issues, fears, and concerns, many of which may not be evident to all stakeholders (Verdini Trejo, 2017). The parties should be willing to externalize these concerns and consider means of addressing the full suite of problems that stakeholders may wish to raise in the negotiations. The respective countries and their stakeholders should each be clear as to why they may need a formal framework agreement that allows place and aquifer specific discussions to go forward when the relevant stakeholders are ready to do so. They should also be clear and transparent as to the consequences of failing to achieve an agreement, of defaulting to the status-quo ante.

If negotiations progress, other conditions for success arise. The parties must agree to the costs of implementation and determine their willingness to commit the monetary and human resources and share the administrative costs that may be required to give the agreement effect. A potential sticking point is sure to be any joint agreement on the management mechanisms that may be utilized under the agreement. Even if the specific arrangements for dealing with particular aquifers are left to subsequent talks on substantive

subsidiary agreements, some general terms of reference are apt to be necessary in the framework agreement to guide those further discussions. Such terms of reference could be based on, but not limited to the lessons learned from transboundary aquifer agreements around the world and include some of the principles described in the UN Draft Articles that have played a significant role on current international agreements such as the Guaraní Aquifer States and others. These lessons and principles can be adapted to the particularities of both the U.S. and Mexico.

In sum, achieving such a framework agreement will be challenging, even it allows ample room for subsequent detailed negotiations of substantive problems affecting specific shared aquifers and groundwater resources along and across the international boundary. However, binational experience, particularly through the IBWC over the last 30 years, have recorded long-term solutions for the binational Colorado River basin that have covered more than surface water and riparian problems. This fact suggests that this could be a favorable path forward if greater cooperation for the sustainable use of transboundary groundwater is to be had along the U.S.-Mexico border.

Figure 2.
Elements and conditions for a Binational Groundwater Agreement between the United States and Mexico

(© Own Elaboration)

Conclusion

Over the past decades, designated workgroups formed by binational scientific teams have worked simultaneously on finding scientific and technical solutions for different water problems. Steppingstones such as the ones described in this paper show that binational relationships are maturing. This suggests a more promising outlook for establishing transboundary groundwater management discussions in a cordial, non-conflicting environment, thereby paving the path toward collaborative groundwater management. Such collaboration could lead to a framework agreement for groundwater resources that sets the stage for follow-on agreements that incorporate the local circumstances of U.S.-Mexico transboundary aquifers. Alternatively, an aquifer-based approach could move forward without a framework Minute, as happened with Minute 242 discussed above. Or perhaps a combination of the two would result. What is clear, though, is that formal institutional involvement of the IBWC and cooperating entities, incorporation of scientific findings and policy considerations specific to each aquifer, and, of course, stakeholder representation and involvement in the policy formulation processes are necessary to reaching workable and sustainable binational groundwater agreements.

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TOPIC 2/Paper 6

What is the 'Science' that Policy Makers Want in Order to Address Governance of Transboundary Aquifers? – Findings from Simulation of Negotiations

Shammy Puri

Abstract

This paper asks: "Is the science of transboundary aquifers (TBA) really so complex that it is nearly impossible to explain it to policy makers, so that they can implement TBA governance?" If the answer to this is 'no', a natural next question follows is: 'What are the primary types of information that the policy makers need to understand, and in what degree of detail, in order to enhance the application of scientific this knowledge for governance?' Answers to these questions were sought through simulations of negotiations conducted by globally recognized experts.

A significant amount of literature has been built up in the recent past on the linkage between science and policy. Policy makers routinely miss the significance of science-based conclusions, especially those that are not explicitly couched in terms of risk envelopes. Although one may lay the blame on policy makers for their lack of understanding or willingness to adopt policy, it is time to turn the tables around and ask, 'What is the science that policy makers need, and how can this information best be co-developed and provided? Is it time for the science community to change its risk excessively adverse stand?'

This paper responds to these questions by presenting the findings of the simulations, which provide a valuable learning resource, along with commentary on the insights that can be gained from them in order to bring the scientific and policy maker communities closer together.

Introduction and the context

It is commonly noted among the scientific community that policies in many nations and sectors do not link particularly well with the science that is behind the domain under consideration (Gluckman 2016). This issue has been discussed among a number of scientists and in many scientific fora, and many opinions have been stated (Kohler 2022) from a number of different angles (Bukowski 2017). Nevertheless, policy makers seem to remain aloof from making direct connections to the relevant science, as science is often presented without the applicable risk envelope.

While the concern of the science community in aiming to support policies and policy makers is a laudable endeavour, it may be worth turning the issue around, and in turn asking, "What is the science that policy makers want?" Alternatively, we can pose the question: "Is the science (in this case that of transboundary aquifers) so complex that it is (nearly) impossible to explain it to policy makers?" Both formulations of the inquiry have the underlying aim of guaranteeing that policy makers can implement sound governance of the aquifers in question.

In discussing the disconnect between the presentation of the science and adoption of policy, the characterisation of 'sound governance' of aquifers can be stated in simplified form: aquifer resource governance is sound when users of the groundwater can rely on uninterrupted access to the water, the aquatic ecosystems that are dependent on aquifer discharges do not deteriorate, and in the long term (say 50 past years and 50 future years) the aquifer system continues to function (i.e., receive, recharge, store and transmit water) and has not 'collapsed'.

This paper will explore the question posed in the title through an interpretation of two sets of simulations of negotiations over transboundary aquifers (carried out in two open webinars) – the first draws on two rounds of transboundary aquifer negotiations conducted in Aug 2021 and Oct 2021, as a build- up to ISARM2021 global conference, and the second is the simulation of a discussion between a policy maker and a scientist conducted within the ISARM 2021 Conference (Tolba Aboelnga & Puri, 2021; Puri, Tolba Abolenga & Elnaser 2020).

While the two sets of knowledge bases mentioned above are 90-minute simulations, they were conducted by some of the world's most eminent experts in the science and policy of transboundary aquifers. Therefore, the arguments and statements made in the simulations represent the most up-to-date appreciation and understanding about transboundary aquifers that underlie the formulation and implementation of policy in this arena. The knowledge base was further enhanced by the webinar audience participation through live polling of opinions, based on the assumption that mainly people with keen interest and involvement to various degrees would participate and also have their own expert opinions as the simulated negotiations progressed. There were nearly 500 downloads of the background materials (the ppt and the text explanations) and 200 responded to the live polling. The findings & results can be seen in the Tolba Aboelnga & Puri (2021) poster in the ISARM Conference.

The policy – science interface

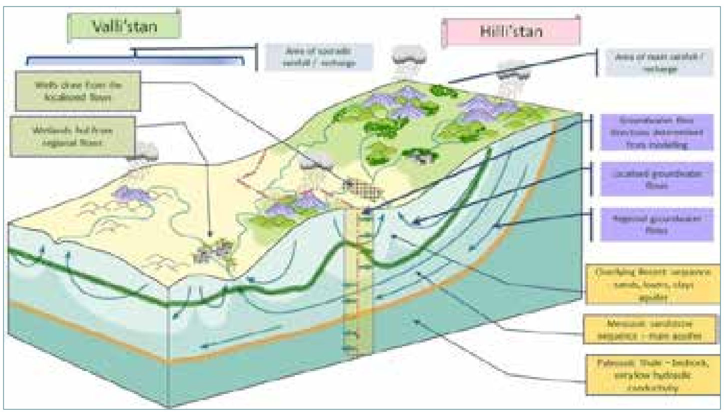
The 'policy-science' interface is a somewhat fuzzy boundary, and various experts in this field have defined the issue in several ways (Kohler 2022, Salman 2015). In order for there to be a smooth interface between them, there is a clear need for multi- disciplinarity linking the science of aquifers to the political economy of the use and the benefits of the resources in those aquifers. It would appear to be rare that individual experts span these several disciplines. A review of the available literature suggests that cross disciplinary collaboration is not yet sufficiently prevalent, and to a large extent advice and analysis is still being formulated and delivered in silos.

Useful evidence of the 'silo situation' can be found in an interpretation of a survey of ministers from 88 countries that was conducted by the Water Policy Group (WPC Report 2021). The lack of a policy-science interface for aquifers is surprising, because the science and the practice of hydrogeology have become mainstream in water resources management over the past 70 years (Howden et al 2013). The simulation of negotiations, and the live polling of a participating audience, are a learning resource and can help to provide further insights into this gap, as discussed below. Arguably, live simulation is more effective than classroom-based teaching (Usherwood 2015; Mekong River Commission 2014).

The transboundary aquifers system used for the simulation of negotiations

The schematic transboundary aquifer that was devised for the simulation is summarised in Fig 1. The 'system' is relatively simple and is representative of several real-world conditions. The accompanying notes for the negotiators provided a significant amount of hydrogeological, socio-economic, and legal background. Two separate sets of briefing notes for the transboundary issues to be negotiated were also provided to the two sets of negotiators, representing either side of a national boundary. Full details of the background notes and other materials can be extracted from www.practicalhydrogeology.co.uk and are not repeated here for brevity.

Figure 1.
Analysis through a simulation of 'transboundary negotiations'



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Two sets of negotiators were involved, representing the two sides: the upstream – recharge area (U), and the downstream – discharge area (D). The negotiators had expertise in science, policy and legal issues and were thus well-equipped to address the scope of shared water resource governance between countries.

The approach adopted

With the transboundary hydrogeology and most of the relevant socio-economic and legal background provided to the negotiators, the issues for them to negotiate were threefold: (i) the urgent need for additional water to be drawn from the aquifer (U), (ii) the option to include a dam to increase surface water resource use (U & D), (iii) expansion of an irrigation area using surface and groundwater (D).

The transboundary aquifer system & key issues

The briefing notes for the negotiators provided a lot of background information, such as the results of past mathematical modelling, information on demands and usage, estimates of rainfall & recharge, and the water quality, as well as the prevailing economies and legislation. Many of these conditions are found in real world transboundary aquifers, such as the Guarani Aquifer, the North Sahara Aquifer, the Nubian Sandstone, and the Rum-Saq (Velis et al 2022, Puri 2021, Varady et al 2016)

The hydrogeological interpretation from these briefing notes suggested several important messages that could underlie the negotiation stances: (a) that there was a scope of increased abstraction from the aquifer, (b) that the flow path was long enough for downstream impacts to be much delayed and alleviated, (c) that through some joint, or even single, investment, new water resource demands could be met for mutual economic gains. The key issues for conducting the negotiations are shown in Box A.

BOX A
SUMMARY OF THE TRANSBOUNDARY ISSUES

An interconnected transboundary aquifer-river system underlies two countries in a semi-arid region. The upstream country (Hilli'stan) wishes to draw on the resources in the aquifers for urgent public supply needs. The downstream country (Valli'stan) is using a large amount of water for irrigation (which could be impacted by the new wellfields in Hilli'stan) and wants to expand irrigation, but needs the upstream neighbour to either construct a damor modify its groundwater use.

Both countries have national legislation on water resources. They are not signatories to any of the international water conventions, though both are familiar with them. Inter-country relations are cordial, though in the past there were conflicts over territory. Both countries conduct international trade and are signatories to the WTO. There is no mutual trade agreement between them, though a significant amount of informal cross-boundary trade takes place.

In this NEGOTIATION the two countries will conduct negotiation over the transboundary ground and surface waters, based on the BRIEFING NOTES.

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Selection and of and briefing to 'negotiators'

Prior to the two webinars in which the negotiators were to conduct their negotiations, it was agreed among them that they would utilise their expertise in transboundary water resources matters, and in order to make the simulation as realistic as possible, they would adopt a negotiating stance based on their own international experiences. It was left to each team to decide how they would approach the issues, and they had the option of keeping their positions confidential.

The webinars were intended to be a learning experience by seeking to understand how in the real world negotiators might approach the issue of transboundary aquifers. It has been repeated ad nauseam that "aquifers are invisible", and thus non-specialists understand neither the dynamics, nor the application of the economics, legislation and other rules. Therefore, insight through these simulations was to be gained under the broad heading of governance, as defined above. The interpretation of the arguments and the statements made by the negotiators in the course of the two rounds are those of the author, who acted as the independent facilitator between the two sets of negotiators.

'Round I' of negotiations

In Round I of the negotiations, both sides in their opening statements committed to be cooperative and constructive in their discussions over transboundary resources, in line with the conventionally agreed approaches. On the substantive matters, one set of negotiators (U) proposed the need for additional studies, data collection, extensive and in-depth water resource and quality evaluations before they could proceed to dealing with the three key issues (listed above). The other set of negotiators (D) broadly agreed with the need for additional studies and outlined a defensive stance on the need to comply with international rules of good behaviour, including a veiled threat that they might seek compensation for any overuse of 'their' water resource. As a way ahead, one set of negotiators proposed a Memorandum of Understanding MoU), while the other set insisted on the need for a Treaty. – and no consensus could be reached.

In their final stance, the negotiators concluded that they were unable to proceed further without the in-depth studies and revaluations, but that they would be open to further negotiations.

The 'Round II' of negotiations – 5 years on

In advance of the second round of negotiations, the negotiators were provided with additional and updated briefing information, the main purpose of which was to clarify that data, aquifer systems, flow paths, etc., was sufficiently reliable to initiate at least some in-country and inter-country cooperative actions. The briefing notes stressed the urgency of water needs, as summarised in Box B

After opening statements of intention to cooperate fully, the Round II negotiations returned to the need to obtain more data, analysis, and additional modelling that would

BOX B
Summary Transboundary Issues
5 Years on

Five years after the 1st Round of negotiations, the demands and needs of the two countries remain the same, though the urgency has increased.

Hilli'stand capital city has increasing water shortages, many private wells have been drilled in the wealthier districts, and the permit applications for the wells is seriously delayed, as the relevant Ministry lacks staff & resources. In the agricultural areas, any suggestion that farmers reduce well pumping was met with a serious threat of community rebellion, and the political representatives of the area have promised to resist legislation to control pumping. As food supplies come primarily from this area, reducing water use seems difficult.

In Valli'stan, the demand for increased cotton irrigation has meant that more river water is diverted, and some well-drilling has started. The private sector financing for this is also creating political difficulties, as the Ministry is being faced with criticism for not taking any action.

As a result of these pressures, the governments in both countries have again nominated their legal and technical experts to negotiate the relevant issues. Guidance on what each country wishes to obtain is given in the individual country briefing notes.

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address climate change, environmental assessments, stakeholder involvement, etc. The negotiators then debated the form of an agreement, with one side (U) preferring an MoU that would set out a step by step approach, starting with data collection and evaluations, that would then be followed by a more formal agreement in the future. The other set of negotiators (D) were adamant that a formal treaty setting out obligations and rights based on international standards was a pre-requisite for any progress, and that any harm that may been caused in the past would have to be recognised and might have to be compensated.

The negotiations concluded without an agreement on the way ahead, though the door was left open for further negotiations.

Commentary on the negotiator's approaches

The 'negotiators' participating in the simulation are highly experienced and have independent international expertise, often engaging in advising UN agencies, governments and other organizations on transboundary aquifers. This commentary therefore interprets their positions as indicative of the current state of affairs in the realm of transboundary water governance.

The statements of the two sides relating to cooperation are a good indication that in dealing with transboundary aquifers, the stakeholders are not adversarial. However, there does appear to be a clear bias towards sovereign rights to water, with implied defensive stances that seek to have an assured, adequate, and full share of 'their' resources.

On the very strong and repeated statements about data, information, in-depth modelling, etc, it is understandable that, without good and reliable 'information', agreements, and indeed negotiations, may not be productive. Bearing this in mind, the background on the aquifer system and the socio-economic and legal situations was presented in some considerable details to the negotiators. The information was augmented for Round II, with a number of remarks in the briefing notes that indicated that the 'science' was understood, and to large extent had been quantified. The mathematical model presented in the notes was stated to be adequately reliable to make at least some decisions. It was very noteworthy, that despite this, the negotiators took the stance that "nothing is known until everything is known". The likelihood that "everything" will be known about a regional aquifer system in any region of the world is a faint hope. Decision-making is usually reached through a risk-based assessment. In this case the risk assessment was left implicit in the notes, anticipating that the hydrogeological and other expertise would implicitly assess the risk as being low and would then move toward at least some substantive negotiations for solving the clearly urgent water demands, which if not met soon, could have both social and economic impacts on both sides of the border.

Simulated conversation between scientist and policy maker

In an effort to further cast light on what the form of a discussion between a scientist and a policy maker could be, a 'conversation' was held within the ISARM2021 Conference… (Ref). The gist of the conversation was that complex technical hydrogeological diagrams and cross sections (taken from a real example in Malawi) did not help in progressing decisions that the policy maker had to make. The shape of the conversation had to be converted from scientific discourse to advice over financing of investments and the scale and level of risk (economic, water security, social wellbeing) that were attached to the use of water from the transboundary aquifer. This is another lesson that would be of value to the science community.

Implications of the simulation in the real world

As discussed above, the commentary on the negotiations throws some light on the reason that inter-country negotiations on real world transboundary aquifers, as well as the international instruments and guidance, are proceeding in slow motion, with "one step forward and two steps back" (Puri 2021). The science community is very risk-averse, and therefore, even with mathematical models having been developed (e.g the Stampriet, the Guarani, the Rum-Saq, the Milk River, the Northwest Sahara), there is slow progress in achieving positive on-the-ground actions, such as joint construction of any observation wells, joint sampling from existing wells, or indeed any planning for managed aquifer recharge, coupled with any collaborative wellfield development to date.

The excessive level of risk aversion among the science community has a direct and explicit impact on the legal, socio-economic and foreign affairs communities. What is "invisible" to the non-specialist becomes "incoherent" and "impossible". The scale of risk aversion in aquifer systems, even where the significant amount of analysis embedded in the construction of mathematical models, is unjustified, and the conclusion is that real, effective, and measurable traction in joint management on transboundary aquifers will take decades to progress.

Summary of the 'science that policy makers want'

Finally, then – what is the science that policy makers want?

The science that policy makers do not want is "nothing is known until everything is known". In the real world of decision-making, statements that imply the foregoing mean that decisions, and even discussions, are postponed or stalled.

Drawing on the case set out in the simulations, the following is an outline of how the science should have been interpreted for negotiations to make progress, such that the outcome of the negotiations was useful to policy makers:

a. Based on the modelling results, an interim agreement enables (low risk) wellfields to be constructed with a watching brief that provides data to both sides, thus allowing them to engage in joint monitoring. Outcome: the policy maker is assured that water demands can be met.

b. A decision is reached in principle that the surface water resource will be developed as a joint or a single investment, with provisions for the transboundary share of the benefit. Outcome: the policymaker seeks funds for the investments needed and prepares for receiving the benefits.

c. Prior to the Round II, one of the parties (U) did draft a 'joint statement' that set out the way ahead, consisting of a joint commission, additional joint studies, concessional financing for the dam, and use of the guidance of the UN Draft Aquifer Articles to move forward to an agreement. Unfortunately, in the actual simulation, this 'draft statement' was never called upon, as the parties remained locked in debate on the form of an agreement – MoU or Treaty – which in effect produced an impasse.

Concluding remarks

This volume of ISARM2021 papers constitutes an important landmark in the two decades of progress over the sound governance of transboundary aquifers and thus casts a backward review of progress and a forward prognosis into the future. The simulations conducted in connection with the bi-decadal conference sums up both of these perspectives. The past has so far been primarily dedicated to defining and inventorying transboundary aquifers, as well as preparing a framework of legal guidelines, encompassed in the Draft Articles. Two notable agreements have been made – the Rum-Saq, and the Ethio-Djibuti (Puri, Wong & Elnaser 2009, Puri 2022) – which are underwritten by significant sovereign financial outlays by the relevant countries in the form of wellfields, pipelines and pumping stations. Neither of these two agreements relies on international frameworks (e.g Draft Articles) to any significant extent. Other agreements and understandings, such as the Guarani, the Stampriet, the US-Mexico and the US-Canada aquifers (Velis et al 2022), are in principle pathways to cooperate and collaborate on the science, with little or no quantifiable commitments to investment in infrastructure or human resources. Other long standing collaborative understandings, such as the Nubian Aquifer, North Sahara Aquifer, and the Iullemeden, remain somewhat in limbo, consisting of statements of intent and few investment actions, apart from seeking more development funds for further technical assistance from willing international agencies.

The simulations conducted reveal the contemporary underlying trends. The risk averseness of the scientific community is being translated into caution and postponement by the policy makers, awaiting signals about the acceptance of levels of risk, and whether they are manageable. Looking forward, with the UN Water and other agencies' huge effort at making the "invisible visible" in 2022 could mark a point of change, with policy makers demanding clearer risk-based recommendations for action. If the science community remains strongly risk-averse, urgent decisions may well be taken from altogether other standpoints, such as eliminating immediate water insecurity, irrespective of the long-term hydrogeological resource sustainability.

Acknowledgements

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Conclusions

by Karen G. Villholth

ISARM 2021 provided a great opportunity to revisit and update the world on progress achieved in TBA science and cooperation, since its predecessor of ISARM 2010. When it comes to the SPI, and while not exhaustive, the following lessons are highlighted, based on presentations, panels, and the closing session of the conference:

1. The SPI is not a linear process, starting with science informing policy. Rather it is an iterative and circular and continuous process, which needs to be a two-way interaction between scientists, policy makers and more broadly the stakeholders affected by decisions in the TBA space. The SPI requires dialogue that opens space for co-learning and benefitting from the various roles and virtues that the actors of the SPI bring to the table.
2. The TBA SPI need to bring in broader aspects of the nexus thinking, i.e., how TBAs are critical to providing best solutions in the water, energy, food sectors - with acceptable trade-offs between them. TBA cooperation has a goal beyond diplomacy, which relates to identifying and delivering opportunities and solutions that enhance e.g., water and food security, resilience, and environmental protection. Science is needed in multiple fields, from identifying, mapping, and characterizing the TBAs, to identifying adaptable institutional arrangements and mechanisms for cooperation, to developing technical, non-technical and economic tools to control and protect groundwater resources for the common good.
3. The SPI process needs to strike a balance between being proactive and identifying and counteracting potential TBA externalities at an early phase (acknowledging the latency, but potential irreversible impacts of poor groundwater management), while also providing enough arguments and evidence for policymakers to react on. This was framed as the 'chicken and egg' dilemma of TBA management.
4. Scientists, on the one hand, need to be good at translating science and making it understandable and actionable for the policy makers, while policy agents on the other hand, need to be agile and responsive to policy advice, bringing it to bear on real-world trustworthy decisions and tangible benefits in accountable ways addressing pertinent equity and environmental issues.
5. Communication, trust building, capacity building, joint scientific assessments, and institutional leadership need to be brought forward at the beginning of any scientific project at transboundary level. There is a need to identify the questions that are to be answered through science, and what is required for (shared) science-based policy to address existing challenges, while also considering the context and drivers behind policy decision making.

6. While associated with more challenges, evoking a risk and benefits framework approach to the SPI process, with solutions based on co-developed menu options with associated uncertainties, may lead to more consensus-driven and lasting decisions.
7. It is important to identify and recognize the barriers to collaboration in the SPI at an initial stage. Different practices [between agencies, in the way to proceed] can be considered as an unwillingness to collaborate, instead of linking it to institutional hurdles.
8. An enhanced dialogue between scientists and groundwater managers should be transparent, open-minded and unbiased. A systematic methodology to improve communication between groundwater managers (who are outcome-focused) and groundwater scientists (who are evidence-focused) is needed.

The following conclusions and recommendations are brought forward to advance the science-policy interface regarding transboundary aquifers:

1. Finalize the transboundary aquifer governance **Practitioners Guide on Putting Science into Policy**[1], a step-by-step guide for:
   a. Simplified science, design, and principles for converting scientific knowledge
   b. Formulate the essence of hydro-diplomacy - in a context where the resources are hidden, and time lags may be 10 to 100s of years
   c. Present real-world examples, providing practitioners with a guide to the scope of current international water conventions and compatibility with their shared resources
   d. A model for stakeholder interaction aimed at improving implementation of an efficient stakeholder analysis, dialectical conflict resolution, and development of a knowledge-based strategic action plan
   e. Participatory monitoring and needs for improvement in approaches
2. Document the application of science (e.g., monitoring networks, numerical modelling) for assessing groundwater quantity and quality variations through time and informing policy for collective action, advancing into joint strategic action planning and formal cooperation agreements.
3. Consider conjunctive transboundary cooperation in TBA settings, in which both groundwater and surface water resources are part of the cooperation space that requires strong SPI environments and capabilities.

1 Presented at ISARM 2021.

Topic 3

Advances in the assessment and mapping of TBA and hydrogeological methods

Introduction

by Rosario Sanchez

The first map of transboundary aquifers of the world was released in 2009. In 2015, there were officially 366 transboundary aquifers reported by IGRAC (Integrated Groundwater Resources Assessment Center). Today, we know there are 468 transboundary aquifers, underlying almost every nation. After 7 years, almost 100 aquifers more were identified around the world, and that number will continue to grow as the pressure on groundwater increases with population growth, climate uncertainty, and surface water scarcity. The main challenge, however, remains the assessment of those underground resources as the basis for the ultimate purpose: the shared management of transboundary groundwater resources. Only a handful of agreements of shared groundwater resources have been recorded, even though additional efforts driven at national/formal level and at local and regional scales are currently taking place and paving the road towards this objective.

This section highlights research related to recent developments on the delineation, understanding and assessment of transboundary aquifers around the world. How those new efforts, techniques, approaches can provide alternative methods and practices that can be useful to improve water cooperation challenges across countries. The importance of localities, cultural and social conditions also highlight the need to expand the analysis beyond the physical assessments.

TOPIC 3/Paper 7

Transboundary Diagnostic Analysis: Eastern Kalahari-Karoo Transboundary Basin Aquifer

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Abstract

A Transboundary Diagnostic Analysis (TDA) of the Eastern Kalahari-Karoo Transboundary Basin Aquifer (EKK-TBA) system was conducted to provide a comprehensive understanding of the state of surface water and groundwater resources, uses, spatial and temporal variability, interactions, and human impacts as well as benefits derived from ecosystem services and existing infrastructure. The EKK-TBA is shared between Botswana and Zimbabwe. Water-related issues of the Basin were identified and laid the foundation for an EKK-TBA Strategic Action Plan (SAP).

The EKK-TBA straddles two river basins: Okavango and Zambezi and covers an area of 127,000 km^2 (Botswana 65%; Zimbabwe 35%) (Figure 1). The gradient of the topography is, by and large, very low (880-1400 m amsl from southwest to northeast) and the climate is semi-arid (rainfall: 325-625 mm/yr, mostly <500 mm/yr). Surface water drainage is mainly through ephemeral rivers towards the Makgadikgadi Pans in the southern part of the Basin and the Gwayi River system in the northeastern part flows towards the Zambezi River. The 2020 human population of the Basin is estimated at 595,000 (Botswana 16%; Zimbabwe 84%), and the economy is mostly driven by diamond mining, ecotourism and agriculture (livestock and cropping).

Groundwater forms the main source of potable water. The Kalahari Group constitutes shallow aquifers and the main aquifers of the underlying Karoo Supergroup are the deep Ntane/Forest Sandstone and the Mea Arkose Sandstone. Wellfields for mining activities and for domestic water use have been developed along the southern and southeastern fringes of the Basin where the sandstone aquifers outcrop and are recharged from rainfall making the groundwater fresh.

The transboundary nature of the EKK-TBA requires joint governance and management by the Okavango River Basin Water Commission (OKACOM) and the Zambezi Watercourse Commission (ZAMCOM) within the SADC water institutional framework.

Key water-related issues identified as part of the TDA include:

- Water insecurity due to increasing water demand and limited potable groundwater resources
- Data scarcity, inaccessibility and poor quality
- Land degradation from deforestation and poor agricultural practices
- Inadequate resources for effective and efficient groundwater management
- Lack of joint transboundary groundwater governance and management

Keywords: Eastern Kalahari-Karoo Transboundary Basin Aquifer, Transboundary Diagnostic Analysis, Okavango and Zambezi River Basins.

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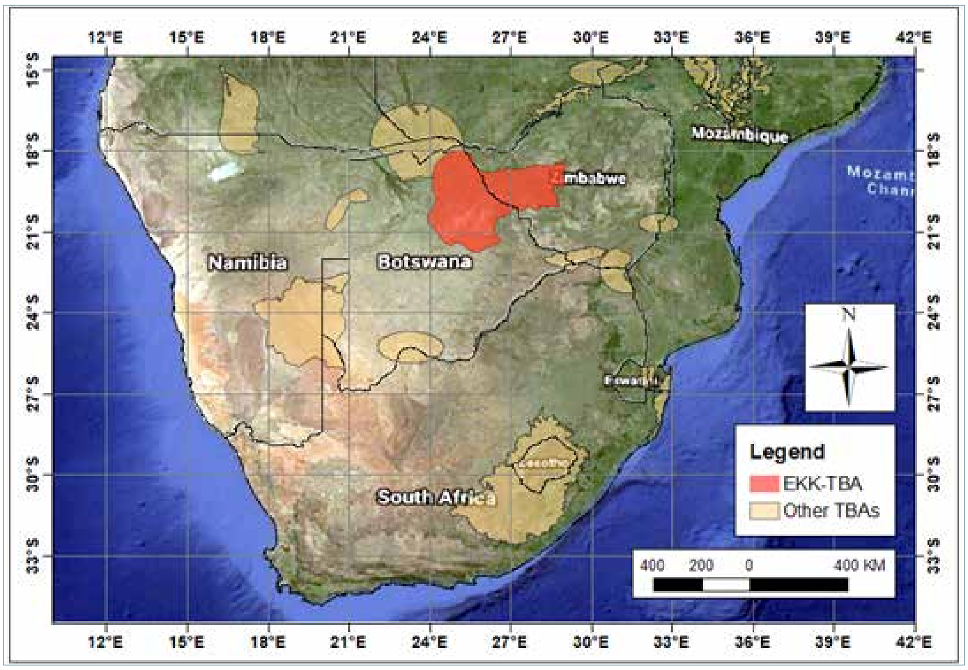
Introduction

In 2020, a Transboundary Diagnostic Analysis (TDA) of the Eastern Kalahari-Karoo Transboundary Basin Aquifer (EKK-TBA) system was conducted as part of the Southern African Development Community Groundwater Management Institute (SADC-GMI) "Water Management Research in the EKK-TBA" project (SADC-GMI, 2020a). The EKK-TBA is a multi-layered aquifer system and is shared between Botswana and Zimbabwe and constitutes the study area, Figure 1.

The TDA is a multi-disciplinary technical assessment, through which water-related issues of thematic areas (demography and socio-economy, surface water and groundwater resources, land use and land cover, environment, institutions and water governance) of a transboundary basin are identified and discussed, providing the baseline and justification for the development of a Strategic Action Plan (SAP) to address the issues. Since groundwater is the main source of water in the Basin, a basin-wide hydrogeological study (SADC-GMI, 2020b) was simultaneously undertaken to better inform the TDA.

Figure 1.
TBAs in Southern Africa south of Latitude 15O S



(modified after SADC-GMI, 2020a; IGRAC, 2021) (© Open Street Maps, Own Elaboration)

Methodology

Thematic data and information were derived during the course of the project (April 2020 – December 2020) from peer reviewed publications and technical reports. Additional data and information were acquired through SADC-GMI focal persons within the two countries. Field visits could not be made, and neither could some of the data be collected due to the COVID-19 pandemic restrictions, hence, Basin multi-stakeholder virtual workshops were held for stakeholder input and validation of findings during the TDA development process.

Borehole data and related information within the area bounded by longitudes 22o and 30o East and latitudes 16o and 22o South were obtained in electronic format from the SADC-GMI Groundwater Information Portal (SADC-GIP). Quality control filtered out usable data. The identified key issues were fed into the EKK-TBA Strategic Action Planning process and implemented in the last phase of the project.

Results and discussion

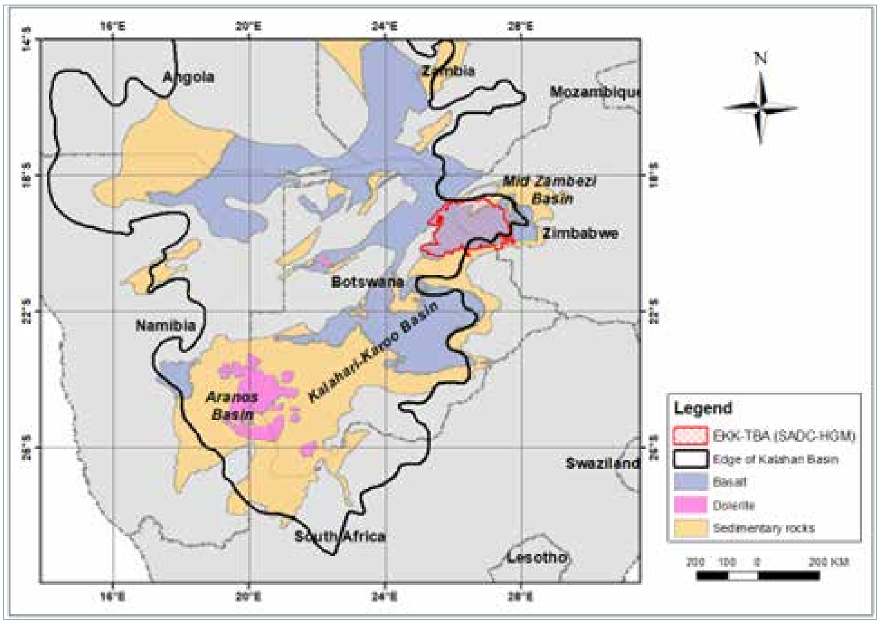
EKK-TBA boundary delineation

The EKK-TBA boundary was defined during the SADC-Hydrogeological Mapping Project (SADC-HGM, 2010) and was mainly based on the topography and surface water drainage. The boundary was re-evaluated as part of this project based on an analysis of regional lithostratigraphy and piezometry.

The EKK-TBA extends from eastern Botswana to western Zimbabwe and comprises Kalahari Group deposits overlying lithostratigraphic units of the Karoo Supergroup (Basalt and Upper and Lower Karoo sediments), in turn underlain by Basement Complex. Sedimentary rocks and Basalt from the Karoo Supergroup extend well beyond the EKK-TBA area demarcated by the SADC-HGM (2010) (Figure 2).

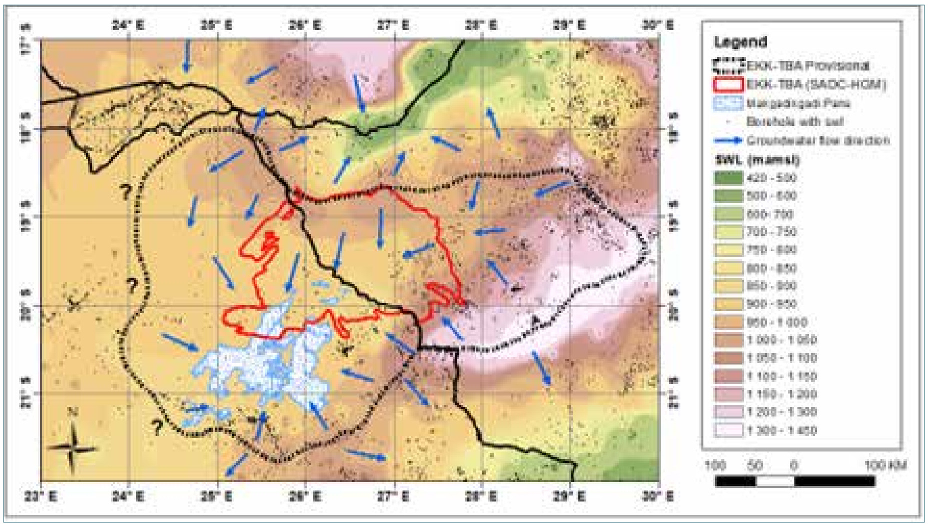
Regional piezometry and deduced groundwater flow directions, mainly of the Kalahari Group aquifer, based on the SADC-HGM database (2010), indicate a larger size for the EKK-TBA. The EKK-TBA boundary in the north, east and southeast was revised based on groundwater divides (Figure 3). Groundwater information in the western and southern sections of the area is very scanty. Since this area is also very flat, a pragmatic approach was adopted for demarcation of that part of the Basin boundary. The EKK-TBA boundary is subject to review when additional groundwater information becomes available.

Figure 2.
Old EKK-TBA extent within the Kalahari-Karoo Basin



(modified after Haddon, 2005; SADC-HGM, 2010) (© Open Access, Own Elaboration)

Figure 3.
Revised EKK-TBA boundary based on topographical divides and inferred groundwater flow pattern



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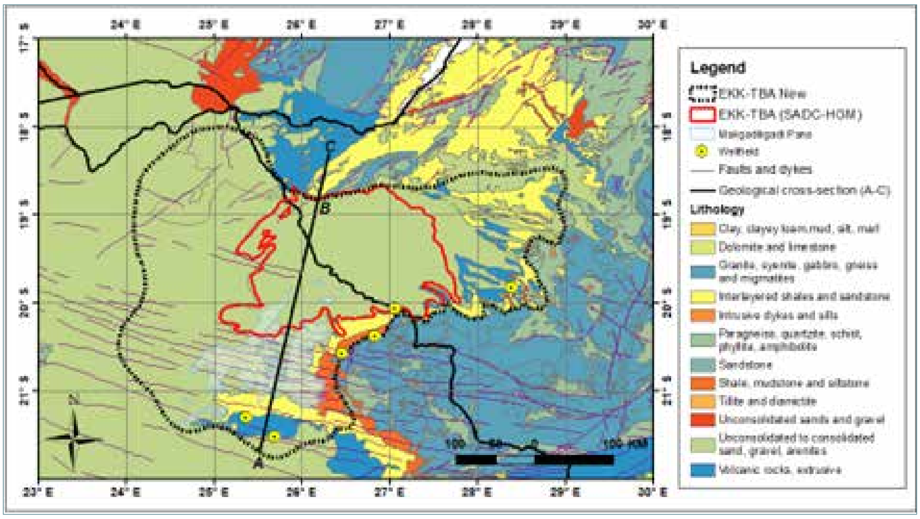
The boundary was further refined, excluding outcropping basement rocks to the south and southeast (Figure 4). The size of the new EKK-TBA is ~127,000 km^2, more than triple the original size, with 65% in Botswana and 35% in Zimbabwe.

The new EKK-TBA boundary overlaps part of the Okavango and Zambezi River Basins and includes major wellfields in Botswana and Zimbabwe as well as the Makgadikgadi Pans (Figures 4 and 6), which are the surface water and groundwater discharge zones. The upper course of the Gwayi River system (Khami and Umguza Rivers) forms part of the EKK-TBA even though the largely perennial Gwayi River ultimately drains into the Zambezi River (Figure 6).

Figure 4.
New EKK-TBA boundary excluding basement rocks

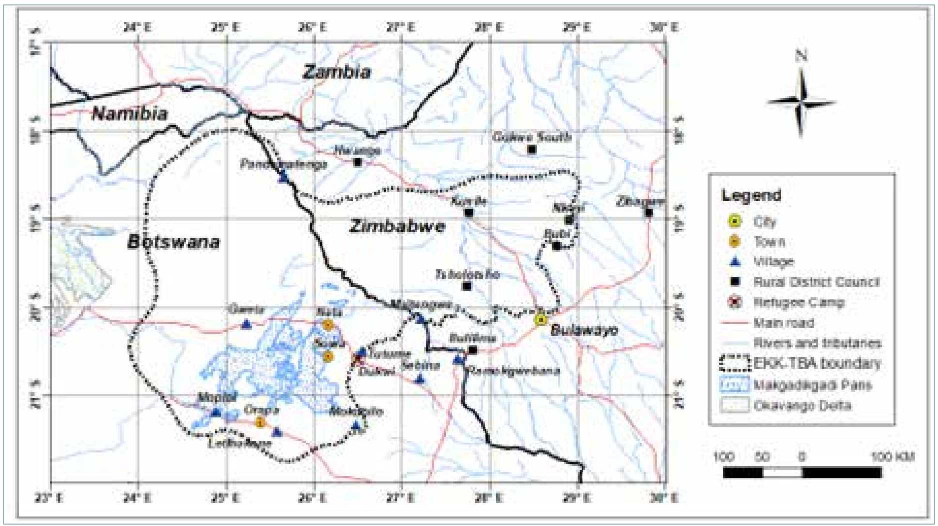


(modified after SADC-GMI, 2020a and 2020b) (© Open Access, Own Elaboration)

Demography and socioeconomy

Figure 5 shows the location of towns/settlements within and just outside the new EKK-TBA.

**Figure 5.
Location of Bulawayo City, towns, villages and Rural District Councils**



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For 2020, the EKK-TBA population is estimated at 595,278 (Botswana: 16% and Zimbabwe: 84%) and is projected to almost double by 2050, which will put great strain on the limited potable water resources of the Basin. Mining (diamonds), tourism (National Parks: Makgadikgadi Pans and Hwange National Park (Figure 7) and game reserves), and commercial and subsistence farming are the key socioeconomic activities in the Basin and also heavily rely on groundwater resources. The growth in water demand against a backdrop of limited potable water resources pose a challenge of possible water conflicts between the various users, particularly between the local farmers and mining firms on the Botswana side of the Basin and between the local farmers and the Zimbabwe National Water Authority (ZINWA) (abstracting groundwater for the City of Bulawayo) on the Zimbabwean side.

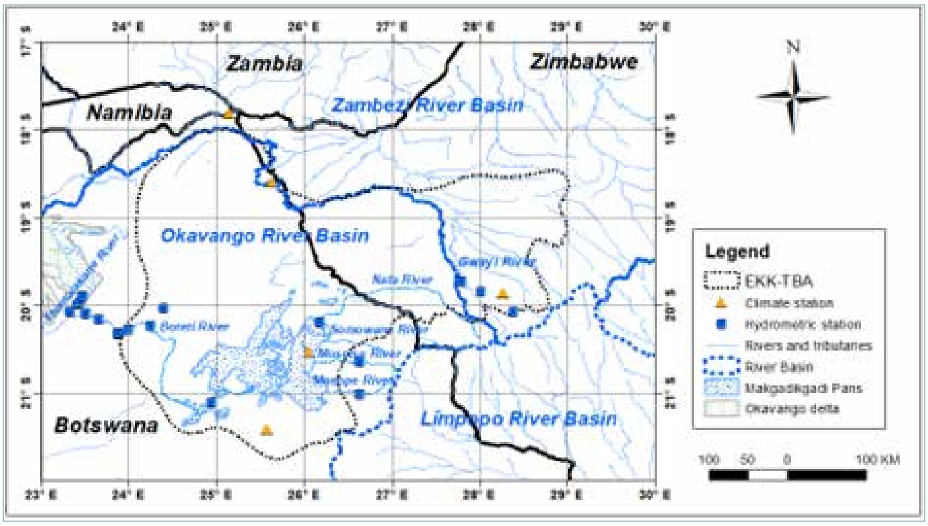
Climate

Rainfall and temperature data from five climate stations (4 from Botswana and 1 from Zimbabwe) (Figure 6) and the Climate Research Unit (CRU) Version 4.04 dataset were used. The selected CRU data period was 1970-2019, which represents a period where historical climate observations are consistently available in the two countries. The EKK-TBA mainly lies in a semi-arid region with average annual rainfall ranging from 325 mm/yr in the southwest to 625 mm/yr in the north and northeastern parts. Mean monthly minimum and maximum temperatures range from 13 to 15 °C and 27 to 30 °C, respectively from the eastern to the western parts of the EKK-TBA. The temperatures have been established to be increasing over the years. The flatness of the Basin does not favor reservoir construction and the generally low rainfall restrict groundwater recharge which adds to the Basin water insecurity given the anticipated exponential increase in potable water demand due to rapid Basin population growth, increased agriculture and commercial activities. High interannual rainfall variability and increasing temperature are also adding to the Basin's water insecurity.

Surface water

The EKK-TBA covers parts of the Okavango and Zambezi River Basins and mostly comprises ephemeral rivers (Figure 6). The EKK-TBA is linked to the Okavango River system by the Boteti River, which drains into the Makgadikgadi Pans. The Boteti River only flowed in 2010 after some 20 years of no flow. On the eastern side, the Nata River, originating from Zimbabwe, flows into the Makgadikgadi Pans. The largely perennial Gwayi River system in the eastern part of the EKK-TBA, flows northwest towards the Zambezi River. The Basin's surface water availability is thus very constrained.

Figure 6.
EKK-TBA surface water drainage and climate and hydrometric stations



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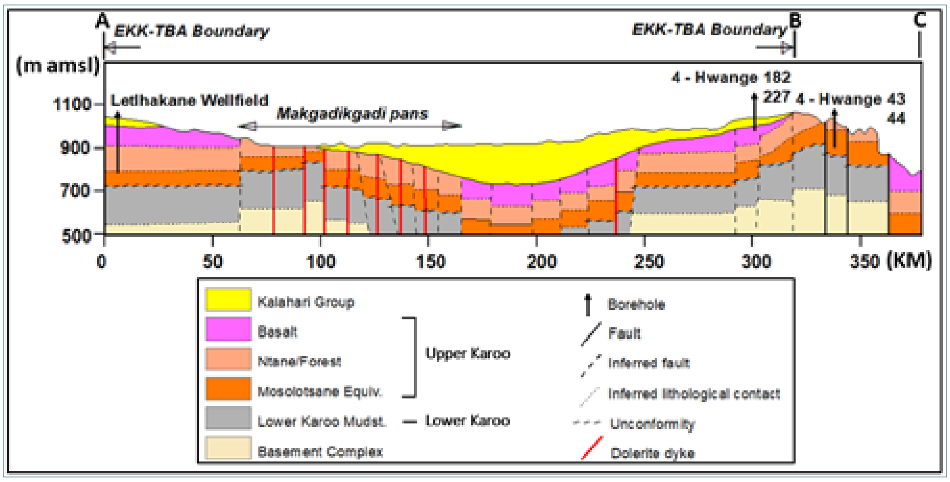
Groundwater

Local information (mostly from wellfields) was upscaled to the Basin level after verifying findings with peer-reviewed publications, technical reports and published geological and hydrogeological maps. Upconing of saline groundwater has been seen in some of the mining firms' boreholes and there is also the risk of saline water intrusion into the fresh shallow aquifers.

Geology

A simplified geological cross-section, from SW to NE (Figure 7; A-C in Figure 4), shows the Kalahari Group deposits and Karoo Supergroup (Upper and Lower Karoo) Basalt and sediments (harmonized lithologies between the two countries) with a general horst and graben morpho-tectonic style. The horsts correspond to uplifted basement complexes/highlands and the grabens to Karoo sedimentary depressions. The numerous structural features compartmentalise groundwater resources resulting in very low groundwater flows and often a rapid build-up of salinity thereby rendering the groundwater not suitable for many purposes.

Figure 7.
SW-NE geological cross-section (A-C in Figure 4) through the EKK-TBA



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Hydrogeology

The Kalahari Group deposits (aeolian sands, silcrete, conglomerate, limestone, calcrete ferricrete, ironstone, limonite, silcretized/ calcretized sandstones and mudstones) constitute the shallow unconfined to semi-confined aquifer and the Ntane/Forest Sandstone and the Mea Arkose Sandstone of the Karoo Supergroup constitute the deeper confined aquifers. Regional piezometry of the Kalahari Group aquifer, Figure 3 shows that groundwater flows from Zimbabwe towards the Makgadikgadi Pans in Botswana and conforms to the findings of WWF (2019) study carried out in the Hwange National Park. Groundwater flow in the individual wellfields, when not pumped, also conforms to the regional flow, which is towards the Makgadikgadi Pans.

Average annual groundwater recharge has been established to be generally <3% of the average annual rainfall (SADC-GMI, 2020b) and is similar to what was found in groundwater recharge studies in other semi-arid regions (Beekman et al., 1996; Xu and Beekman, 2019).

Groundwater chemistry of the Ntane/Forest and Mea Arkose Sandstone aquifers is generally 'fresh' in the recharge zones and deteriorates in quality with increasing depth and movement away from the recharge zone which occurs in the southern to the eastern peripheries of the Basin and is represented by the location of the various wellfields (Figure 4).

The Ntane/Forest Sandstone and Mea Arkose Sandstone Aquifers are the main source of groundwater. Yields are much higher at the peripheries of the Basin where the groundwater is also fresh.

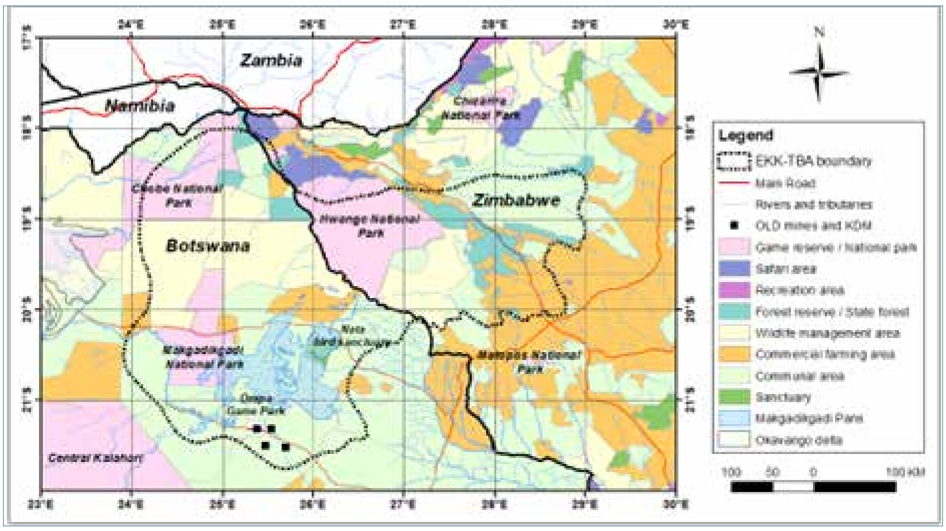
Groundwater use of the EKK-TBA is estimated at: domestic 22%, agriculture 15% and industry (mining) 63% and is currently outstripping supply.

Groundwater monitoring (water levels, water quality and abstraction volumes) mostly takes place at the wellfields and the data and information are mostly in paper form. The monitoring data is not consistently collected and in some instances is of poor quality. Electronic databases are generally not user friendly, thus making them redundant. There is no standardization of the databases between the various institutions, and this creates challenges of compatibility and exchange of data. It is also a challenge to access data from the various institutions within the Basin due to unending bureaucratic processes, particularly the Zimbabwe National Water Authority (ZINWA).

Land use and land cover

The EKK-TBA is dominated by the presence of national parks, forest reserve areas, wildlife management areas, mining (mostly in Botswana) and agriculture (cropping and livestock) (Figure 8). The Basin has limited access to electrical or power grid and hence the communities heavily rely on wood for their energy needs. This has seen rampant destruction of vegetation including from protected forest areas and is resulting in land degradation through soil erosion. Poor agricultural practices are also leading to land degradation as has been noticed in some areas of the Basin. Expansion of agricultural land into wildlife areas has also seen a rise in human-wildlife conflict, which has resulted in loss of human lives, destruction of crops and killing of wild animals particularly in Zimbabwe. This could negatively impact the countries' tourism sector and ultimately their socio-economic development.

Figure 8.
Land use in the EKK-TBA



(SADC-GMI, 2020a) (© Open Access) (Orapa, Letlhakane, Damtshaa (OLD) Mines and Karowe Diamond Mine (KDM))

Groundwater governance

The Water Utilities Corporation (WUC) and the Department of Water and Sanitation (DWS) are the two primary institutions tasked with monitoring of water resources in Botswana whereas the Zimbabwe National Water Authority (ZINWA), a parastatal under the Ministry of Lands, Agriculture, Water and Rural Resettlement (MLAWRR) manages water resources in Zimbabwe with the assistance of Catchment Councils and Sub-catchment Councils. Mining firms in Botswana monitor their own wellfields. There are no EKK-TBA governance and management structures and hence there is no collective management (Botswana and Zimbabwe) of the groundwater resources of the Basin. Legislative frameworks are only specific to the two countries. These key institutions mandated with groundwater management within their respective countries have inadequate human, financial and material resources to effectively and efficiently carryout groundwater management. This has resulted in the drilling of unregulated boreholes and groundwater overexploitation in some parts of the Basin in both countries. The lack of human resources is also hampering the deployment of innovative technologies such as remote sensing in groundwater resources management.

Conclusion

Identified key issues are:

- Water insecurity (human, mining, agriculture, wildlife and ecosystems):
  - High interannual rainfall variability and increasing temperature
  - Upconing of saline groundwater and possibility of intrusion of saline groundwater into shallower and lower salinity aquifers
  - Potential water related conflicts between mining companies and local farmers on the Botswana side and between local farmers and the Zimbabwe National Water Authority (ZINWA) (abstracting groundwater for the City of Bulawayo) on the Zimbabwean side
- Data and databases:
  - Data unavailability/scarcity and inaccessibility and poor quality
  - Lack of good quality hydro(geo)logical databases and limited standardization
- Land degradation from deforestation and poor agricultural practices
- Groundwater management:
  - Inadequate resources to carry out effective and efficient groundwater management
  - Groundwater over-exploitation
  - Unregulated borehole drilling
  - Inadequate use of innovative technologies such as remote sensing to fill data gaps
- The EKK-TBA boundary asymmetry:
  - Involvement of two River Basin Organisations adds complexity to the governance challenges
  - Lack of joint transboundary groundwater governance and management framework

Acknowledgements

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TOPIC 3/Paper 8

Sustainable Transboundary Groundwater Management using Groundwater Modeling and Hydrochemical Investigation

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Abstract

In recent decades, substantial development of irrigated agriculture and city expansion has occurred in the border regions of Sultanate of Oman and the United Arab Emirates (UAE) with enhanced exploitation of groundwater in this region. Therefore, it is critical to develop integrated modeling and hydrochemical approaches to evaluate groundwater behavior of the region. A three-dimensional stratigraphic model representing four principal hydrogeologic units was generated using data collected from drilled boreholes. Layer elevations and materials for four layers grid cells were taken from the stratigraphic model. Results show that the long-term lateral groundwater flux ranging from 4.23 to 11.69 Mm3/yr, with an average of 5.67 Mm3/yr, drains from the fractured eastern ophiolite mountains into the alluvial zone. Moreover, the long-term regional groundwater sustainable groundwater extraction is 18.09 Mm3/yr for 17 years, while it is, respectively, estimated as 14.51, 16.31, and 36.00 Mm3/yr for dry, normal, and wet climate periods. Groundwater samples were analyzed for hydrochemistry. While the water-rock interaction is the dominant process controlling the groundwater chemistry, evaporation and groundwater mixing affect the hydrochemistry at the UAE borders. Therefore, groundwater evolves from carbonate-dominant in the North Oman Mountains (NOMs) into sodium-chloride dominant close to the UAE borders.

Keywords: Transboundary aquifer; groundwater modeling; hydrochemistry; Oman.

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Introduction

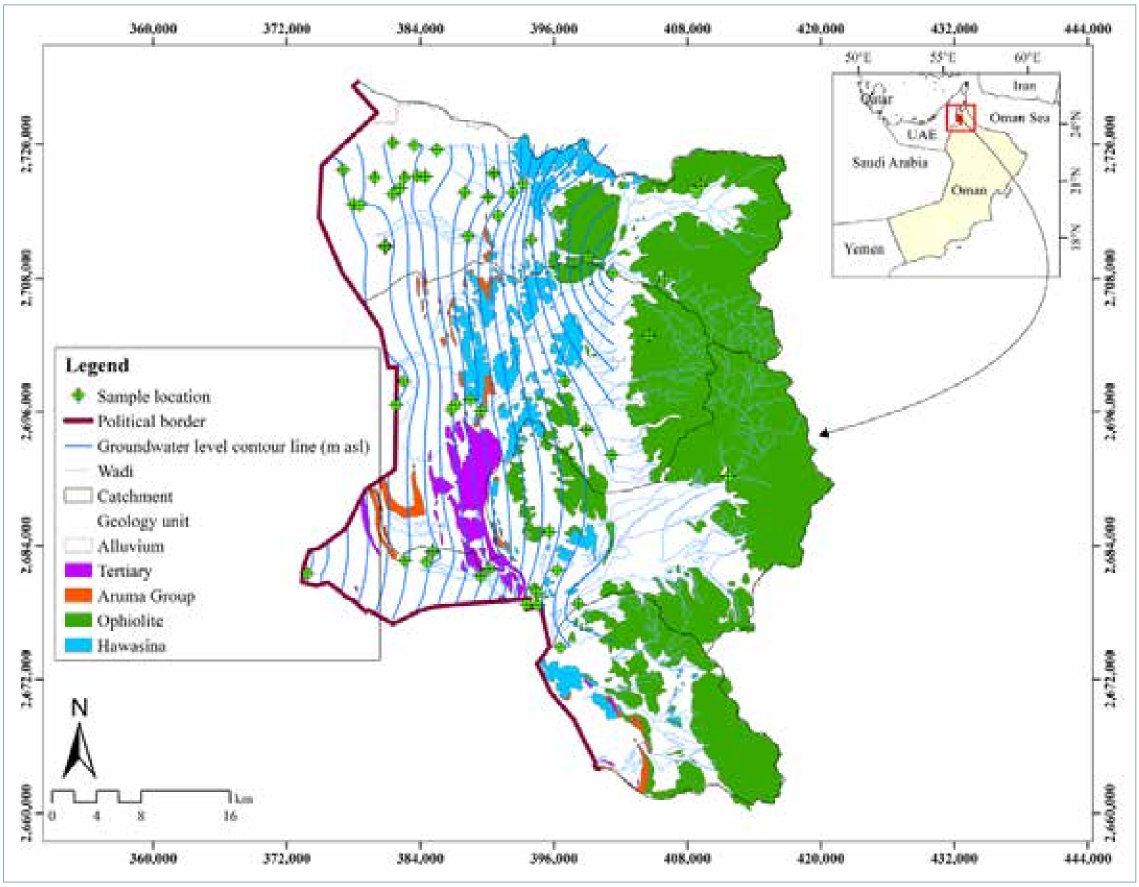
Proper management of transboundary groundwater aquifers, which cross the borders of countries, is imperative for sustainable development. Groundwater in the border regions separating the Sultanate of Oman and the United Arab Emirates (UAE) represents an important resource for sustainable agricultural and urban development. While North Oman Mountains (NOMs), located in the eastern part of the area, have been delineated as the principal recharge source, there is no prior quantitative groundwater resources analysis in this region. Given that the assessment of transboundary groundwater is not straightforward, it is critical to develop integrated modeling and hydrochemical approaches to evaluate groundwater behavior of the region. Modeling is an important component of transboundary groundwater management systems which can enhance understanding of transboundary aquifer conditions. The hydrochemical study is an important part to comprehend the availability and nature of groundwater through identifying moisture sources and different geochemical processes that control the quality of water. Therefore, the objectives of this study are to simulate groundwater behavior and to utilize hydrochemistry to realize the processes controlling the groundwater chemistry in the transboundary aquifer of Oman–UAE border.

Material and Methods

Study area and Geology characteristics

Study area is located between 24° 22′ N to 24° 38′ N latitude and 55° 44′ E to 56° 14′ E longitude. It covers around 1,600 km^2 and is bounded by the border with the UAE on the west and by the ridge of NOMs on the East. It is characterized by an annual average rainfall of 82 mm. The annual potential evapotranspiration is about 2700 mm. Three main geologic units in the study area are Semail Nappes (Ophiolite), Hawasina Nappes, and post-nappe strata units (Aruma group and Tertiary bedrock and Quaternary alluvium) (Fig. 1). The term "ophiolite" refers collectively to igneous rock that crops out in the study area with various dark, colored, crystalline and microcrystalline characteristics. The Hawasina exposures mainly occur as broken hills in the eastern piedmont zone. The post-nappe strata consist of the Aruma Group and Tertiary bedrock that were deposited in a foredeep basin downfolded along the frontal margin of the nappes. Folding associated with mountain building in the Late Tertiary turned over the Tertiary strata into their present structural configurations. Afterwards, erosive processes associated with flowing water led to the deposition of alluvium throughout the piedmont and alluvial fan zones to the west of the mountains (Kaczmarek, 1988).

Fig. 1.
Study area in the Oman–UAE border along with sample location. Groundwater level contour lines is showing the groundwater flow direction from east to west



(Adapted from Abdalla et al. 2018). (© Creative Commons)

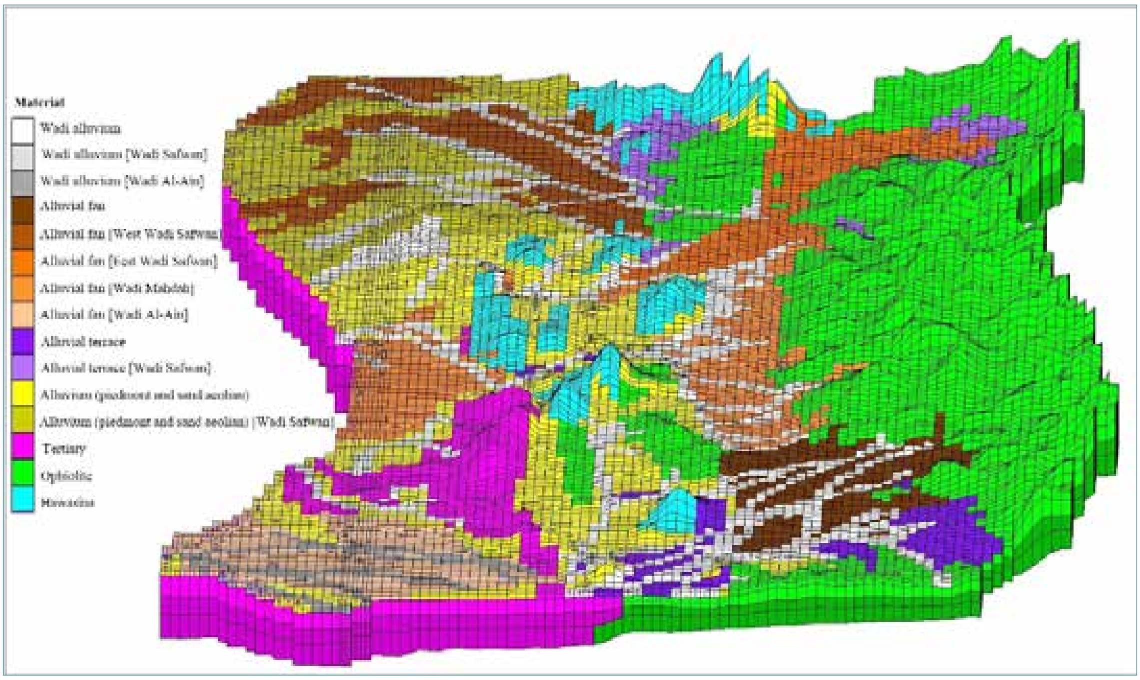
Groundwater Conceptual Model

A proposed framework by Izady et al. (2014) is employed to develop a conceptual model of the groundwater flow for the study area. Groundwater flow generally occurs from the east to the west. A three-dimensional stratigraphic model representing four principal hydrogeological units was generated using data collected from 196 boreholes. The depth of boreholes varies from 37 to 388 m with a mean of 70 m. The total thickness of this model varies from 300 to 700 m in the different parts of the study area, with the alluvial portions ranging between 27 m and 77 m in thickness. The eastern boundary of the study area, in the highlands of the NOMs, is considered representing a surface and groundwater divide. Because the northern and southern boundaries of the study area are approximately parallel with the general groundwater flow direction, that can be associated with no-flux groundwater conditions. The western boundary of the study area along the Oman–UAE border is considered as an outflow boundary toward the UAE. Based on aquifer tests, values of hydraulic conductivity for the alluvium aquifer vary from 7.79 m/day to 116 m/day while the regional specific yield ranges between 0.01 and 0.15. The regional hydraulic conductivity and specific yield of the ophiolite were estimated as 1.0×10^{-6} m/s and 0.018. The hydrodynamic properties of Tertiary formations are higher than the ophiolite in the study area and estimated as 1.0×10^{-5} m/s and 0.02 for hydraulic conductivity and specific yield, respectively. Annual groundwater abstraction from agricultural and domestic wells is approximately 26.6 Mm^3 and from aflaj is 2.2 Mm^3. The recharge values estimated by water-table fluctuation (WTF) method (Izady et al., 2017) were used as initial recharge values for the groundwater modeling (Davison 1982; Kaczmarek et al., 1993).

Model Setup and Structure

MODFLOW is used to conduct transient groundwater modeling in which model calibration and validation were carried out for the period of Oct. 1996 to Sep. 2008 and Oct. 2008 to Sep. 2013. Layer elevations and materials for the numerical model were obtained from the stratigraphic model (Fig. 2). Stress period, time step, and time unit was implemented as monthly, monthly, and daily, respectively. A regular mesh and a finite difference grid with 0.125 km^2 cells (250 m × 500 m) with a total of 184 rows, 108 columns and 4 layers were considered. Specific head boundary condition was considered for the west boundary which is associated with a groundwater outflow path. The hydrodynamic properties were assigned for different units in the model. The abstraction values corresponding to all wells were assigned. The recharge rates computed by the WTF method were accounted for as initial values in the model. The Empirical Bayesian Kriging interpolation method (Izady et al. 2017) was used to generate groundwater contour lines from the observation wells. Model calibration was accomplished by trial and error and the PEST (Doherty, 1998). Coefficient of determination (R2), Root Mean Square Error (RMSE) and Normalized RMSE performance criteria were used to evaluate the efficiency of the model.

Fig. 2.
3D view of the grid with different materials for the Al-Buraimi region



(After Izady et al. 2017) © Open Access

Sample Collection

54 locations (Fig. 1) were sampled, including hand-dug wells, boreholes, monitoring wells, precipitation and *aflaj* (an ancient water supply system), in which the depth to groundwater varies from 9.8 to >100 m with an average of 33 m. Different parameters, including temperature, electrical conductivity, pH, and total dissolved solids, were measured in the field. Three samples (for cations and anions) at each location were collected in 500-ml plastic bottles for analyses. The bottles collected for cations analysis were acidified using 2-3 drops of diluted (5%) nitric acid. All samples were immediately analyzed for the major ions and alkalinity in the Sultan Qaboos University (SQU) using Ion Chromatography (IC) and Inductively Coupled Plasma Mass-spectrometry (ICP-MS).

Results and Discussion

Model Calibration

The model performance statistics for the calibration period are given in the Table 1. The Al-Buraimi study area is characterized by the remarkable geological and hydrogeological diversity and is constituted of very thin alluvium in comparison with hard rock thickness (Figs. 1 and 2). Therefore, for the study area, with a total difference in groundwater level in the order of 228 m and 12-year monthly calibration period, a RMSE of 2.71 m is considered quite reasonable. The RMSE was normalized regarding the groundwater level fluctuations of each observation well. For the whole study area, a normalized RMSE of 18% is a satisfactory result.

According to Table 1, the model performance is similarly good in the validation period as the calibration results, indicating remarkable predictive ability of the calibrated model. The normalized RMSE is 32% for the validation period, which is larger than the calibration period. The least matching results are for observation wells which are located at the western boundary where heavy groundwater abstraction takes place inside UAE (Davison, 1982). The volume of such abstraction is not precisely known and was not considered during the current study. Therefore, this might be postulated for getting the higher NRMSE for the validation period.

Table 1.
Model performance statistics for the calibration and validation periods (After Izady et al. 2017)

Period	Weighted RMSE (m)	Weighted R^2	NRMSE (%)
Calibration	2.71	0.69	18
Validation	3.47	0.65	

Sustainable Groundwater Extraction

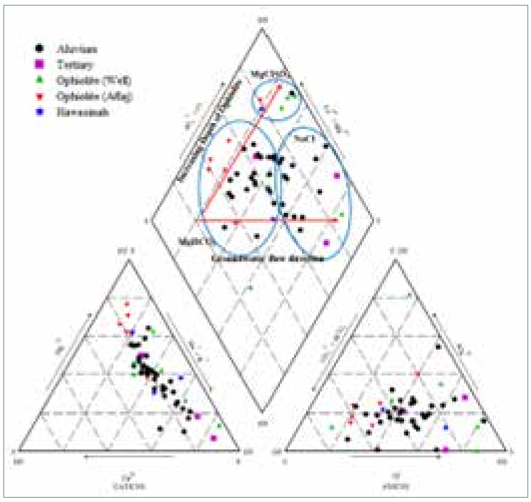
The annual groundwater budget components were calculated from Oct. 1996 to Sep. 2013. The long-term regional groundwater recharge provides 18.09 Mm^3/yr. The long-term groundwater outflow from the study area toward UAE side is equivalent to 32.79 Mm^3/yr. The groundwater abstraction from different sources is estimated as 27.3 Mm^3/yr. The groundwater balance components show a mean annual deficit of 41.99 Mm^3. The source of long-term reliable recharge to the alluvial aquifer in the study area is the drainage from the fractured eastern ophiolite toward the alluvial zone. The results show that the long-term lateral groundwater flux ranges from 4.23 to 11.69 Mm^3/yr, with an average of 5.67 Mm^3/yr drains from the fractured eastern ophiolite mountains into the alluvial zone.

Sustainable groundwater extraction rate was estimated for the long-term and different wet, normal and dry periods. The long-term regional groundwater sustainable groundwater extraction is 18.09 Mm^3/yr for 17-years. It is also, respectively, estimated as 14.51, 16.31, and 36.00 Mm^3/year for dry, normal, and wet periods. It is found that even with the exclusion of abstractions, the water budget of the aquifer is still deficit due to the high outflows toward the UAE side, even for normal years. Indeed, groundwater discharge towards the UAE side is an important component in the water budget and actually exceeds the amount of groundwater extraction. Even if the groundwater pumping rate is restricted within the sustainable groundwater extraction, large water budget deficit will remain because natural recharge is not sufficient to sustain lateral groundwater outflow to the UAE side. It is known that heavily abstraction is taking place at the western side of the study area inside UAE (Davison 1982); the volume of such abstraction is not precisely known. As a result, the groundwater outflow toward the UAE side is mostly affected by the abstraction on the UAE side.

Chemical Composition

Groundwater hydrochemical data are represented in the Piper diagram (Fig. 3), where three dominant Mg-HCO_3, Mg-Cl-SO_4 and Na-Cl groups can be highlighted. Except for one sample that may suggest a deeper source, all the aflaj samples belong to the Mg-HCO_3, circulate within the ophiolite rocks and are located along the slope of the NOMs. The dominance of the carbonates indicates exchange with the atmospheric CO_2 and circulation of modern water at shallower depths. The Mg is the weathering product of the ophiolites at shallower depth where the pH favors the dissolution of brucite which is a magnesium hydroxide. In addition, about half of the alluvium groundwater falls within the Mg-HCO3. This group of alluvium groundwater represents recent recharge from direct infiltration through streambeds. The dominance of Mg in these samples is attributed to the presence of ophiolitic fragments in the alluvium. In general, the groundwater chemistry evolves with increasing depth and proximity to the NOMs signifying the role of water-rock interaction. The NOMs mark the region of freshwater and groundwater salinity increases away from NOMs with increasing mineral dissolution.

Fig. 3
Piper diagram illustrating groundwater classification in different geological formations



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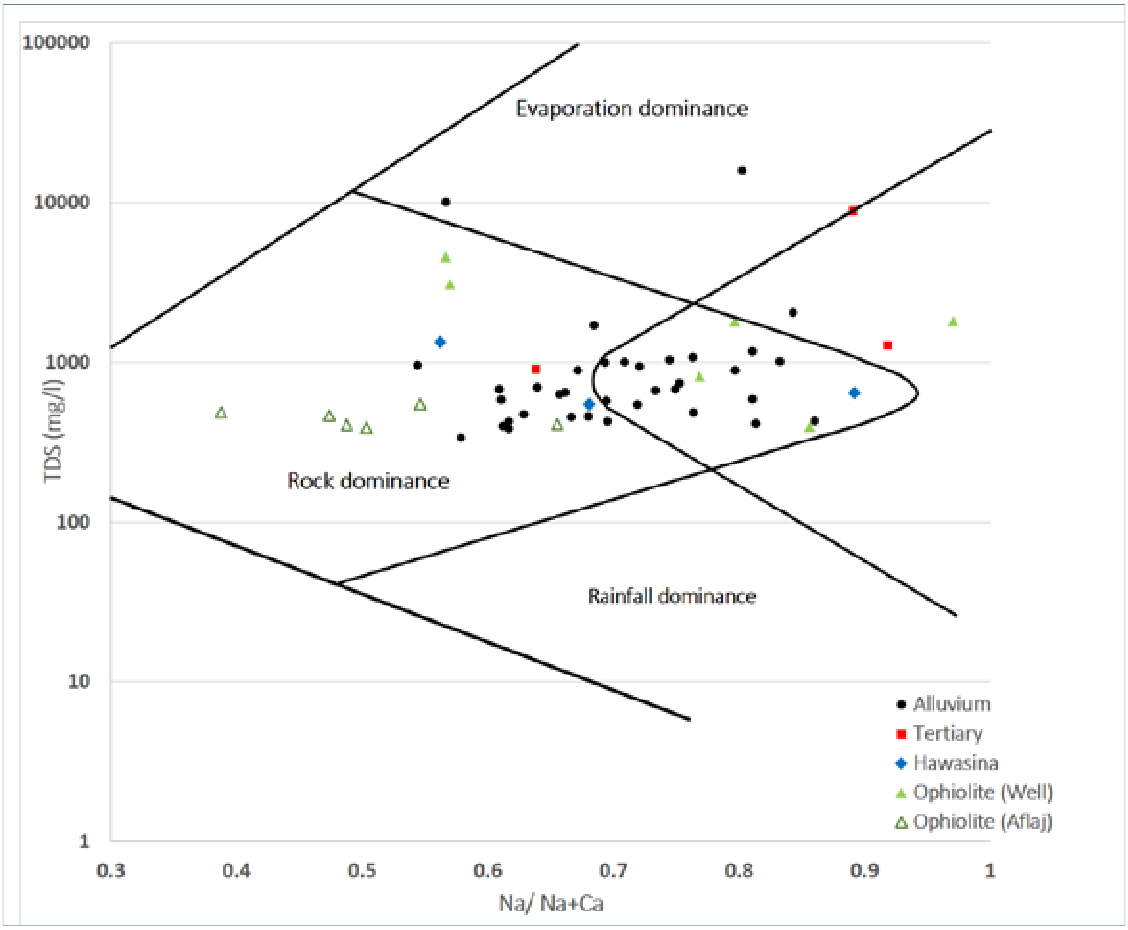
The plot of samples in the Gibbs diagram (Fig. 4) suggests that the chemical composition of most of the samples is controlled by weathering rather than evaporation, except for a few samples that show evaporation dominance. Evaporation can be atmospheric which takes place during precipitation or may occur during runoff as direct evaporation of surface water. The surface water evaporation is observed in the plain areas. The surface water evaporation in the highlands is unlikely due to the steeper slope and thus the residence time of water on the surface is short, which allows no direct surface water evaporation. Thus, only the effect of atmospheric evaporation could be seen. However, in the plain areas where the runoff along the wadis gets ample time on the surface, direct evaporation is significant and therefore the TDS of the groundwater progressively increases.

Fig. 4
Gibbs diagram compares the role of evaporation and water rock interaction processes on groundwater



(After Abdalla et al. 2018). (© Creative Commons)

Conclusion

The developed groundwater model would help decision makers to have a better understanding of the groundwater budget components in such an important transboundary aquifer, located at the Oman–UAE border. As indicated by the imbalance of the water budget analyzed during this study, the groundwater system is under transient state shown by high outflow, which indicates notable abstraction rates across the border. This study, however, was carried out inside Oman and no data from the UAE side was available. It would have been optimum to develop the model in both regions, which requires mutual understanding and interest. The developments of better understanding of the technical issues that are facing the shared resources are fundamental to ensure groundwater sustainability and hence secure agricultural, domestic and industrial activities. This study provides the water balance estimation across the boundary, which gives important boundary data for further modeling efforts in UAE side. Once technical aspects are agreed upon, parties can agree on policy and governance of the resources. In fact, regional cooperation is required to address policy, ownership and technical aspects to achieve sustainability of groundwater resources for this shared aquifer. In the view of the hydrochemistry findings, it can be observed the evolution of the groundwater chemistry from the recharge zone in NOMs dominated by ophiolites to the discharge zone in the plain area at the UAE borders dominated by alluvium cropping at the surface. Induced recharge in the shallow zones of the ophiolite and alluvium increases Mg and HCO_3 concentration.

Acknowledgments

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TOPIC 3/Paper 9

Groundwater-Surface Water Interaction in the Sava River Basin

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Abstract

Sava River has been identified as the main recharge source for the alluvial aquifers in its basin, especially in the upper part of the flow, in Slovenia and Croatia. However, there has not been a lot of research downstream of the Zagreb area, which could show the magnitude of influence of the Sava River on the groundwater resources.

The goals of this research are to establish an international working group; to establish new GNIP (Global Network of Isotopes in Precipitation) and GNIR (Global Network of Isotopes in Rivers) monitoring points; to define groundwater-surface water interaction in the Sava River basin; to identify areas in which the Sava River has relevant influence on groundwater resources; and to see if evaluation of historical and new data indicates the impact of climate change. All this will help to identify and implement measures for sustainable groundwater resources management of the transboundary aquifers in the Sava River basin.

To realize the goals of this project, monitoring points (three in each country) will be established in Slovenia, Croatia, Bosnia and Herzegovina, and Serbia. At each monitoring point, precipitation, river water and groundwater will be sampled. Water isotopic composition will be measured over the period of two years. Water stable isotopes will be measured in all monitoring points and on all types of water, while tritium will be measured at one monitoring point in each country. Within the project we will quantify and separate groundwater recharge from both Sava River and from precipitation in all monitoring points, as well as estimate the groundwater velocities at the monitoring points where tritium will be measured.

Firstly, all available hydrological and meteorological data must be examined. We present a first statistical analysis, based on (precipitation values, Sava River water levels, and groundwater levels) from one selected location in each country (Ljubljana and Krško Drnovo in Slovenia, Zagreb in Croatia, Orašje in Bosnia and Herzegovina, and Šabac in Serbia). First results indicate the existence of different patterns in groundwater-surface water interaction, as well as different types of aquifers. Furthermore, trend analysis shows negative groundwater and surface water level trends in the downstream parts of the Sava River basin.

This research presents one of the case studies within the IAEA Regional Technical Cooperation Project RER7013, which goals are the development of new technical capacities and competencies in isotope hydrology, and the clarification of persisting issues in the region related to the sustainable management of transboundary water resources.

Keywords: Sava River basin, groundwater-surface water interaction, transboundary aquifers.

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Introduction

Groundwater is one of the main sources of potable water in the world. Demand for clean potable water is continuously growing, especially in arid regions (Chen et al., 2015). Also, it has been shown that many alluvial aquifers have problems with groundwater depletion, while recent research points out that these problems have become a global issue (Gleeson et al., 2015). Today, these problems are also becoming evident in moderate climate areas, too. This can be especially seen in unconfined alluvial aquifers which are in direct contact with rivers under the influence of climate change (Gampe et al., 2016; Vrzel et al., 2019). All this suggests a detailed investigation of groundwater recharge mechanisms and their relationship is needed to ensure sustainable potable water supply from these aquifers for future generations. Sava River is one of the main rivers in Slovenia, Croatia, Bosnia and Herzegovina and Serbia. It has two springs, forming the Sava Dolinka and the Sava Bohinjka. These headwaters merge to form the Sava in northern part of Slovenia. It has been shown that in some parts of the Sava basin recharge of the alluvial aquifers is closely related to water levels in the Sava River. For example, this can be especially seen in the Zagreb area, where the Sava River presents the main source of the recharge for the Zagreb aquifer (Parlov et al., 2019). Other research has shown that the Sava River and local precipitation are the main recharge sources for the alluvial aquifer in Ljubljana (Slovenia), but also that groundwater shows spatial variability in its composition (Vrzel et al., 2018). Although a range of research has been done in alluvial aquifers in the Sava River basin, not all areas are investigated to the same level of detail, and neither the monitoring of groundwater nor river water level observations started in the same year. Due to differences in morphological, geological, and hydrogeological characteristics along its entire length, it can be expected that the impact of the Sava River on groundwater resources is not everywhere the same.

To further explore this issue and to determine if the long-term data suggests climate change impact on groundwater resources in the Sava River basin, this research has been accepted as one of several case studies that are currently conducted within the IAEA (International Atomic Energy Agency) Regional Technical Cooperation (TC) Project RER7013. The main goals of this project are closely linked to technical capacities building and the strengthening of regional competencies in isotope hydrology, but also to the clarification of main issues in the Sava River basin related to groundwater-surface interactions and the influence of climate change on groundwater resources. The project should create a new international scientific research team and new GNIP and GNIR monitoring points. The expected outcome of the project is new knowledge that will contribute to the sustainable management of transboundary water resources in the Sava River basin.

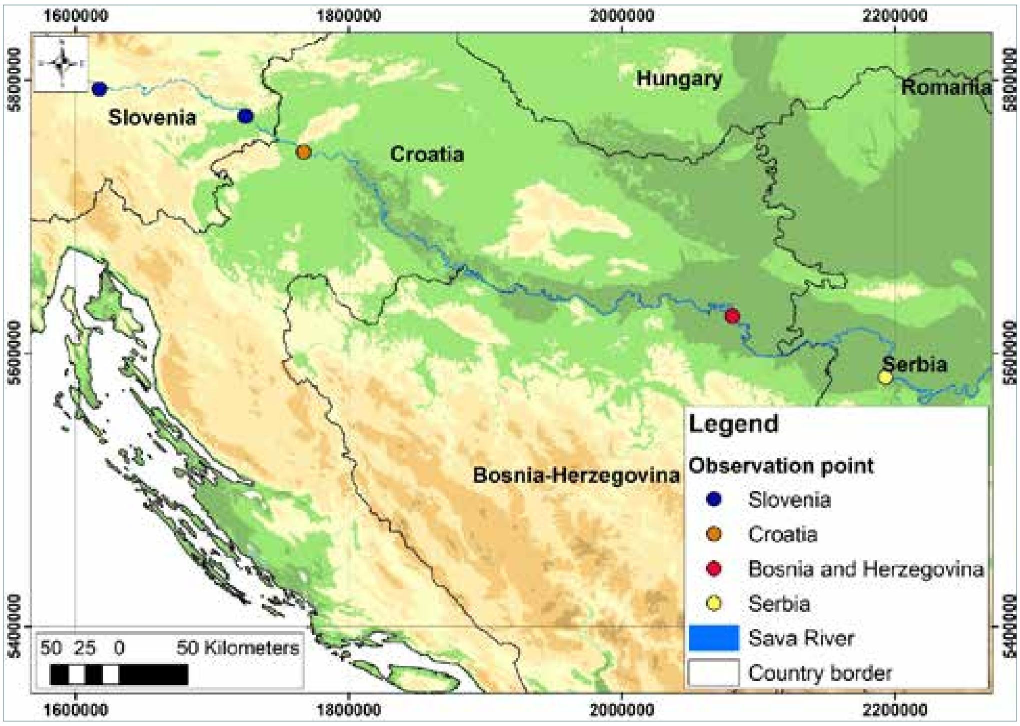
Methodology

The Sava River water levels, groundwater levels (GWL) and precipitation amounts have been examined. Due to data availability, Slovenia water levels are presented as monthly values (from 1976 to 2019), for Croatia and Bosnia and Herzegovina as daily values (from 1997 to 2019 and from 2019 to 2020 respectively), and for Serbia in most cases the time interval is between five to ten days (from 2010 to 2019). All precipitation values are observed on a monthly basis, while for Serbia some precipitation data is available only in quarterly intervals. Time periods for precipitation data vary from 1976 to 2019, 1981 to 2019, 2019 to 2020 and 2009 to 2021 for Slovenia, Croatia, Bosnia and Herzegovina and Serbia, respectively. In addition to basic statistical parameters (mean, median, min, max, standard deviation), linear regression is used to provide trend estimations, while Pearson`s correlation coefficient and cross-correlation analysis is used to test the relationship between groundwater and river water levels. Cross-correlation analysis has been widely used in meteorology and hydrogeology research (Crosbie et al., 2005; Lee et al., 2013; Welch et al., 2013). For estimation of lag times, a Microsoft Excel spreadsheet application for cross-correlation analysis is used (Posavec et al., 2017). Statistical significance for correlation and trend analysis is ascertained with a t-test (α=0.05). Estimated significance levels are not adjusted for autocorrelation in the time series, which might be indicated for future refinements of the data analysis.

Data has been provided by different agencies (Environmental Agency of Slovenia, Croatian Meteorological and Hydrological Service, Sava River Basin District Agency, and Republic Hydrometeorological Service of Serbia) and from different web sources. All calculations are made with Microsoft Excel. In Slovenia, groundwater levels are evaluated from the Krško area (site Drnovo), while river water levels are presented for the Čatež hydrological station, which are both located in the eastern part of Slovenia. Precipitation data is shown for the meteorological station Ljubljana-Bežigrad, which is in the central part of Slovenia. In Croatia, all observation points are in the City of Zagreb, while in Bosnia and Herzegovina all observation points are located in the northeastern part, in the area of Orašje municipality. In Serbia, the research area is related to the city of Šabac (Figure 1). It must be emphasized that some of the observation points are very old, some are new, while for some others only part of the existing data series is available. The aim was to maintain the same time period when evaluating river and groundwater levels in each country separately. These are therefore preliminary results of four locations, and in the IAEA RER7013 project all types of water will be sampled (precipitation, river water and groundwater) and different kind of water isotopes analysis will be done at additional eight locations (in total 12) to establish mixing models and evaluate the relationship between the Sava River and alluvial aquifers throughout the whole river basin. At one location in each country, the tritium content will also be measured to evaluate the age of water and to estimate approximate groundwater velocities, as shown in Barešić et al. (2020).

These results, together with detailed statistical analysis of hydrometeorological variables, will improve the management of the transboundary aquifers, which are in direct contact with the Sava River, and provide a new basis for sustainable management of transboundary water resources.

Figure 1.
Location of observation points



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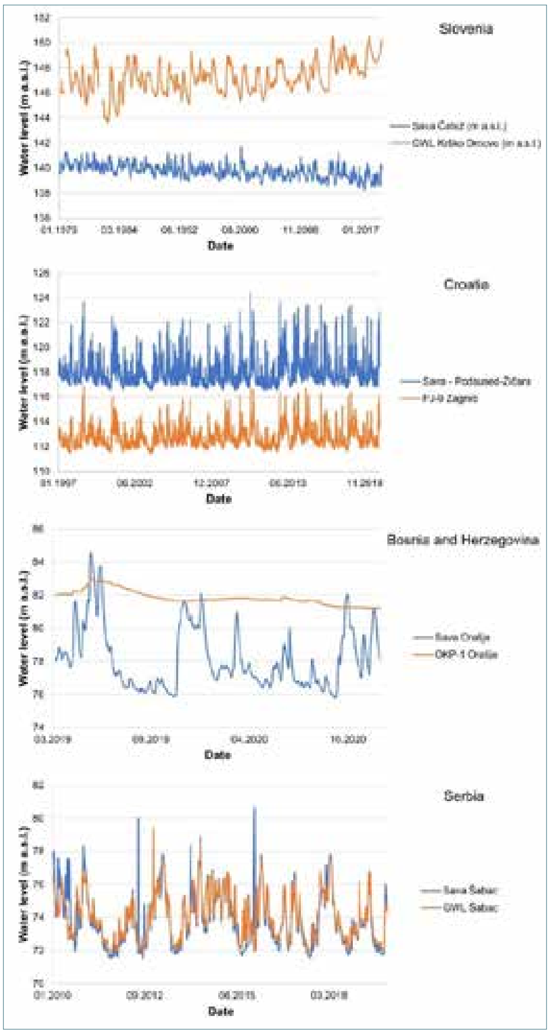
Results

In Figure 2 groundwater and river water levels are presented. In the area of Krško Drnovo (Slovenia) groundwater levels are higher than Sava River water levels from Čatež. The correlation coefficient is only -0.02. In Zagreb (Croatia), Sava River water levels are higher than in observation well PJ-9, with a high correlation coefficient of 0.93. In Orašje (Bosnia and Herzegovina), Sava River in general has lower water levels than groundwater and the correlation coefficient is 0.27, while in the Šabac area (Serbia) Sava River and groundwater levels are very similar with a high correlation coefficient of 0.85. All correlation coefficients are statistically significant except the one for Slovenia. These results suggest that the relationship between Sava River and groundwater bodies in the Sava alluvium is different between the four locations. To get more detailed information about the relationship between surface and groundwater, cross-correlation analysis has been done (Figure 3). Cross-correlation analysis confirmed a very fast aquifer response of hydraulic heads for Zagreb (rlagmax = 0.942; lag = 1 day) and for Šabac (rlagmax = 0.848; lag = 0 which translates to 5 to 10 days). In Zagreb the response lag therefore is one day, while in Šabac it is less than five to ten days (depending on the fluctuating time interval). In Orašje (rlagmax = 0.471; lag = 79 days) there is slower aquifer level response. Although rlagmax is associated with 79 days, a first peak of the cross-correlation function can also be seen after 34 days. In Slovenia the situation is more complicated (rlagmax = -0.366; lag = -5 months). For successful interpretation more detailed analysis is needed in the future. The results are difficult to interpret, probably because the Sava River/ aquifer relationship is more dynamic than anticipated, and data on a regular, daily basis might be needed to provide more robust results. Furthermore, results from Figures 2 and 3 indicate the existence of different types of aquifers. Response of the observation well in

Orašje is different from the other three points, which suggests the existence of semi-confined or confined conditions in the Orašje area. This finding, as well as other similar issues, will be investigated in more detail in future research.

**Figure 2.
Groundwater level and Sava River surface water level at one selected location in each country**



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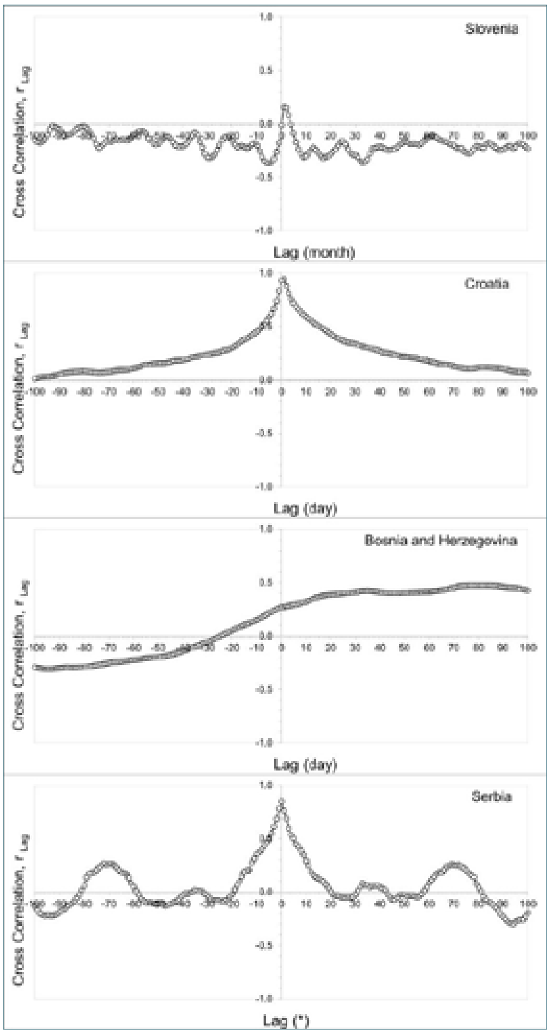
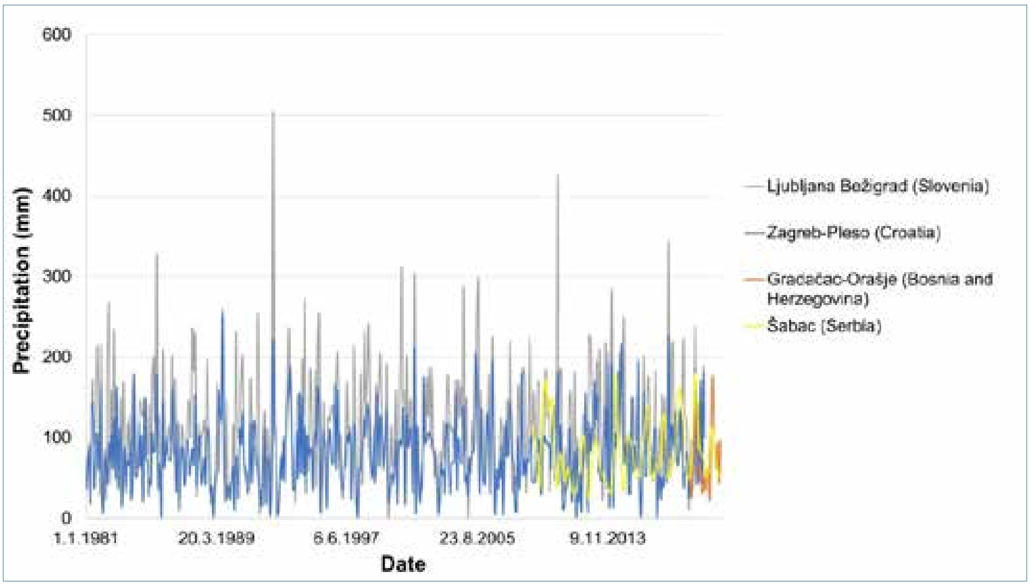
In Figures 4 and 5 precipitation values are shown. In Slovenia more precipitation falls than in the other countries. Also, the temporal pattern is not the same. In Slovenia and Croatia more precipitation falls in the second part of the year, while in Bosnia and Herzegovina and Serbia there is a huge difference in precipitation patterns from May and June with respect to the other months.

**Figure 3.
Cross-correlation between groundwater and surface water levels at the selected sites
Note that Lag is on different timescales**



Lag (*) units for Serbia are on a heterogeneous timescale of five to ten days. (© Own Elaboration)

Figure 4.
Time series of monthly and quarterly (Serbia) amounts of precipitation



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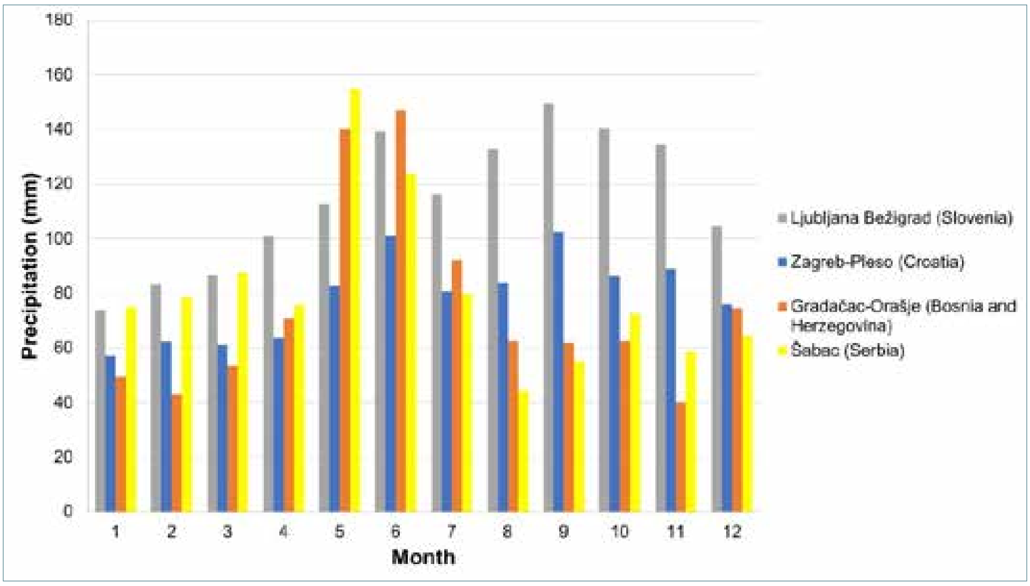
In Table 1 basic statistical parameters are summarized for all observation points, as well as trend estimations. There is no trend for precipitation in all four locations. This is consistent with the outcomes of previous research on statistical evaluation of precipitation trends in the Zagreb area, where no significant trend was established either (Krajcar Bronić et al., 2020). On the other hand, different kinds of trends are evident regarding Sava River water level and groundwater levels, but mostly negative. An exception is related to the upstream part of the river, probably due to regulation of the Sava River by hydropower plants.

Figure 5.
Average monthly precipitation values



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Although the observed time period is not the same across the four locations, minimum, maximum and standard deviation of groundwater and Sava River water levels also suggest that the relationship between surface and groundwater is not similar. In general, Sava River in Čatež has the smallest variation between minimum and maximum water levels (3.39 m), while this difference increases downstream, from 7.87 m in Zagreb up to 9.11 m in Šabac (Serbia). The same is observed for the groundwater levels, except for the observation well in Orašje, which has the smallest range of variation, but probably due to the shortest observation period. Standard deviation values show a similar pattern for Sava River water levels, which are smaller upstream and larger downstream. However, further investigations should be undertaken in the next project step, considering not only river levels but also river discharge fluctuations. Regarding groundwater, standard deviation values are higher in the Slovenia and Serbia area and smaller in the middle part of the Sava River flow, i.e., in Croatia and in Bosnia and Herzegovina. In the future all available hydrometeorological data will be examined using different statistical analysis and water stable isotope mixing models, in a manner similar to Shahul Hameed et al. (2015) and Vrzel et al. (2018).

Table 1.
Basic statistical parameters for precipitation amount, river water level and groundwater level

Type of water/statistical parameter	Slovenia Precipitation (mm)	River water (m a.s.l.)	Groundwater (m a.s.l.)
Time period		1976 - 2019	
Mean	114.51	139.76	147.21
Median	108.65	139.74	147.14
Minimum	0.10	138.29	143.65
Maximum	504.90	141.68	150.46
Standard deviation	65.5	0.59	1.24
Trend	-	negative	positive
Croatia			
Time period	1981-2019	1997-2019	1997-2019
Mean	78.76	117.85	112.70
Median	72.75	117.58	112.52
Minimum	1.00	116.53	111.42
Maximum	252.00	124.40	116.80
Standard deviation	45.22	0.98	0.76
Trend	-	positive	positive
Bosnia and Herzegovina			
Time period		2019-2020	
Mean	74.80	78.18	81.85
Median	61.70	77.61	81.75
Minimum	24.50	75.84	81.22
Maximum	176.50	84.55	83.02
Standard deviation	40.63	1.90	0.43
Trend	-	negative	negative
Serbia			
Time period	2009-2021	2010-2019	2010-2019
Mean	81.59	74.10	74.15
Median	70.17	73.80	73.98
Minimum	23.90	71.53	71.82
Maximum	180.50	80.64	79.36
Standard deviation	40.67	1.73	1.48
Trend	-	negative	-

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Conclusions

This study indicates that different patterns of groundwater-surface water interaction exist in the Sava River basin. Furthermore, it shows that the dynamic relationship between surface water and groundwater does not have the same strength in all parts of the basin, which suggest the presence of different aquifer types. Some parts of the Sava River basin are better investigated, but there are still a lot of areas which need more detailed inspection.

No precipitation trends are evident at the four locations. However, downstream parts of the basin might exhibit negative temporal trends for the Sava River water level and for groundwater levels of the associated alluvial aquifers. No decreases in river water level are however observed in the upper part of the river, probably due to upstream hydraulic regulation of the Sava.

Although these first results are preliminary, research on the influence of climate change on groundwater resources and groundwater-surface water interactions in the Sava River basin will be continued under IAEA project RER7013, which will provide new data and results helping to update and define new measures for sustainable management of transboundary aquifers in the Sava River basin.

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TOPIC 3/Paper 10

Recent Advances with the Integrated Hydrological Model of the Stampriet Transboundary Aquifer System (STAS)

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Abstract.

The STAS is a large transboundary aquifer system (>120 000 km^2) shared between Botswana, Namibia, and South Africa. It provides the only water resource in this arid region. As part of the GGRETA project, UNESCO and local stakeholders have been promoting the development of a groundwater model for the assessment and the sustainable management of this shared resource. In this communication, we retrace recent progress and lessons learnt from this modelling project. First, a detailed hydrostratigraphic study allowed us to refine the geometry of the STAS and in particular the position of its boundaries. This study also highlighted links between the STAS and the neighboring Central Kalahari Basin. To the south, a large complex of salt pans was identified as the regional outlet for the basin (Hakskeen, Koppieskraal, Uitsak pans). Second, although the isotope data for the basin were compiled in phase 1 of the GGRETA project, they had, to date, never been used as information for the STAS numerical model. Integration of environmental tracer data allowed the identification of key hydrological recharge, discharge, and aquifer exchange processes. In particular, the hydrochemical and isotopic synthesis highlighted the importance of land surface and groundwater interactions. In turn, this led us to select an integrated hydrological model capable of simulating interaction between land surface (UZF; Niswonger et al. 2006) and groundwater (MODFLOW). A feasibility study showed there would be great benefits moving from a former stand-alone model, which requires manual updating, to a state-of-the-art integrated modelling platform that can be shared by all stakeholders and updated automatically with remote sensing data.

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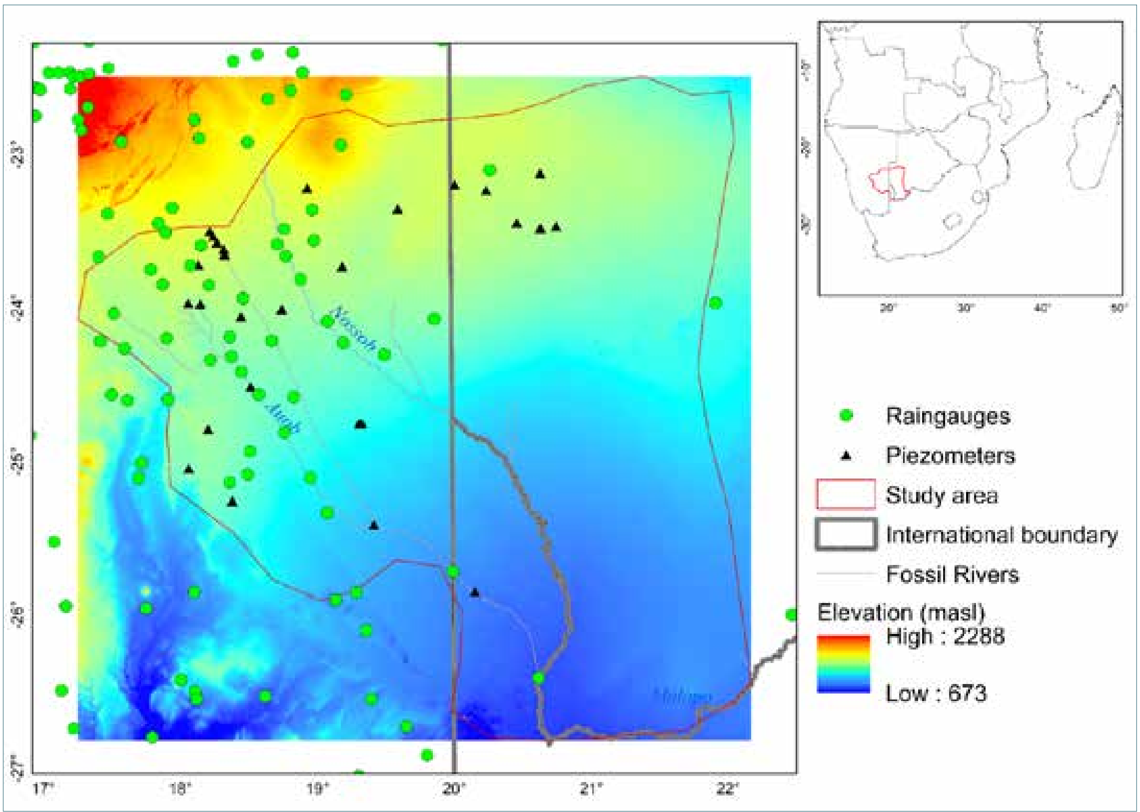
Introduction

GGRETA is an international project aimed at gaining experience in Governance of Groundwater Resources in Transboundary Aquifers. GGRETA is funded by the Swiss Agency for Development and Cooperation (SDC) and is implemented by the UNESCO International Hydrological Programme (UNESCO-IHP) in close partnership with the International Union for Conservation of Nature (IUCN), the UNESCO International Groundwater Assessment Centre (IGRAC) and local project teams. GGRETA has three pilot studies of Transboundary Aquifer (TBA) systems: the Trifinio aquifer in Central America, the Stampriet aquifer system in Southern Africa and the Pretashkent aquifer system in Central Asia.

In the context of the GGRETA project, the objectives for STAS were to address key issues relating to (i) hydrogeological perspectives -i.e., defining among others, system boundaries and aquifer extent, main aquifers of the STAS, status of groundwater quality and quantity and establishing a groundwater modelling framework for the area; (ii) socio-economic and environmental components (groundwater use, level of sanitation, and pollution sources); (iii) legal and institutional components (status of domestic laws/legislation and institutions used to manage groundwater in each of the three STAS countries), as well as highlighting the existing regional legislations/frameworks for groundwater management in the SADC region; and (iv) gender considerations, i.e., documenting the degree of gender considerations in the management of groundwater in the STAS (UNESCO, 2016; Kenabatho et al., 2021).

The Stampriet Transboundary Aquifer System stretches from Central Namibia into Western Botswana and South Africa's Northern Cape Province and lies within the Orange River Basin (Fig.1). It covers an area of over 120,000 km^2. The topography of the area is relatively flat with an elevation of 1500 m to 900 m above mean sea level from the northwest to the southeast. Rainfall normally occurs between October and April predominantly in the form of thunderstorms (high intensity and short duration) and ranges between 150 to 250 mm. The highest rainfall months are from January to March whilst the lowest months are from June to September. Potential evapotranspiration is as high as 3800 mm in the southern part of the basin, and in normal years little or no local runoff is generated (UNESCO, 2016).

Fig. 1.
Location of the Stampriet Transboundary Basin



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Hydrostratigraphy and aquifer geometry

Different nomenclature is used to describe geology in various sub-basins of STAS. For instance, the nomenclature adopted in the SW Botswana sub-basin follows Smith et al., (1984) while Aranos and Kalahari Gemsbok in South Africa follows SACS (1980) nomenclature. It was therefore important to harmonize the nomenclature and definition of the hydrostratigraphic units across the basin. This process involved revision of lithology of every borehole in order to classify them into the appropriate hydrostratigraphic units. The hydrostratigraphy of STAS was classified into six units including the unconfined Kalahari and Lebung aquifers, the Inter-Karoo Aquitard, Auob Aquifer, Mukorob Aquitard and Nossob Aquifer (Table 1; Kinoti et al., submitted).

The result of this work on the STAS hydrostratigraphy and 3D geometry under the GGRETA project will be published shortly in a paper (Kinoti et al., submitted) and can be summarised as follow:

- the size of the STAS is increased by 25% compared to the previous study (Fig. 1).
- Studies conducted in various sub-catchments of STAS adopted different nomenclature and thus the first and most important step was to harmonize the stratigraphic units across the basin (Table 1).
- Inclusion of faults in the 3D geological model revealed that the groundwater flow system in the basin is not entirely influenced by surface topography but is also influenced by regional faults.

- 3D geometry provided a first estimate of groundwater reserves for the 4 aquifers. Based on specific yield and storage coefficient estimates and volume of each aquifer, groundwater resources of STAS range between 3 to 5.1 x 10^{12}; 2.1 to 7.3 x101^{1}; 1.7 to 6.1 x10^{12} and 4.5 to 2.6^{11} m^3 for Kalahari, Lebung, Auob and Nossob aquifers, respectively. More accurate estimates will be obtained from the numerical model.

Table 1
Stratigraphy and hydrostratigraphy of STAS, modified

Description / Period	Super Group	Group	Region: Mariental-Asab area (1)	Vreda Area (2)	South-East (3)	Ncojane (4)	Matlho-a-Phuduhudu	Hydrogeological layers
Tertiary to Quaternary	Post-Karoo	Kalahari	Kalahari group					Kalahari Aquifer
Cretaceous to Jurassic	Upper Karoo	Karoo Basalts & Dolerites	Kalkrand Basalts	Karoo Dolerites		Dondong Formation	Ntane Sandstone	Lebung Aquifer
Triassic		Lebung	Rietmond Member					
Upper Permian	Lower Karoo	Rietmond				Beaufort Group		Inter Karoo Aquitard
Lower Permian		Ecca	Auob Member	Mukorob Member		Otshe Formation		Auob Aquifer
			Mukorob Member			Upper Kobe Formation		Mukorob Aquitard
			Nossob Member			Ncojane Sandstone	Lower Kobe Formation	Nossob Aquifer
Mesoproterozoic		Dwyka	Dwyka Group					Basement Aquiclude
Archaean	Pre-Karoo		Nama and Damara			Okwa Complex		

(Kinoti et al., submitted)

Environmental tracers

As part of the GGRETA project we conducted a synthesis of environmental tracer data in the Stampriet Transboundary Aquifer System. The hydrochemistry data (including 807 TDS values, 713 Cl/Br ratios, 692 NO3/Cl ratios, 73 radiocarbon, 54 tritium, and 108 18O and 2H values) was collated from many previous works in the region (from the Ministry of Agriculture, Water and Forestry in Namibia, Department of Water and Sanitation in Botswana, and Department of Water and Sanitation in South Africa, and Kirschner et al., 2002), and was compiled for the UNESCO GGRETA 1 project. We mapped and analysed the multiple environmental tracers to help inform on the conceptual model of the Stampriet Basin. In particular, we used information from the environmental tracer data to improve our understanding of recharge, discharge and inter-aquifer mixing processes for the Kalahari, Auob and Nossob aquifers. A summary of the processes identified is presented below.

Recharge Processes

Groundwater is mostly recharged during high rainfall levels (≥ 200 mm/month; as indicated by ^{18}O and ^{2}H values), which are rare events. For example, during a 38-year rainfall monitoring period, rainfall ≥ 200 mm/month occurred only 4 times (Jan-94, Jan-97, Jan-06 and Feb-09). The groundwater flow is slow resulting in mean ^{14}C residence times ranging up to 22100, 39000 and ≥40000 years in the Kalahari, Auob and Nossob aquifers, respectively. ^{14}C mean residence times show no clear trends with regional flow pathways in each of the aquifers and are likely impacted by heterogeneous inter-aquifer mixing processes. In the northern section of the Auob and Nossob aquifers, there are even areas where groundwater represents paleorecharge conditions, and therefore reflects even slower flow rates compared to the rest of the basin.

Evaporation and transpiration processes

Results from the ^{18}O and ^{2}H values highlight that all groundwater sampled were impacted by evaporation, and that transpiration was a less dominant process. From the environmental tracer data, it was not evident whether evaporation occurs directly from the water table, and/or whether the evaporated ^{18}O and ^{2}H signature is the result of mixing with infiltrating waters evaporated in the unsaturated zone.

Inter-Aquifer Mixing Processes

This study includes an area where the environmental tracer data (TDS, ^{18}O and ^{14}C values) indicates flow in both directions between the Kalahari and Auob aquifers. Aquifer vertical flow exchange in this area is also supported by the long-term hydraulic head data (over a 9-year monitoring period) that show declines in the hydraulic heads of the Auob aquifer relative to the more stable Kalahari aquifer. Therefore, there has been a reversal of the vertical hydraulic gradient between the Kalahari and Auob aquifers from upward to downward direction. The mixing zones between the Kalahari and Auob aquifers identified from the environmental tracer data show some correlation with the Inter-Karoo aquitard thickness (5 of the 14 mixing zones have an aquitard thickness ≤ 3m), and a higher correlation with the location of faults (8 of the 14 mixing zones have faults that pass nearby the mixing zone).

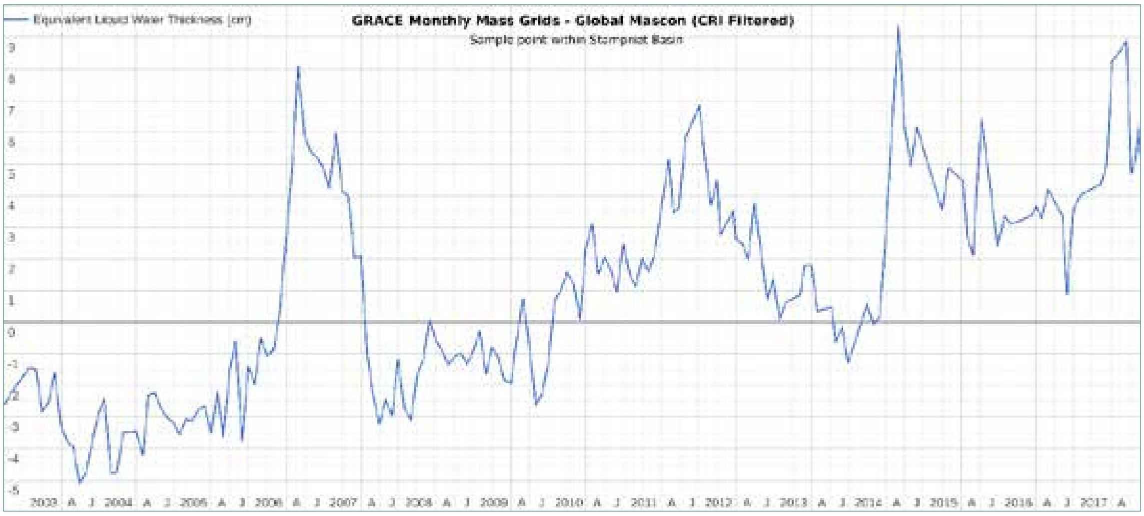
Automated update of the STAS groundwater model with remote sensing

The STAS integrated hydrological model requires daily rainfall data as a driving force. Rain gauges are scarce in the STAS and observations are not available in real time. Hence satellite rainfall estimates provide an effective alternative (Satge et al., 2020) and are used as input data for the model. Here we selected data from IMERG, which combines information from the Global Precipitation Measurement (GPM) constellation (https://gpm.nasa.gov/data/imerg; Huffman et al. (2021)). The latest Version 06 release of IMERG, which is used here, fuses the early precipitation estimates collected during the operation of the TRMM satellite (2000-2015) with more recent precipitation estimates collected during operation of the GPM satellite (2014-present).

Potential Evapotranspiration (PET) is the main driving force moving water out of the STAS. It is used as an input variable by the UZF package to calculate real evapotranspiration from the unsaturated zone and from the water-table. Here we sourced PET estimates from NASA Global Land Data Assimilation System (GLDAS) (Beaudoing and Rodell, 2019).

Since 2002, the GRACE missions I and II (Follow-on) have been providing the first observations of total water storage (TWS) at a global scale. These missions have been extremely useful in particular with regards to our knowledge of the water cycle and climate change. In arid regions such as the STAS, GRACE TWS data correspond to storage variations in the saturated and unsaturated zones. Our integrated hydrological model of the STAS also simulates saturated (MODFLOW) and unsaturated (UZF) storage. So here, the GRACE data are not required as an input for the model, instead they will provide, at a later stage, independent observations with which to compare water storage simulated by the model. As observed in Figure 2, GRACE data show a significant increase in TWS over the STAS from 2003 to 2017.

Fig. 2.
Variation in total water storage (cm water equivalent) over the STAS from 2003 to 2017



(© CSR Mascon release 6) (https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/).

Discussion

The integrated hydrological modelling approach has been useful in furthering our understanding of the STAS in relation to other neighboring aquifer systems (the system boundaries, main aquifers and their extent, regional groundwater flow, resource quantification estimates, among others). In addition, the flexibility of the framework in allowing the use of remotely sensed data to augment the limited data in the area is another important contribution of this study. Although this is important, there remains a need to develop groundwater and hydrological monitoring networks to improve in situ data availability in the area. Overall, the work and findings from this study further demonstrate the importance of science in the overall understanding and management of water resources to inform policy development/ direction in an area highly dependent on groundwater such as the STAS. In future, the proposed model needs to assist with providing answers to the following questions in order to improve water resources management in the STAS area:

What will be the effect of increased pumping in the STAS area when considering possibilities of more water consumption due to mining, for example? There are already new mining activities in the Ghanzi area in Botswana.

- How can the model be used to evaluate the effects of climate change/variability on groundwater recharge/discharge in the STAS area?
- What (and how much) does it take to maintain the model so as to derive maximum benefit with the management of groundwater in the area?

- The GGRETA project started in 2014 and addresses issues related to transboundary aquifers and responds to the pressing need to increase knowledge about their physical and socio-economic characteristics. GGRETA forms a part of the UNESCO's International Hydrological Program (IHP), the International Shared Aquifer Resources Management Initiative (ISARM) and the Transboundary Water Assessment Program (TWAP).

On the last account, 72 TBAs have been identified in Africa (40% of the continent). The mapping of these TBAs is regularly updated (Nijsten et al., 2018) and the difficulty encountered here to establish the STAS boundaries is a clear reminder of the need for this mapping program to continue.

Scaling up of the approach developed for the case study of the Stampriet to other TBAs is possible. In particular, we found the application of remote sensing to model groundwater very useful. As more and more remote sensing data become readily available this method could easily be extended to other regions.

This study also highlights the complexity of the STAS and the many aspects that need to be taken into account for its study and management. Though useful for comparison across TBAs, this complexity serves as a warning about the dangers in summarizing such a system into a series of simple indicators.

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TOPIC 3/Paper 11

Hydrogeological conditions on the border between Serbia and Bulgaria to assess the transboundary groundwater transfer

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Abstract

Serbia and Bulgaria have a common state border of about 360 km. The aim of the present study is to analyze the boundary groundwater bodies in the two countries and to determine the probability of groundwater transfer. The groundwater bodies are defined separately in both countries - on the territory of Bulgaria, they are 11, and on Serbia there are 14 included in UNECE evaluation made in 2008. The first step of the present study is to clarify the factors influencing the formation and movement of groundwater. Geological conditions predetermine the presence of different types of groundwater. Along the state border the most widespread are the fractured aquifers' water, formed mainly in the weathering zones of magmatic, metamorphic, and sedimentary terrigenous and terrigenous-carbonate rocks - about 78% of the total length of the border. Different types of aquifer systems with porous media have been identified. The typical karst aquifers have a relatively small distribution along the surveyed border area Sarmatian sediments form a layered complex, with well-defined aquifers in it, attached to sands and detrital limestones in the northernmost parts of the border. The analysis of the factors proves that during most of the border between Bulgaria and Serbia the probability of cross-border transmission is insignificant. There is a possibility for such a transfer only for the karst basins and for the Sarmatian complex.

Keywords: groundwater, Serbia, Bulgaria.

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Introduction

Until the end of the last century, each country used different methods and approaches for research, exploration and management of its water resources. In this regard, a step to improve better hydrological and hydrogeological professional communication between European countries is the adoption of the Water Framework Directive 2000/60 (WFD, 2000; EC, 2012), which is important for the unification of water management by introducing the basin principle, including for the territory of the countries of the Balkan Peninsula (Skoulikaris, Charalampos, 2014, Skoulikaris et al. 2021). Nevertheless, with regard to groundwater, the problem of frequent mismatch of the boundaries and characteristics of the separated groundwater bodies falling within the border areas of two neighboring countries remains. Delineation of the groundwater bodies in Bulgaria and Serbia have not been result of cooperation of hydrogeologists of the two countries. This complicates the assessment of the likelihood of possible transboundary transfer between them. We started our work later on in order to improve GWB status assessment and evaluate if there is a significant transboundary impact. To solve these problems, it is necessary to conduct joint research by experts and scientists from neighboring countries, in which to analyze the physico-geographical and geological factors to future synchronization of water management. Such studies were performed on the Bulgarian border with Greece (Spasov et al. 2017) and with Romania (Machkova 2008, Gerginov, Orehova 2007), while on the Serbian border with joint hydrogeological surveys of Bulgarian and Serbian hydrogeologists have been carried out only for the region of the Western Balkans (Benderev et al. 2016), divided between the two countries, which comprises less than 10% of the total length of the border (about 360 km).

Groundwater bodies close to state border

The aim of the present study is to analyze the boundary groundwater bodies in the two countries and to determine the probability of groundwater transfer. According to the Water Framework Directive 2000/60 (WFD, 2000), the Groundwater Body (GWB) is the management unit.

This study includes clarification of the factors and conditions for the formation of groundwater in the border areas, taking into account the recharging zones and the directions of water movement.

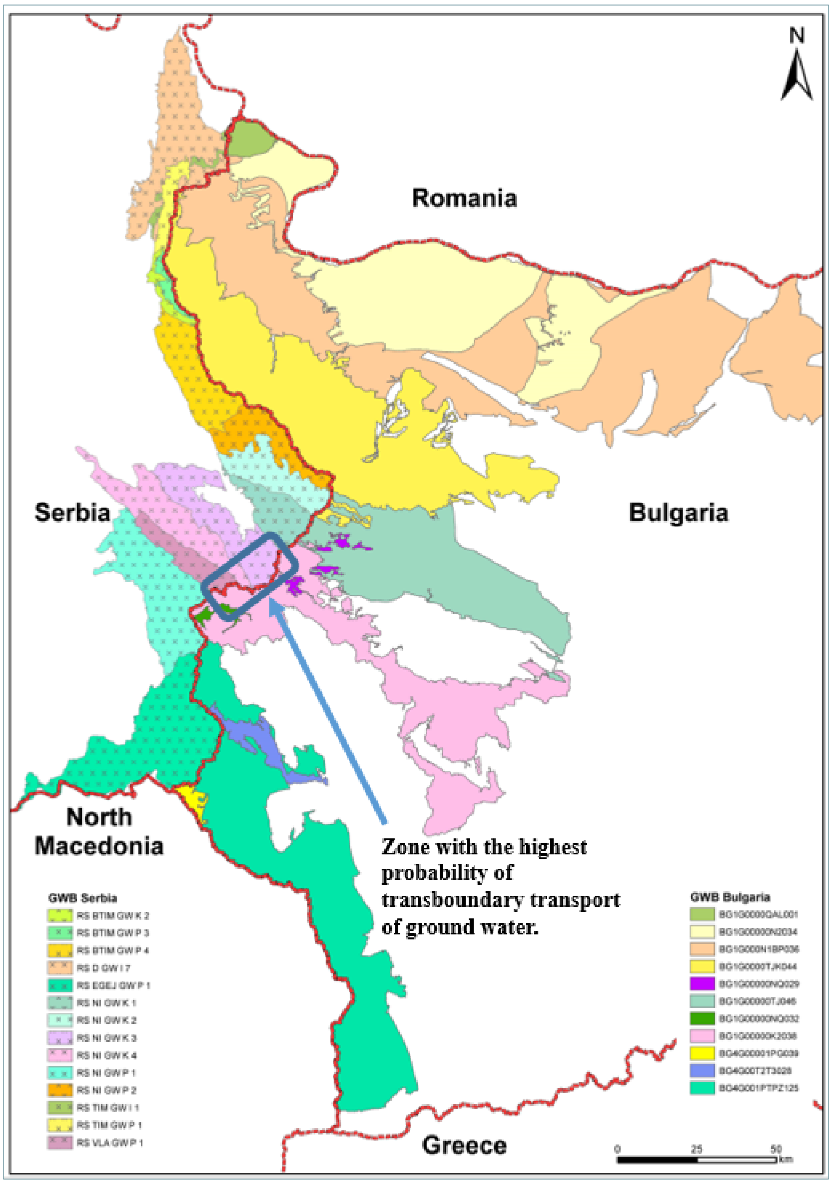
According to the extremely diverse hydrogeological conditions (Antonov, Danchev 1980; Dimkić et al. 2011) on the territory of Bulgaria there are over 170 groundwater bodies (Mihaylova et al. 2006; WEB page of MOEW), and in Serbia – 153 (Official Gazette of the Republic of Serbia, 2010). The groundwater bodies are defined separately in both countries. Close to the state border - on the territory of Bulgaria, they are 11, and on Serbia there are 14 included in UNECE evaluation made in 2008 (Table 1, Fig. 1). The analysis of the information of the boundary groundwater bodies shows that for some of them, similar in geological structure and hydrogeological conditions, we have a complete coincidence of their boundaries. It can be assumed that in the future they can be considered as common water bodies on both sides of the border – for example: BG1G0000QAL001 - Porous aquifer's water in Quaternary Aquifer - Bregovo-Novoselska Lowland and RS_TIM_GW_I_1 - Veliki Timok – alluvium porous aquifer. For others, a divergence or more detailed division has been established, mainly on the territory of

Serbia for the areas from the northern slopes of the Western Balkans to the Erma River near the village of Strezimirovci. This is probably due to a relatively larger amount of information about these areas in Serbia or the policy of the Ministry of Environment and Water in Bulgaria to consolidate groundwater bodies, mainly fissure or karst in nature, in order to facilitate their management.

Table 1.
Brief characteristics of GWBs close to the border between Bulgaria and Serbia

N	Euro Code	Name	Area, km²	Border length, km
		BULGARIA		
1	BG4G00T2T3028	Karst groundwater in Zemen karst basin	188.5	8.31
2	BG4G00001PG039	Porous-Fissured aquifer in Osogovo Paleogenic volcano-sedimentary complex	60.9	9.73
3	BG4G001PTPZ125	Fissured aquifer in Vlahina-Ograzhden-Maleshevo-Osogovo metamorphic rocks	3079.61	74.32
4	BG1G00000NQ032	Porous aquifer’s water in Neogene-Quaternary Aquifer - Znepole valley	42.0	0.92
5	BG1G00000K2038	Fissure aquifer’s water between Erma and Nishava rivers	2111	73.77
6	BG1G00000NQ029	Porous aquifer’s water in Neogene-Quaternary Aquifer-river Nishava	67.0	1.73
7	BG1G00000TJ046	Karst Basin- Godech massif	1843	15.72
8	BG1G0000TJK044	Karst Basin- West Balkan	3368	142.93
9	BG1G000N1BP036	Karst Basin- Lom- Pleven depression	6561	49.34
10	BG1G00000N2034	Porous aquifer’s water in Neogene aquifer - Lom- Pleven depression	3088	12.17
11	BG1G0000QAL001	Porous aquifer’s water in Quaternary Aquifer - Bregovo--Novoselska Lowland	145.1	22.60
		SERBIA		
1	RS_EGEJ_GW_P_1	Egejski sliv – Fissured aquifer	1154	68.5
2	RS_NI_GW_P_1	Vlasina – Fissured aquifer	764.9	29.8
3	RS_VLA_GW_P_1	Crni Vrh – Fissured aquifer	217.6	13.3
4	RS_NI_GW_K_4	Suva planina – Karst aquifer	485.1	7.6
5	RS_NI_GW_K_3	Belava i Vlaška planina - Karst aquifer	509.1	24.6
6	RS_NI_GW_K_1	Vidlič - Karst aquifer	284.5	16.7
7	RS_NI_GW_K_2	Stara planina - Karst aquifer	336.8	11.5
8	RS_NI_GW_P_2	Stara planina sever – Fissured aquifer	343.1	48.5
9	RS_BTIM_GW_P_4	Beli Timok – jug – Fissured aquifer	455.6	35.3
10	RS_BTIM_GW_P_3	Beli Timok – istok – Fissured aquifer	76.8	26.6
11	RS_BTIM_GW_K_2	Vrska čuka - Karst aquifer	67.4	4.4
12	RS_TIM_GW_P_1	Veliki Timok – Fissured aquifer	142.3	22.1
13	RS_D_GW_I_7	Zaječar Negotin-Neogene porous aquifer	832.2	29.2
14	RS_TIM_GW_I_1	Veliki Timok – alluvium porous aquifer	65.7	21.8

Fig. 1.
Location of the GWBs along the state border between Bulgaria and Serbia



(© Open Street Maps, Own Elaboration)

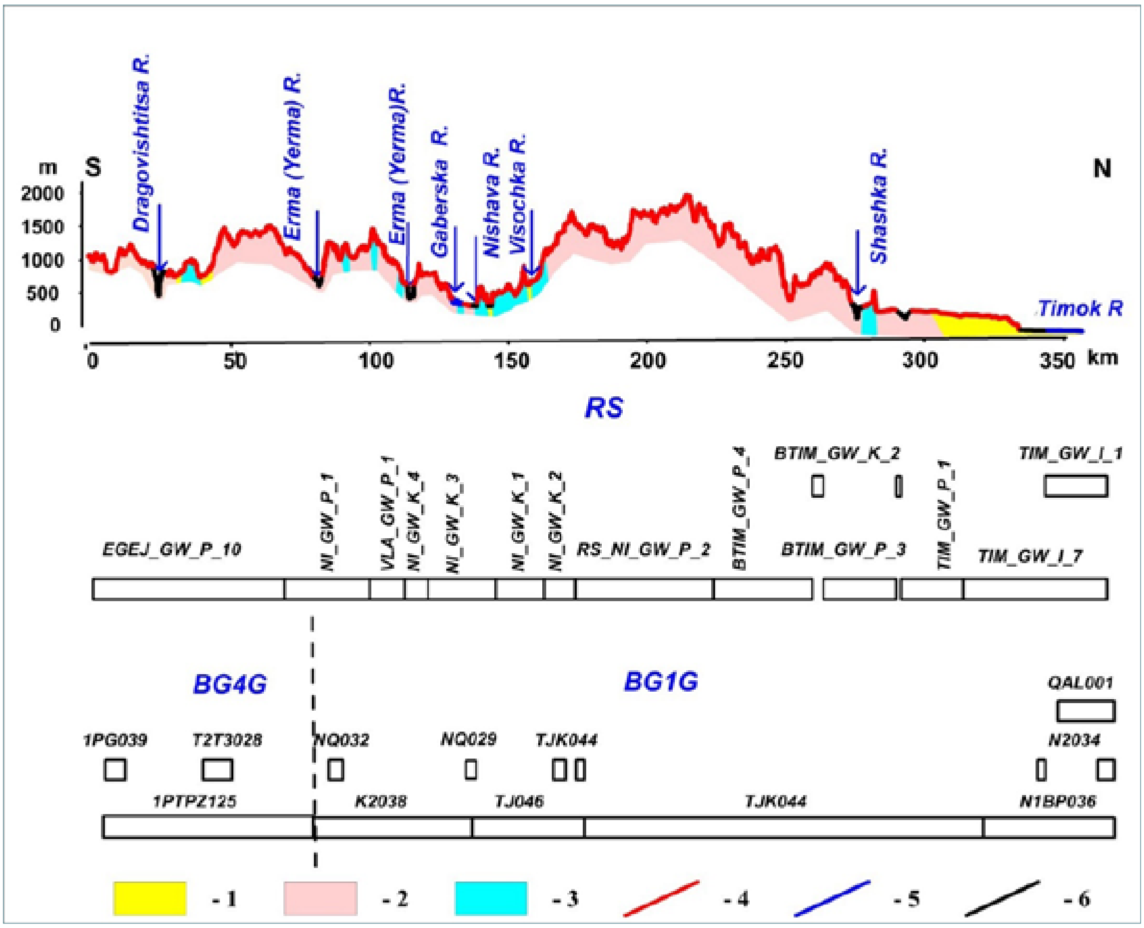
Methodology

To determine the probability of transboundary water transport between Bulgaria and Serbia, the methodological approach presented by Spasov et al. (2017) and their experience on the border with Greece. The reason for this is given by the fact that both borders have a similar character in geomorphological and hydrogeological terms. Using GIS, the main border areas of water bodies are considered, paying attention to:

- Geological conditions and mainly the type of rocks and tectonic structure, which allows to locate areas with porous (intergranular), fissure and karst aquifers and their waters. For this purpose, the geological maps of Bulgaria and Serbia in M 1: 100000 and some published materials were used (Tchoumatchenco et al. 2011; Benderev et al. 2016)
- The relief conditions along the state border, paying attention to whether there is a coincidence with surface watersheds and rivers. Information from topographic maps and DEM models is used. It is assumed that for a mountain massif with fissure aquifer's waters the surface watershed usually coincides with the underground one, and the rivers are most often borders with constant pressure, which drain the surrounding massifs;
- Establishment of the recharge and discharge zones and the direction of groundwater movement. Clarification of their spatial situation makes it possible to establish cross-border transmission where these areas are located in different countries. Such conditions are often present in karst areas, as well as in the presence of layered aquifers;
- The anthropogenic factor may also be important, but in the study area it is insignificant for a probable change in the direction and speed of groundwater movement.

For better visualization of the role of these factors, a schematic profile from South to North has been prepared, facilitating the analysis of the available information (Fig.2).

Fig.2.
Schematic profile along the border between Bulgaria and Serbia, with the location of the groundwater bodies



(© Own Elaboration): 1. Distribution of porous (intergranular) water collectors; 2. Fissured groundwater reservoirs (systems); 3. Karstic groundwater collectors; 4. State boundary follows main or secondary surface water divide; 5. Coincidence of state border with rivers; 6. No hydrogeological boundary along the state boundary

Results and discussion

The first step is to clarify the factors influencing the formation and movement of groundwater. Geological conditions predetermine the presence of different types of groundwater. Along the state border the most widespread are the fractured aquifer's water, formed mainly in the weathering zones of magmatic, metamorphic, and sedimentary terrigenous and terrigenous-carbonate rocks - about 78% of the total length of the border. Different types of aquifer systems have also been studied. The first type includes the alluvial deposits of the Timok River, which is the northernmost part of the state border (27.8 km). The second type are imposed outcrops of unbound Neogene sediments with limited extension. In places the border crossings the terraces of some smaller rivers with not very large, often interrupted terraces. The typical karst aquifers have a relatively small distribution along the surveyed border area. Some of them form parts of clearly defined karst basins, linearly extended in the east-west direction and having important hydrogeological significance. Such are the karst basins on the southern slopes of Balkan Mountains. Previous studies (Benderev et al. 2016) based on detailed studies and summaries of geological, geomorphological, hydrogeological and speleological information have established the possibility of transboundary transport of karst groundwater, both from Bulgaria to Serbia and from Serbia to Bulgaria. Other types of karst collectors are isolated tectonic blocks with small areas bordered by non-karstic rocks. They are characterized by the development of a typical mountain type of karst and are located north of the Nišava River, which crosses the border. Sarmatian sediments form a layered complex, with well-defined aquifers in it, attached to sands and detrital limestones in the northernmost parts of the border. At this stage, it is not clear whether there is transboundary water transfer in this aquifer. This needs to be determined in the near future, due to the importance of this aquifer for water supply to settlements on both sides of the border and an anthropogenic pressure from agriculture.

The analysis of the factors proves that during most of the border between Bulgaria and Serbia the probability of cross-border transmission is insignificant. After Stevanović (1991) the contribution of groundwater inflow from Bulgarian side to Serbian karst aquifer Vidlič in border area, is about 6% of its total discharge. This is due to the wide distribution of fractured aquifers groundwater in the weathering zone of the rocks, whose direction of movement coincides with the slope of the terrain and the fact that the most part (about 82%) of the state border passes along the watersheds. Therefore, a possibility for such a transfer exists only for the karst basins and for the Sarmatian complex, but this, at this stage, is not yet sufficiently clarified. Only for the well-developed dominantly cavity karst systems in the Western Balkans the presence of transboundary groundwater transfer has been established (Fig. 1).

Conclusion

The obtained results allowed to locate, although not very large areas of the state border between Bulgaria and Serbia, in which future research should be directed. An important step in this regard will be the systematization of the existing hydrogeological information from both sides of the state border in a single database. It would be used for future GIS analyzes and model solutions, which would allow to look for an opportunity to unite some boundary groundwater bodies into common transboundary ones. Authors of this paper found that lack of monitoring of the existing springs and small streams is major obstacle for more sustainable water management. It is thus proposed to establish new monitoring network and ensure data exchange between two countries through Common Consultative Body (CCB), which also has to include groundwater specialist. This would significantly help the overall protection of water resources and their joint management by the two countries.

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TOPIC 3/Paper 12

The Hydrogeological Assessment of the Milk River Transboundary Aquifer (Alberta, Canada – Montana, Usa): A Basis Towards Joint Management Plans

Marie-Amélie Pétré[1], Alfonso Rivera[2], René Lefebvre[2], Attila J.B. Folnagy[3], John LaFave[4], and Dan Palombi[5]

Abstract

The Milk River Aquifer (ISARM #20N) is one of the ten transboundary aquifer systems identified along the Canada-USA border. This regional groundwater system (26,000 km^2) has been exploited for over a century and constitutes a major groundwater resource for agricultural, municipal, and industrial use in southern Alberta (Canada) and northern Montana (United States). The aquifer is shared by multiple stakeholders spread out within six jurisdictions: federal, state or provincial and municipal.

Concerns about the depletion of the groundwater resources were raised since the mid-1950s, and the aquifer is still solicited on both sides of the international border in the absence of an agreement between the US and Canada on the use of this shared resource. This situation contrasts sharply with the surface water from the Milk River which has been apportioned by the Canada-US International Joint Commission since 1921. The transboundary management of the Milk River Aquifer is challenging due to the data and information fragmentation (previous studies were limited by the border; independent stratigraphic frameworks were developed) which led to gaps in the knowledge of the aquifer's hydrodynamics.

To expand the knowledge of the flow system, a set of three cross-border models were developed: a three-dimensional geological model, a conceptual hydrogeological model and a three-dimensional groundwater flow model. These models followed the physical boundaries of the aquifer, instead of the jurisdictional boundaries. This approach required to combine and harmonize geological, hydrogeological and isotopic data and conduct focused field work on both sides of the border, with active involvement of the aquifer's stakeholders.

Results include the first delineation of the transboundary extent of the Milk River Aquifer and the quantification of the transboundary fluxes from Montana into Alberta. The numerical model was used to define the conditions for the sustainable exploitation of the aquifer and showed that the entire aquifer system was affected by groundwater withdrawals. While the extent of the Milk River

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Aquifer is larger than that of the Milk River watershed, the study revealed that transboundary groundwater management would be warranted in a localized area comprised between the recharge area in Montana and the southern reach of the Milk River in Alberta.

Thus, the hydrogeological assessment of the Milk River Aquifer constitutes a common basis of scientific knowledge for all jurisdictions on both sides of the border; it lays the foundation for future shared management of the aquifer. A few paths towards shared governance have been proposed.

Keywords: transboundary aquifers, groundwater management, joint management, Milk River aquifer

Introduction

The Milk River Aquifer (MRA, ISARM#20N) is a 26,000 km^2 regional groundwater system spanning southern Alberta (Canada) and northern Montana (USA). The MRA has been exploited for over a century and concerns about the mismanagement and depletion of both aquifer storage and hydraulically connected surface waters were raised since the 1950s in Alberta. Today, the MRA is the source aquifer for various users (e.g., municipal, agricultural, and industrial) and is shared by multiple stakeholders under six jurisdictions (e.g., federal, provincial/state, and local governments). In the absence of a joint aquifer management plan, mismanagement and depletion of both aquifer storage and hydraulically connected surface waters could continue to justify serious concerns by stakeholders especially if groundwater demands increase.

This groundwater situation contrasts sharply with surface waters from the transboundary Milk River and the adjacent St Mary River which have been apportioned in Article VI of the 1909 Boundary Waters Treaty, and ultimately the International Joint Commission's 1921 Order (IJC, 1921). The terms of the 1921 Order have been questioned at least three times, most recently in 2003 (Halliday and Faveri 2007). The Boundary Waters Treaty does not include groundwater, ecosystems protection, climate change or aboriginal rights, which are all challenges today. The lack of a joint aquifer management plan, despite the intensive historical exploitation of the MRA, might be due to the fragmentation of geoscience information at the regional scale. Previous studies were limited by the border, so independent stratigraphic frameworks were developed in the two countries, resulting in knowledge gaps of the MRA's hydrodynamics, which makes the development of a joint groundwater management plan not possible. Our unified hydrogeological assessment enables transboundary analysis to occur similar to that in place for surface water.

Considering surface water shortages in this region and increasing groundwater demands, it is obviously relevant to improve our understanding and protection of the MRA and to establish a comprehensive representation of the aquifer across the Canada-U.S. border, a prerequisite towards joint management plans. The MiRTAP project (https://milkrivertransboundaryaquifer.weebly.com/) was launched in 2009 by the Geological Survey of Canada to carry out the hydrogeologic assessment of the MRA, following its natural boundaries.

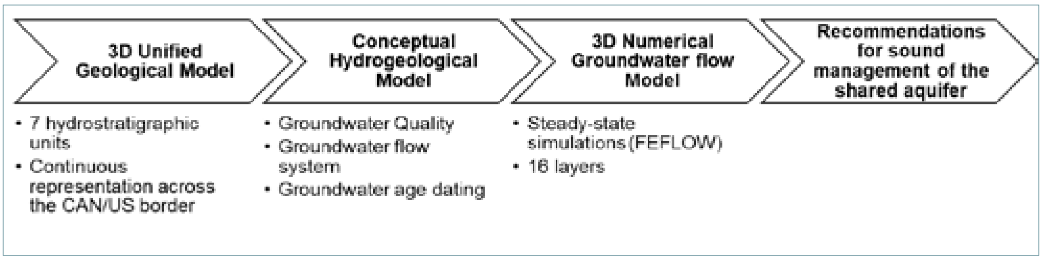
The objectives of this paper are to: 1) present the workflow and main results of the study and their implications for management, and 2) highlight the challenges and opportunities towards joint management of the MRA.

Methods

The hydrogeological assessment was carried out following recommendations formulated in the Draft articles on the Law of Transboundary Aquifers (ILC, 2008), and methodological guidelines on the study of transboundary aquifer systems (Brachet *et al.* 2012; Machard De Gramont *et al.* 2011)"plainCitation":"(Brachet et al. 2012; Machard De Gramont et al. 2011.

A series of three cross-border models were developed: a three-dimensional geological model, a conceptual hydrogeological model, and a three-dimensional numerical groundwater flow model (Figure 1). In this framework, the models followed the physical boundaries of the aquifer instead of jurisdictional boundaries. To overcome the fragmentation of information and the multiple stratigraphic nomenclatures in the study area, geological, hydrogeological and isotopic data were combined and harmonized, with the addition of focused field work on both sides of the border, in collaboration with stakeholders.

Figure 1 Successive stages of the Milk River Aquifer transboundary assessment



Results

The results of these studies were published in three peer-reviewed articles (Pétré *et al.* 2015, 2016, 2019), a PhD thesis

The proposed transboundary delineation of the MRA is shown in Figure 2. Two transboundary flowpaths were defined and quantified (with a total flux of 6 Mm3/y): 1) an eastern flow path from the Sweet Grass Hills to the north and (2) a western flow path from the northern part of Cut Bank to the north. Three natural sub-systems were also defined, based on the directions of groundwater flow in the MRA. The Milk River and its tributaries intercept a large proportion of the transboundary flux from northern Montana. North of the Milk River (downgradient), the groundwater flow is very slow as indicated by age dating tracers (14C, 36Cl), and the MRA contains fossil groundwater with no significant modern recharge.

As a transboundary aquifer, a joint management strategy of the MRA would be warranted, especially in the area comprised between the groundwater divide in Montana and the Canadian reach of the Milk River (zone 1a, Figure 2). This area benefits from the totality of the transboundary groundwater flux, which is almost entirely intercepted by the Milk River downgradient.

The numerical groundwater flow model represented seven hydrostratigraphic units and was used to define the conditions required for the sustainable development of the MRA. The numerical model was in agreement with the previously formulated conceptual model and thus supported its hydraulic plausibility. Steady-state simulations of three groundwater extraction scenarios revealed that groundwater withdrawals affected the entire flow system. More specifically, groundwater extraction has resulted in a loss of aquifer storage, less outflow and more inflow, illustrating the important role of capture in regional groundwater flow systems.

The MRA is therefore part of a regional groundwater flow system, involving cross-formational flow and hydraulic communication through confining units, hence it should not be managed as an isolated hydrostratigraphic unit.

Overall, the workflow of the MRA assessment was successful in producing the first unified transboundary conceptual model and developed a hydrostratigraphic framework for numerical simulation helping to quantify the water balance of aquifer. This scientifically-based knowledge of the MRA is a prerequisite to aquifer management and informed decision making. The study was limited by a lack of geological and hydrogeological data in northern Montana and limited information on the current groundwater extraction rates in both Alberta and Montana. Further studies are required to estimate the extracted volumes and the potential degree of impact on the groundwater resource. Also, the steady-state simulations do not allow for the determination of storage changes over time, as well as the time required to reach an equilibrium.

Figure 2 Delineation of the MRA and three natural zones (zone 1a/1b, zone 2, and zone 3)

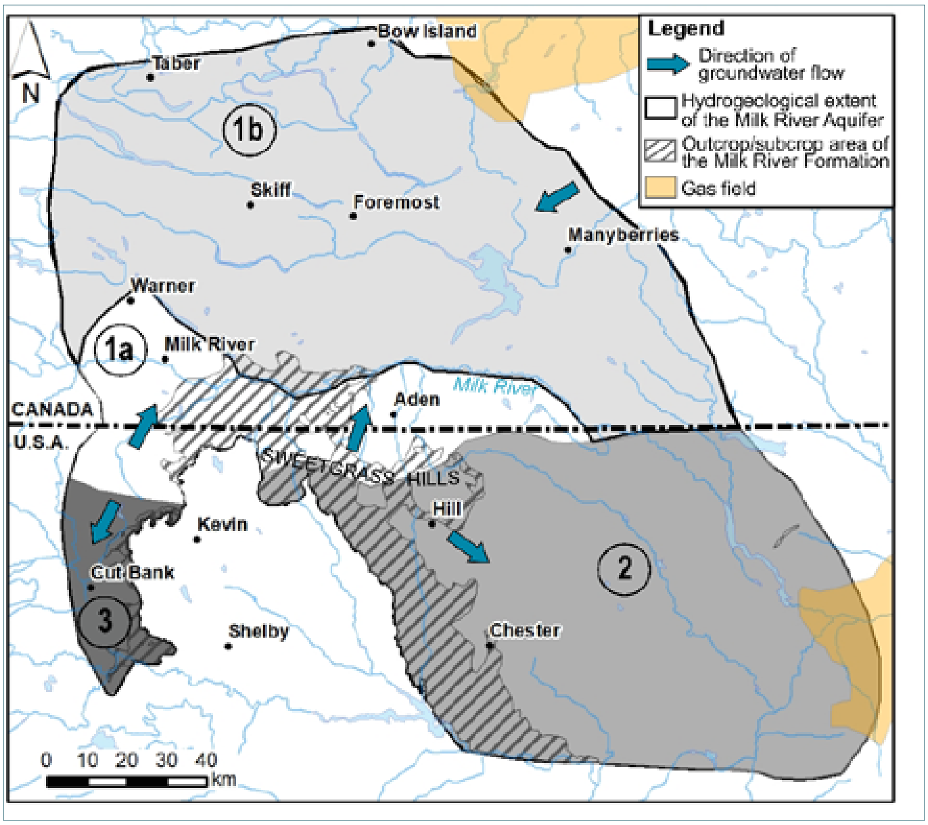


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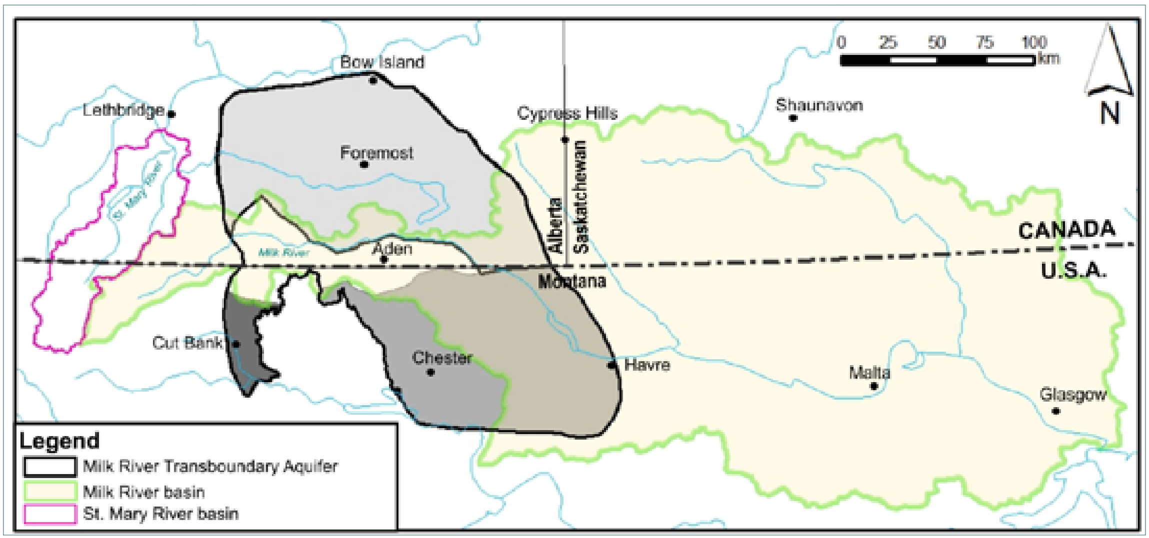
Figure 3.
Extent of the MRA and the St Mary and Milk River watersheds



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Challenges and Opportunities towards Joint Management of the MRA

One of the main challenges to initiate management of the MRA is coordinating the multiple jurisdictions and stakeholders involved. Developing a joint aquifer management plan and establishing an international technical advisory committee (TAC) will ensure that existing water users from the MRA can continue to divert their permitted volumes while monitoring and adapting to changing climatic conditions. A TAC would prioritize investigations of future development of the MRA to serve the needs of various interests (e.g., Indigenous and First Nations, municipal, agricultural, and industrial uses), as well as the natural systems, habitats, and groundwater-dependent ecosystems.

Understanding potential groundwater pumping impacts to surface water sources, specifically, the MRAs connection to the Milk River and tributaries, will be critical for future management decisions. The hydrogeological assessment showed that the Milk River is the main natural discharge feature of the MRA. Aquifer management plans must therefore include groundwater-surface water interactions and may consider conjunctive management in the future.

Another challenge is that the MRA extent is different from that of the Milk River and St. Mary River watersheds (Figure 3). However, the appropriate transboundary groundwater management unit (zone 1a) is localized and mostly comprised within the limits of the Milk River basin. For successful management of the MRA, zone 1a must be a priority for future study and monitoring to better quantify the transboundary flux and recharge of the aquifer. An important aspect will be to refine the potential issues concerning groundwater development in zone 1a and assess the compatibility of the current monitoring program. An update of the inventory of active wells will be also necessary to quantify the actual volume of water being pumped from the aquifer.

Future work is needed on the unified numerical groundwater model by Pétré et al. (2019) and must include updating the model by building a calibrated transient numerical model that reflects new data and water use information. To further develop numerical models of the MRA, it is recommended that the TAC prioritize model objectives that include future groundwater development scenarios, selection of focus areas for model evaluation, and identification of additional field data to be collected. Once this is complete, all jurisdictions may agree that the numerical model be used to support management decisions. In addition, the model could be useful to evaluate groundwater-gas migration in the adjacent northern-most boundary of the aquifer (Figure 2). The giant southeastern Alberta gas field is approaching its end of life and commingled well abandonments are underway to safely close the field (Lemay et al. 2019). The geological and numerical models are publicly available (Pétré 2016) and can be updated and improved as new data are acquired.

Most importantly, this work may build on existing transboundary relationships relative to the management of St. Mary and Milk rivers. Diplomacy is needed to open talks between the two countries on an operational agreement that could include provisions for annual meetings, exchange of information and data, updates to the joint aquifer management plan, and other joint activities. The ILC Draft articles on the Law on Transboundary Aquifers (ILC 2008) and UNECE Water Convention (UNECE 1992) could be used as a tool to bring parties together and provide guidance for bilateral arrangements for the sound management of the MRA.

Conclusion

The hydrogeological assessment of the MRA constitutes a common basis of scientific knowledge for all MRA jurisdictions on both sides of the border; it lays the foundation for future joint management of the aquifer. We recommend the following:

1. Build on existing transboundary relationships and diplomacy.
2. Use ILC Draft Articles on the Law on Transboundary Aquifers to bring parties together.
3. Establish an international technical advisory committee.
4. Develop a joint aquifer management plan accounting for groundwater-surface water interactions.
5. Prioritize zone 1a for future study and monitoring to support joint management.
6. Update the unified numerical groundwater model by Pétré et al. (2019) and use the model to support management decisions.

The three models previously developed could be used as important and powerful tools for the sound joint management of the MRA. These recommendations will improve stakeholder engagement in the joint management of the MRA while adapting to changing water use and climatic conditions.

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TOPIC 3/Paper 13

Conceptual Model Development for the Assessment of Transboundary Groundwater Resources in Cross-Border Area (Estonia- Latvia).

Inga Retike[1], Magdaleena Männik[2], Andres Marandi[2], Dāvis Borozdins[3], Jekaterina Demidko[3], Jānis Bikše[1], Aija Dēliņa[1], Konrāds Popovs[1], and Agnese Kukela[1]

Abstract

Both Estonia and Latvia are Member States of the European Union (EU) since 2004, thus are required to ensure joint assessment of transboundary groundwater resources and implement the so-called EU Water policies. The conceptual model was developed for cross-border area (~9500 km^2) between Estonia and Latvia based on exchanged information about groundwater composition, geological and hydrogeological conditions (obtained from regional 3D hydrogeological model PUMA), and dominant pressures (mainly water consumption and land use). The borders of the transboundary area were set based on the surface watersheds as this study concentrates on the active water exchange zone that contains freshwater and is being used for water abstraction in this area. Semi analytical groundwater flow estimation method was developed to identify borderline areas where significant groundwater flow from one to another country occurs. Main characteristics of groundwater quality was identified based on the results obtained from Multivariate Statistics (PCA and HCA).

Study area is in the North-East of Europe, on the coast of the Baltic Sea where sedimentary aquifers (mainly sandstones) contain large freshwater resources and supply drinking water. The total thickness of sedimentary aquifers in the study area is up to 135-352 m and they contain fresh Ca-Mg-HCO_3 groundwater with total dissolved solids (TDS) less than 0.5 g/l. The land cover in the cross-border area is dominated by forests (63%) and followed by agricultural lands (32%) and wetlands (3%). The area is sparsely populated (~30 inhabitants per km^2) and the water consumption can be rated as moderate (on average ~7000 m^3/day) and stable as no significant trends for the past 10 years were identified.

This study presents the workflow used for identification and assessment of transboundary aquifers between Estonia and Latvia. We propose certain approaches on how to delineate and justify transboundary aquifers, classify dominant water types, and identify major pressures on the area. This study is a prerequisite for further development of transboundary groundwater monitoring programs that are necessary to gather new data and update the status of shared groundwater on a regular basis according to EU Water policies.

Keywords: monitoring, water quality, cooperation.

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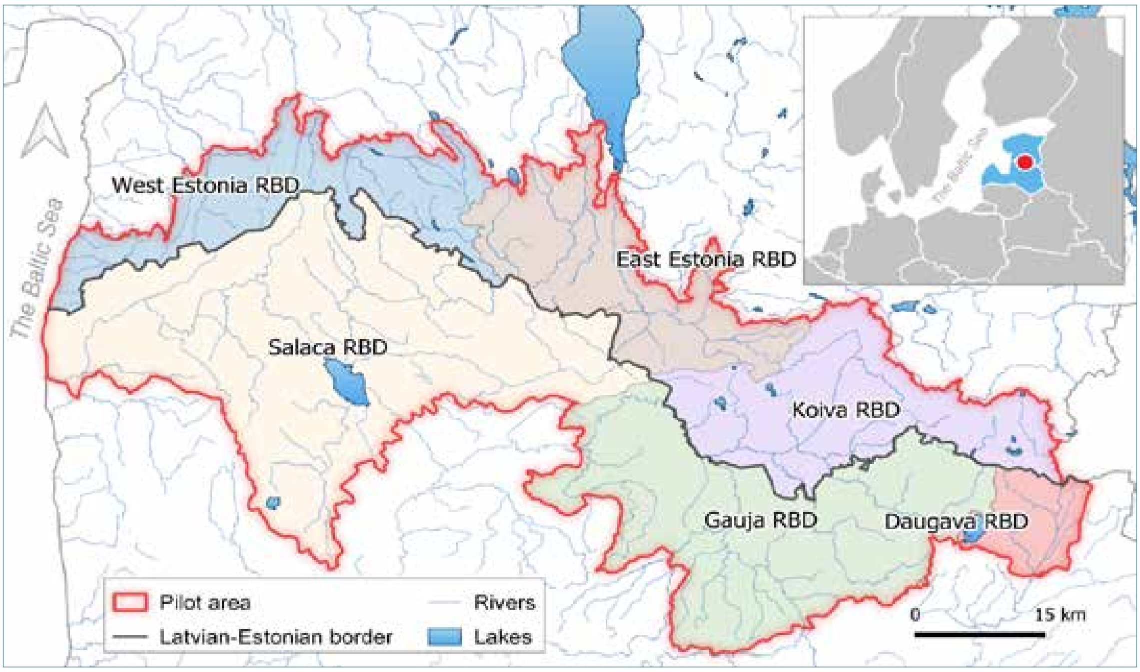
Introduction

The European Water Framework Directive (WFD, 2000) and Groundwater Directive (GWD, 2006) stipulate that member states must achieve good quantitative and chemical status of groundwater to protect human health and dependent ecosystems (Voutchkova et al., 2021). A variety of actions must be carried out to assess the status of groundwater, identify major pollutants and their trends, and improve overall groundwater management.

Initial step is to identify boundaries of groundwater bodies (GWB), that could be understood as a "working area". Due to the high heterogeneity of European aquifers, there is no unified methodology on how to delineate them (Sánchez et al., 2009). The final number of GWBs and their sizes (as well as delineation methodologies) vary significantly between EU Member States. For instance, Estonia and Latvia have 39 and 16 GWBs, while the number of GWBs in Sweden and Finland exceed 3000 (WISE, 2018). Considering the total area of GWBs, Estonia and Latvia have one of the largest median GWB sizes, 1130 and 2964 km^2 respectively. On contrary, Finland and Sweden have the smallest average GWB sizes (<2 km^2). The identification of GWBs is an ongoing process, therefore boundaries can change when new monitoring (groundwater levels and chemistry) and supplementary data (such as land use, fertilization rates and water abstraction rates) are gathered.

Figure 1.
Boundaries of transboundary groundwater aquifers: Estonia-Latvia pilot area



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It is well known that groundwater does not follow human drawn boundaries such as a country border. The actions causing pollution or water overexploitation on the one side of the border can negatively influence groundwater availability and quality on the other side of the border. Therefore, transboundary aquifers (TBAs) should be delineated at first, then monitored and assessed in close cooperation between countries sharing the same groundwater. It is a complex task that involves not only data and knowledge exchange, but also development of trust (e.g., to share sensitive data), willingness to find compromises (e.g., harmonize monitoring and assessment approaches) and often devote time, human and financial resources to become expertise partner and provide training.

This study presents a simplified workflow how to delineate TBAs and carry out their first assessment. We hope that this article will be of use for other countries starting the cooperation on transboundary groundwater.

Delineation of transboundary aquifers

Transboundary aquifers between Estonia and Latvia were delineated based on the surface watersheds (also called catchment areas or divides) as the study concentrates on the freshwater aquifers used for drinking water and being addressed by EU Water policies. Then the boundaries were extended to cover whole cross-border area and include major towns and cities (Figure 1).

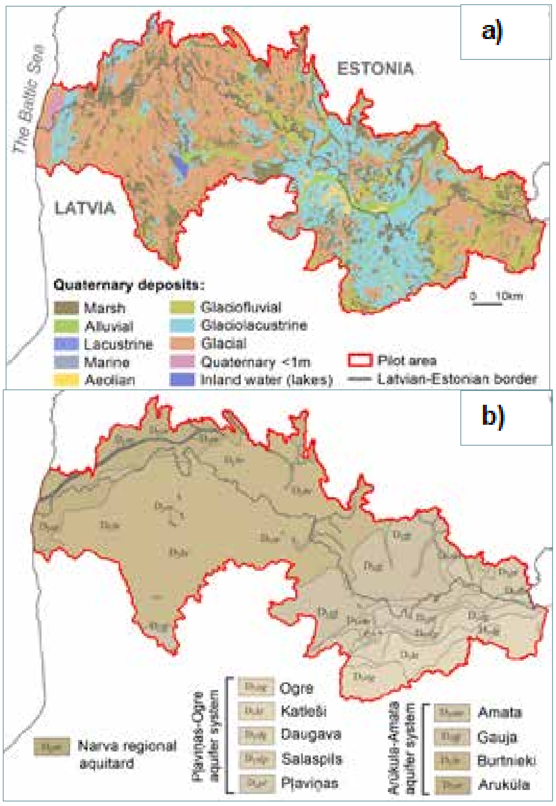
Typically, the hydrological boundaries match with the hydrogeological boundaries of upper aquifers (in this study Quaternary and Upper Devonian Pļaviņas-Ogre aquifer systems), while the deeper aquifer systems (like Middle to Upper Devonian Aruküla-Amata) have much larger watersheds. In this study we applied hydrological boundaries rather than hydrogeological mainly because the transboundary territory should not be too large to ensure a balance between monitoring costs and data analysis, and delineated area still ensures meeting all management goals (e.g., includes groundwater dependent ecosystems that rely on the upper aquifers).

Hydrogeological setting

Pilot area is in the central part of the multi-layered sedimentary Baltic Artesian Basin (BAB) – one of the largest groundwater basins in Europe (Lukševičs et al., 2012; Virbulis et al., 2013). The total thickness of sedimentary aquifers in the study area is up to 135-352 meters (Solovey et al., 2021).

Based on the aquifer hydrodynamic interconnection and water chemical composition, they are usually grouped into aquifer systems: (1) Quaternary, (2) Upper Devonian Pļaviņas-Ogre, and (3) Middle to Upper Devonian Aruküla-Amata. The Quaternary aquifer is formed of sand and loam (Figure 2 a), while the dominant water bearing material in bedrock aquifers (Figure 2 b) is sandstone. Local aquitards are composed

Figure 2.
Hydrogeological conditions of the pilot area a) Quaternary cover, b) bedrock aquifers.



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of clay and siltstone, while regional Narva aquitard composed of marl and clay separates the shallow aquifers from deeper, sometimes brackish aquifers. Below the Middle to Upper Devonian Aruküla-Amata aquifer system lies Middle Devonian Pärnu aquifer which also contains fresh groundwater in transboundary area but was not the subject of this study.

Justification of transboundary aquifer borders

Quaternary aquifer was automatically included into further conceptual model as it is essential for groundwater dependent ecosystems – aquatic (i.e., rivers and lakes) and terrestrial (i.e., fens, spring mires, swamp forests). Moreover, Quaternary aquifer is commonly used to provide drinking water in rural areas (shallow wells, dug wells) (Retike et al., 2016a). However, the inclusion of bedrock aquifers in the conceptual model first had to be justified. For that reason, a semi analytical groundwater flow estimation (SAGFE) method was developed.

Table 1.
Transboundary groundwater flows in major aquifer systems

Aquifer system	Aquifer	Total net Q from Latvia to Estonia, m3/d
Upper Devonian Pļaviņas-Ogre	D3*dg*	-146.5
	D3*slp*	-55.7
	D3*pl*	-1285.2
	Total	-1487.4
Middle Devonian Aruküla-Amata	D3*am*	747.5
	D2*gj*	3658.2
	D2*br*	17.8
	D2*ar*	-742.1
	Total	3681.3

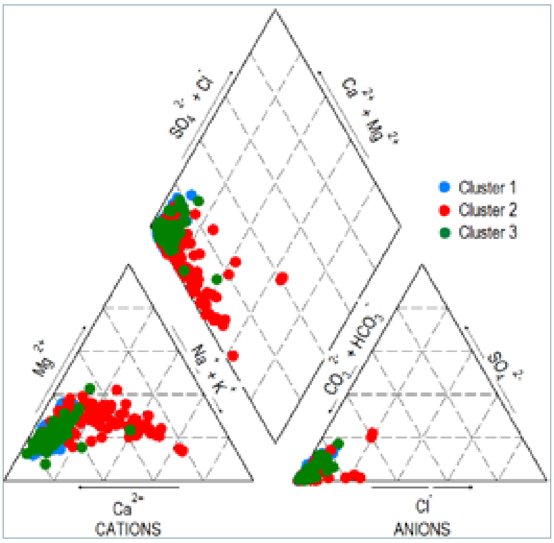
SAGFE used already available piezometric head data for each aquifer - modelled piezometric head data from PUMA numerical model which covers all the Baltic Artesian Basin (Virbulis et al., 2013), including pilot area. SAGFE used piezometric head distribution, aquifer geometry and hydraulic gradient of aquifers across Estonia-Latvia borderline that consisted of 160 individual segments to calculate transboundary groundwater flow according to Darcy's law. As a result, groundwater volumetric flow rate in each individual borderline segment was calculated for each aquifer and aquifer system.

It was found that in Pļaviņas-Ogre aquifer system, that is located only in eastern part of Estonian-Latvian borderline and have local importance in pilot area (Figure 2b), groundwater flow is directed mainly from Estonia to Latvia with a total net discharge rate of 1487 m^3/d (Table 1). On contrary, the main groundwater source in the pilot area is Aruküla-Amata aquifer system that flows in both directions across the borderline: total flow from Latvia to Estonia is 9488 m^3/d, from Estonia to Latvia 5807 m^3/d, therefore total net discharge rate is 3681 m^3/d that flows from Latvia to Estonia. However, important groundwater flow occurs parallel to the borderline because of discharge area in the Baltic Sea.

Geochemical classification of groundwater

To identify the dominant water types and geochemical processes in the pilot area a Multivariate statistical analysis was conducted using the combination of Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA). All data pretreatment processes, and analysis were carried out according to Retike et al., (2016b) approach using SPSS Statistics 26 software.

Figure 3. Piper diagram of groundwater samples labeled according to their clusters (from HCA analysis)



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First, the data from two major sources were compiled into a joint database: national groundwater monitoring and water supply databases maintained by Latvian Environment, Geology and Meteorology Centre (Latvian hydrogeological database "Wells", 2021) and (2) Estonian Environment Agency (Estonian Nature Information System, 2021; Environmental Monitoring Information System, 2021).

The initial number of observations (n=5182) was strongly reduced after removal of observations with missing records (n=1026). Thirty-six samples having an ionic balance error greater that ±10% were rejected from further analysis (n=990). Multiple observations from the same location were averaged as the database contained records from 1970s until 2021. The final database consisted of 437 observations, and contained information about major ions (Ca, Mg, Na, K, SO_4, HCO_3 and Cl), biogenic elements (NH4, NO_3, Fetot) and field parameters (pH and EC).

About half of the chemical parameters (except Ca, Mg, HCO_3, pH and K) were positively skewed, thus the data were log-transformed to achieve close to normal distribution. Then, standardization was applied on both log-transformed and non-transformed data so that each variable weights equally. Three Principal components (PCs) were extracted explaining 64% of the total variance in the data set. Variables with PC loadings greater than 0.5 are considered significant.

The first PC1 explains the greatest variance (26%) and groups high positive loadings of Ca, Mg, HCO_3 and EC. This PC reflects the most common and widespread Ca-Mg-HCO_3 freshwaters in the pilot area. The source of major ions is glacial material in Quaternary deposits and carbonate cement for the sand grains in sandstones (Levins and Gosk, 2007; Retike et al., 2016a). PC2 also explains great variance (21%) of the data set and is characterized by highly positive loading of K, Na and Mg and negative Ca. This component can be explained as base-exchange softening where Ca in solution is exchanged for sodium on clay minerals. PC3 explains 16% of the variance and groups positive loadings of SO_4, NO_3 and Cl as well as negative NH4 and Fetot. This PC describes redox conditions and possibly slight anthropogenic influence.

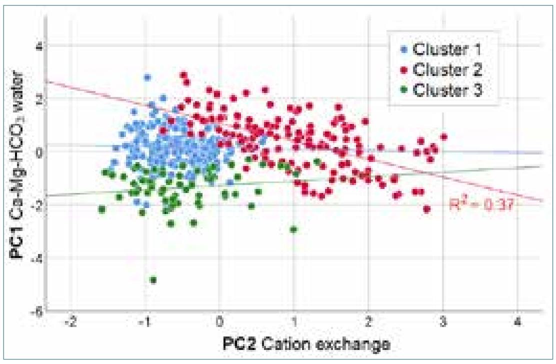
From HCA dendrogram three clusters were visually selected. Their averaged composition is represented in Table 2 and water type in Figure 3.

Table 2.
Geochemical characteristics of each cluster (averaged values, in bold – highest, underlines – lowest)

Cluster	Ca	Mg	Na	K	HCO_3	Cl
	mg/l					
1	**76**	21	4	3	334	8
2	60	**29**	**15**	**6**	**356**	12
3	<u>52</u>	<u>16</u>	<u>3</u>	<u>3</u>	<u>238</u>	<u>7</u>
	SO4	**TDS**	**NO_3**	**NH_4**	**Fe_{tot}**	**pH**
	mg/l					
1	11	457	**2.2**	0.2	**1.7**	7.4
2	8	**486**	<u>0.8</u>	0.2	<u>1.1</u>	7.5
3	7	<u>326</u>	1.5	0.2	1.2	**7.6**

All three clusters represent Ca-Mg-HCO3 fresh groundwater with TDS less than 0.5 g/l. In all clusters Fetot exceed the permissible drinking water standard 0.2 mg/l that is typical for the area. At the same time NO_3 drinking water standard 50 mg/l has not been exceeded in any of the samples and averaged values represent natural baselines levels (Retike at al., 2016b). All Quaternary, Pļaviņas-Ogre and Aruküla-Amata aquifer systems are present in Cluster 1 and 3. While in Cluster 2 Pļaviņas-Ogre is not present and Aruküla aquifer strongly dominates. No significant difference in well screen depths could be found when compared between clusters.

Figure 4.
Plot of loadings from PCA for the first and second PC



(©Own Elaboration) Groundwater samples are grouped according to their clusters from HCA.

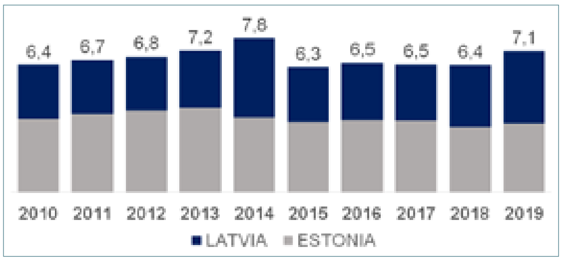
As can be observed from Figure 3 and 4, the HCA results support the hypothesis that cation exchange is an important process controlling groundwater composition in the pilot area and is represented by cluster PC2 and C2.

Identification of significant pressures

The land cover in the pilot area is dominated by forests (63%) and followed by agricultural lands (32%) and wetlands (3%) (The Copernicus Programme, 2018). Population density is low, around 30 inhabitants per km^2 on average in the pilot area.

According to the groundwater abstraction data from 2010 to 2019, average groundwater consumption in pilot area is 7000 m3/d and rather stable over years (Figure 5). Slight decrease of water abstraction could be observed from 2015 that could be associated with the influence of global economic crisis from 2007-2010 as the consequences in Baltic States emerged with a delay.

Figure 5.
Total groundwater abstraction in Latvia-Estonia pilot area in the period 2010-2019 (thousands m^3/d)



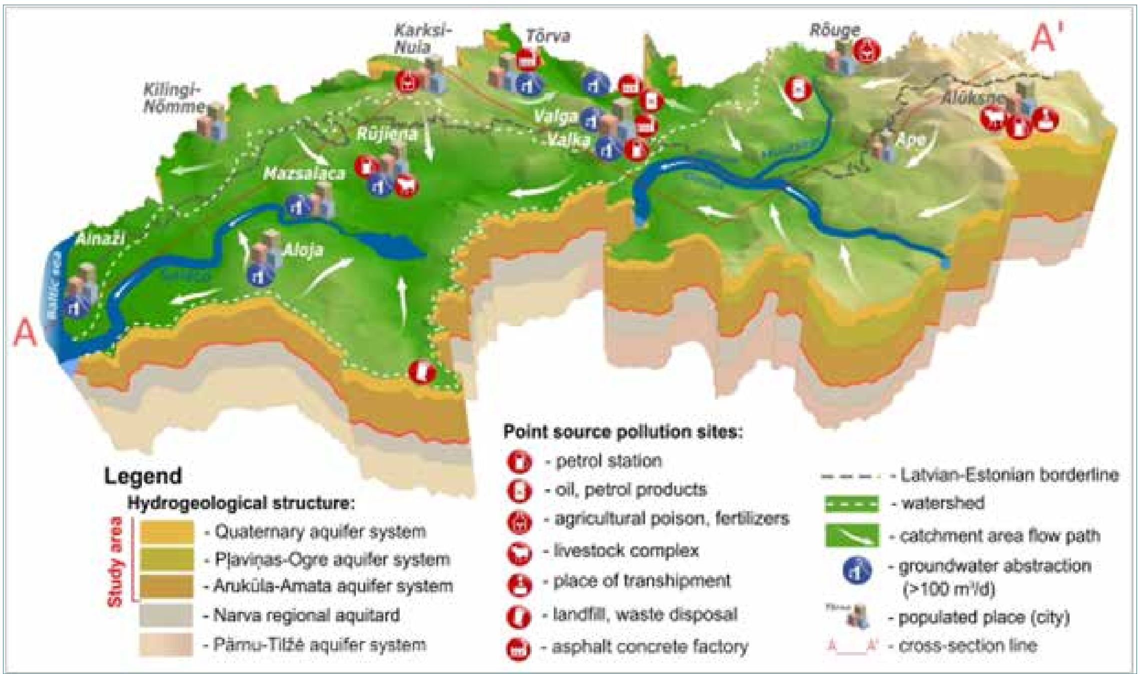
(©Own Elaboration)

Majority of water is abstracted from Aruküla-Amata aquifer system and main abstraction areas are located near largest cities, especially Valka (Latvia) and Valga (Estonia) – cities that are located exactly on the borderline. Importance of Pļaviņu-Ogres aquifer system increase in the eastern part of the pilot area, but only in Latvian part. The importance of Quaternary aquifer in water abstraction is negligible and local.

Table 3.
Averaged groundwater abstraction from major aquifer systems in period 2010-2019 (thousands m³/d)

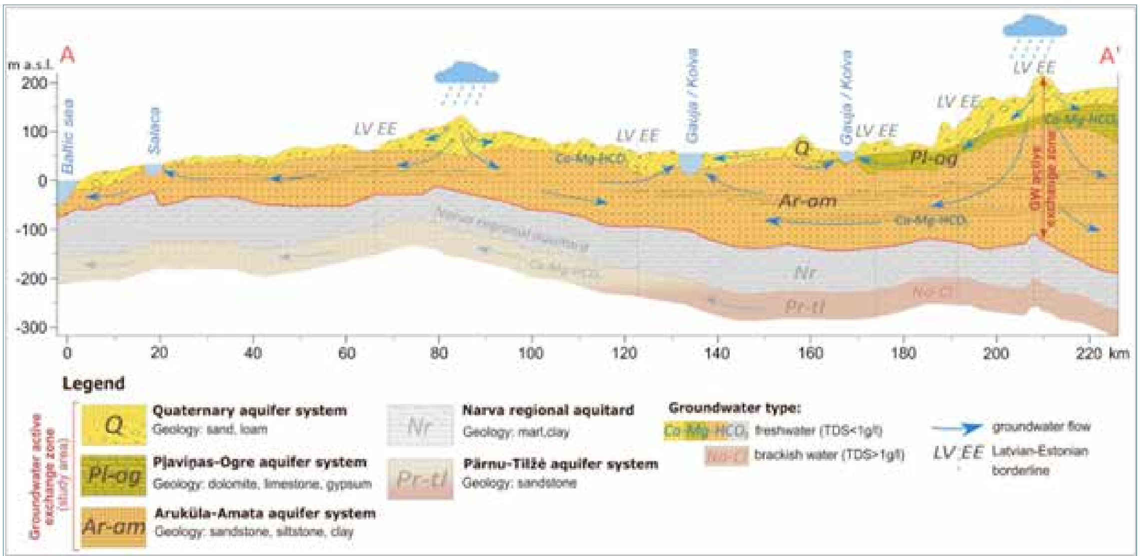
Aquifer system	Thousand m³/d	% of all abstraction
Quaternary	0.02	0.4
Pļaviņas-Ogre	0.3	5.7
Arukūla-Amata	5.4	93.9

Figure 6.
Conceptual model of the Latvian-Estonian transboundary aquifers



(©Own Elaboration)

Figure 7.
Conceptual hydrogeological cross-section of the Latvian-Estonian transboundary aquifers. See the red cross section line in Figure 6



(©Own Elaboration)

Conceptualization of the study area

The conceptual model developed for the study can be seen in Figure 6, while conceptual cross-section of the pilot area in Figure 7. The pilot area mainly contains Ca-Mg-HCO_3 fresh groundwater with TDS less than 0.5 g/l and naturally highlighted Fe_{tot} content above drinking water standard. Cation exchange (mainly Ca in solution exchanged with Na on clay surface) can be observed and no direct influence of NO_3 pollution from agricultural activity was identified.

Significant transboundary groundwater flows were identified in both Upper Devonian Pļ aviņ as-Ogre and Middle Devonian Aruküla-Amata aquifer systems, thus both systems were included into transboundary area. Groundwater abstraction can be rated as moderate while the main pressure areas are located near largest cities and towns.

All above mentioned should be considered during establishment of transboundary groundwater monitoring network and planning of monitoring programmes.

The next steps towards common groundwater assessment in Estonia-Latvia pilot are:

1. identification of most representative groundwater monitoring points from the existing networks, assessment of their technical quality by examining at least available long term observation data,
2. identification of possible areas where new transboundary groundwater monitoring wells should be installed,
3. identification of possible springs to be included into transboundary groundwater monitoring network to reduce network installation, sampling, and maintenance costs where it is possible and representative,
4. identification and quality assessment of groundwater dependent springs that receive groundwater input from transboundary aquifers.

Acknowledgments

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TOPIC 3/Paper 14

State of Affairs of Models and Governance of Transboundary Aquifers Along the Mexico-U.S. Border

Alfonso Rivera[1] and Randall T. Hanson[2]

Abstract

Where is there a water crisis along the Mexico-U.S.A. border (MX/US)? If a water crisis is indeed taking place, is it the combination of overexploitation of surface water and groundwater and a lack of governance that stewards the conjunctive use of transboundary water resources? Are these issues further exacerbated by a disconnect between governance and technical knowledge? The mismatch between scientific knowledge and governance is further complicated in transboundary regions by different frameworks of governance as well as different levels of monitoring and analysis. In many transboundary settings a disproportionate emphasis is on monitoring and management of surface-water resources and not enough scrutiny needed to also manage groundwater resources as shared and alternate resources within conjunctive use. We present an overview in an effort to provide some answers and issues related to these questions.

This overview provides a path for discussion and a framework for shared management of transboundary aquifers (TBAs) using state-of-the art tools (integrated models and monitoring) for better analysis and informed groundwater governance between the two countries. A summary of models (numerical and governance) along the borderlands offers insights on the main principles and criteria that can be used for water management purposes at transboundary level by combining monitoring and hydrologic models for the analysis of the use and movement of all waters. Regarding management models for TBAs, unfortunately, the state of the art is rather poor, unpublished, or non-existent for the MX/US border.

This analysis tries to answer three fundamental questions on the TBAs issues encountered along the MX/US border. The study scrutinizes cooperation, collaboration, the use of models, and governance, as join mechanisms to identify and recognize pathways that may facilitate solutions and options for different regions. Our hypothesis in answering these questions could help bridge the pathway that could yield more flexible sustainability of transboundary surface and groundwater resources through conjunctive use long the MX/US border.

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Introduction

The MX/US border spans 3,145 kilometers with numerous TBAs supporting water systems, socioeconomic development, and wellbeing of more than 10 million people in approximately 30 cities along the international border. The border region is a complex set of transboundary watersheds and related transboundary aquifers that not only span different size watersheds and a wide range of climates but also range from undeveloped to highly developed with agriculture, urban, and maquiladora uses for groundwater and surface water. Figure 1 shows a map of the international border with the main rivers and the 11 transboundary aquifers recognized by the two countries, as well as those that have been added by researchers in the U.S., but not yet officially recognized by neither of the two countries.

The UNESCO-International Shared Aquifer Resources Management (UNESCO-ISARM) network of the Americas outlined the management strategies and tools to be used over the TBAs (Rivera, 2015). However, implementation of strategies and application of state-of-the-art tools may take very long before they are applied under a transboundary context. International experience has shown that it takes very substantial cooperation, funding, and collaboration before shared strategies can be adopted. In the MX/US border, for instance, only two treaties exist for the major watersheds, with the majority of the transboundary watersheds not governed by any binational agreements. These two treaties only cover the surface-water aspects of the Rio Grande (Rio Bravo), Colorado, and Tijuana Rivers (USA-Mexico, 1906, 1944). Only Minute 242 (TBA 9N, 1973), written for the Cuenca Baja Del Río Colorado (Yuma-Gila-Mexicali Valleys), provides some limited constraints on groundwater pumpage and water development of the eleven TBAs, no other TBA has any binational agreement that includes groundwater.

More recently, Sanchez et al., (2016) catalogued 25 additional TBAs, and of the total, only a few aquifers have been analyzed in a binational context (Hanson et al., 2020; Heywood and Yager, 2004, Callegary et al., 2018; Rodriguez et al. 2020).

Further, the different jurisdictions along the international border have inconsistent criteria for defining transboundary aquifers and watersheds. Local, state, and irrigation district transboundary issues persist for the major rivers at multiple scales within each country. On the US side, there are additional inconsistencies related to governance. For example, the US Environmental Protection Agency designated some of the transboundary aquifers as sole-source aquifers in Arizona and California, which are different from other local or TBA designations. Local designation of aquifers is also inconsistent in the US border states. For example, the designation of Active Management Areas (AMAs) and Irrigation Non-Expansion Areas (INAs) is still not applied for some transboundary aquifers in Arizona; the recent California Sustainable Groundwater Management Act (SGMA) is either absent or not consistent with the actual extent of the aquifers. These local designations do not span the border or provide consistent delineation with or inclusion of the Mexican jurisdictional areas.

In order to provide some clarifications and propose some standardization in describing transboundary issues between the two countries and their potential solutions, we present an overview of the state of affairs along the MX/US border and explore scenarios using numerical and governance models of TBAs. We also acknowledge that first building conceptual models could enormously benefit the design, building, and selection numerical models, which requires more extensive expertise and data.

Figure 1.
Map showing (A) the 3,145 km international border with the main rivers between Mexico and the U.S. (CRS, 2018)

(©Open Access); (B) Transboundary aquifers along the MX/US border from UNESCO (2010); (©Open Access) and (C) Transboundary aquifers along the MX/US border from Sanchez et al. (2016). (© Elsevier)

Transboundary aquifers of the MX/US Border

This paper outlines three major questions related to transboundary aquifer issues in the MX/US transboundary region; it includes an overview of numerical models' capabilities that might help connect the science with the decision-making process going forward. In addressing the three questions below, rather than providing solutions to the water crisis, we describe the pathways that may facilitate solutions and options for different regions that have different supply and demand components, and different hydrologic and climatic settings. We advocate that these three fundamental questions could help bridge the pathway that could yield more flexible sustainability of transboundary surface and groundwater resources through conjunctive use.

Where and how is there a water crisis along the Mexico-U.S.A. international border (MX/US)?

Water crisis is occurring throughout the MX/US transboundary region commonly representing both water quality and quantity (supply). Various levels and forms of water crisis and related conflicts span the entire border region from the Tijuana River watershed and aquifers to the water shared in the Colorado River and underlying aquifers, to the Lower Rio Grande of New Mexico-Texas/Conejos-Medanos (Hanson et al., 2020), further east to the Hueco Bolson (Heywood and Yager, 2003) and the Edwards-Trinity-El Burro aquifer systems. Reduced supply from increasing periods and frequency of drought along with growing agricultural and urban demands, aggravate the balance between supply and demand along the border region of the MX/US, where transboundary surface-water and groundwater use, and movement compete and are rarely managed and used conjunctively.

What is really happening in many parts of the border is that conceptual understanding of TBAs is very poor and incomplete; without some data and a simulation model, there are no metrics for limiting, managing, or assessing overexploitation, and no reliable hydrologic budgets.

Is this water crisis the combination of overexploitation of surface water and groundwater and a lack of governance that stewards the conjunctive use of transboundary water resources, or just additional exploitation?

The increasing growth of land use or intensification of agriculture and increase of water demand through changes from seasonal to permanent crops, has been observed in the Lower Rio Grande over the years. For example, as shown by Hanson et al. (2020), a shift from cotton and other seasonal crops to pecan orchards without much increase in actual irrigated land use resulted in the hardening and increased demand, along with increased urban demand with population growth.

When combined with impacts of a changing climate along the MX/US border, as shown by the recent drought, has become the limiting factor on stewarding supply. Further, shared governance of transboundary aquifers is either deficient or totally absent.

Are these issues further exacerbated by a disconnect between governance and technical knowledge?

The 1906 and 1944 Treaty of the Rivers have limited connection to combined governance of these surface-water and groundwater resources in transboundary aquifers; they do not address combined governance of these. While minutes to the 1944 Treaty of the Rivers include some additional governance of water-quality constraints for selected transboundary watersheds and some limited groundwater pumpage constraints (Minute 242) along the aquifers of the Rio Colorado, the differences in bi-national governance of groundwater remains detached from it. While some limited compilations and sharing of some types of data have been completed for the Hueco (Heywood and Yager, 2003), Conejos-Medanos (IBWC, 2011), San Pedro and Santa Cruz (Callegary et al., 2018), there still remains a disconnect of detailed data needed for water budgets or hydrologic model construction and analysis that could lead to updates in management or governance of transboundary water resources. This type of technical knowledge of the combined resources is also lacking in most other transboundary aquifers. Combined monitoring of water resources with shared quantity and quality databases is generally lacking too.

Cooperation, collaboration, challenges

One of the largest challenges of the TBAs along the MX/US border is the changing uses of land and water combined with climate change/variability. These challenges are amplified in selected TBAs because of the monetary value of the agriculture and related food and water security in regions like the Chihuahua-Rio Conchos, Lower Rio Grande, and Rio Colorado. For example, the Colorado Basin used to deliver about 74 million m^3 to Mexico through leakage from the All-American Canal within the United States (Rivera, 2015). This initially caused water-logging in the Mexicali Valley in Mexico that hampered the development of some lands for agriculture. This was mitigated with construction of the Andrade Drain in Mexico that captured this shallow groundwater for irrigation reuse. More recently the leaking canal was lined in the US which stopped this additional replenishment that helped replenish groundwater resources in Mexico's portion of the TBA. Now the recent mega-drought has resulted in diminished surface-water deliveries that further exacerbate the sharing and distribution of water resources. Colorado River deliveries from the US also are partially replaced with delivery of shallow saline groundwater from this TBA that also further degrades the quality of water available for agricultural uses in Mexico. Finally, additional environmental flows are now being transferred across the border to sustain the wetlands at the outflow of the Colorado River into the Sea of Cortez in Mexico.

There have been a few cases of cooperation (exchange of information in support of each other's local project goals), but no formal collaboration support of a shared long-term vision. A couple of good examples of cooperation are the San Pedro and Santa Cruz TBAs where science and social cooperation arrangements are being further developed (Callegary et al., 2018).

Technical knowledge could increase through cooperation. For instance, combined monitoring of water resources with shared quantity and quality databases could be implemented as transboundary "smart valleys", where for example, an automated supervisory control and Data acquisition (SCADA), could be applied over an entire basin or watershed. Smart valleys could be designed and implemented to inform both transboundary modeling as well as updates to transboundary governance and any SCADA system to distribute and maintain shared water resources. Examples already exists on this type of technology, for the Coachella Irrigation District, Coachella Valley, California; and the Distrito De Riego Del Rio Yaqui, Sonora, Mexico.

Models

Modeling has taken different approaches in different parts of the transboundary aquifers. Both physical-based numerical models and management models are needed to shape the short-term and decadal goals for sustainability within a supply-and-demand framework.

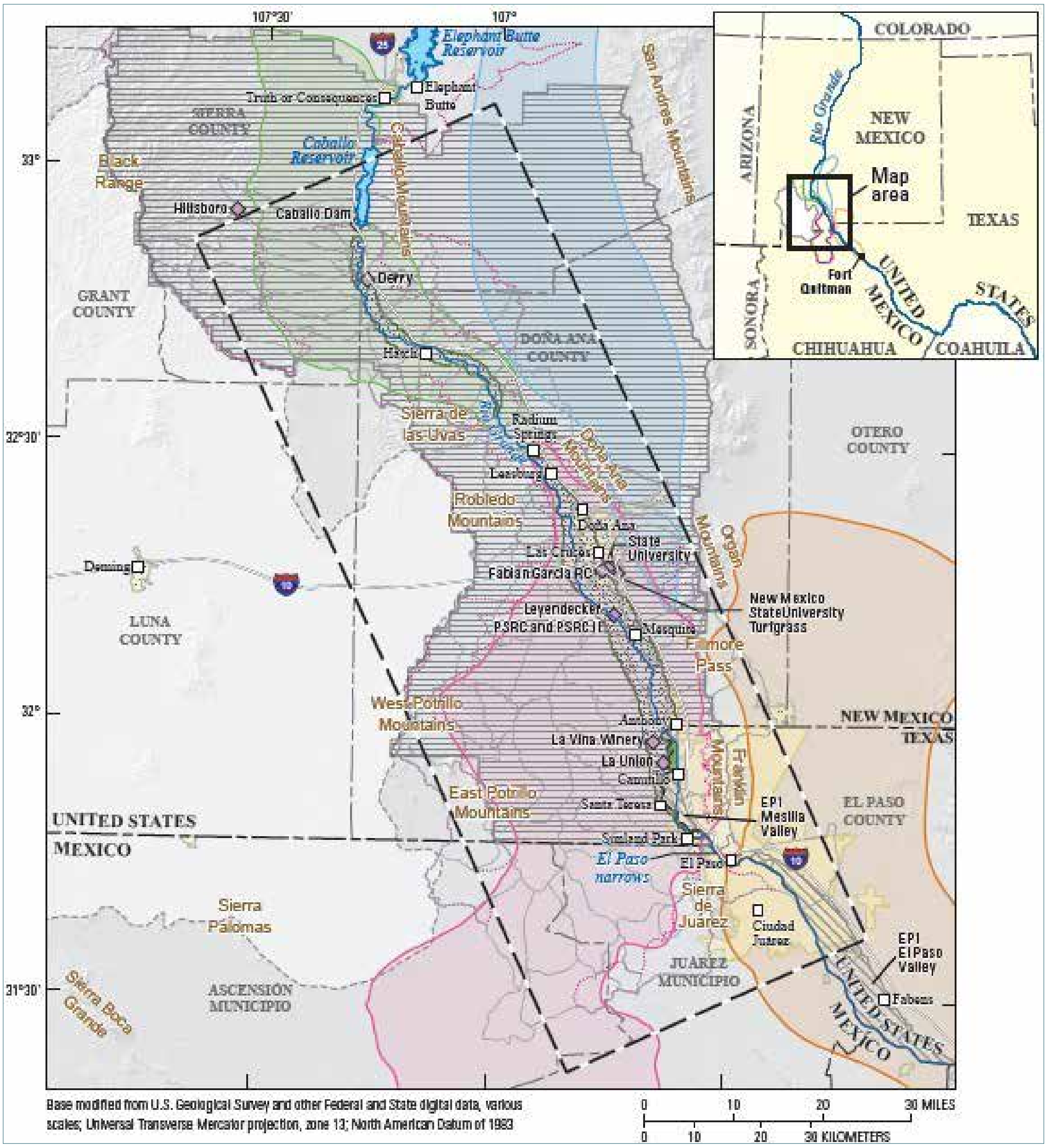
Integrated hydrologic models (IHM), such as Modflow-OWHM2 (Boyce et al., 2020), provide some of the mechanisms needed to address the dynamics of supply and demand; these types of models may be used to dynamically analyze sustainability constraints of water resources, such as subregional surface-water and groundwater allotments, pumping capacities, diversion capacity, and percentages of leaching of salts, among others.

For example, results from IHMs, which include simulated estimates of combined crop consumption with the use and movement of surface water and groundwater, are the types of attributes that can more successfully interact with management models to enhance water conservation. Other efforts to combine water knowledge with water management is by using game-theory; one recent example was developed for the Hueco Bolson aquifer (Mayer et al., 2021). However, this approach does not include all of the critical feedbacks of conjunctive use that affect sustainability such as salinity, water reuse, captured conveyance of surface water, and captured discharge, which may be provided from more detailed IHM modeling of conjunctive use (Boyce et al., 2020).

Using a conjunctive surface-water/groundwater framework (Fig 2), a complete approach was used to model the transboundary Lower Rio Grande. The model was capable to confirming the efficacy of the 2008 operating agreement subject to climate change in a US Environmental Impact Statement (Bureau of Reclamation, 2016), including reservoir operations. The operating agreement includes surface-water deliveries to Mexico (USA-MX, 1906), which are subject to growing interference from more land use, increased water demand, groundwater pumpage, and drought (Fig 3). This type of model is more complete and can respond to a broader variety of mitigation and climate-change alternatives, as well as provide output needed for management models such as dynamic agent-based management models.

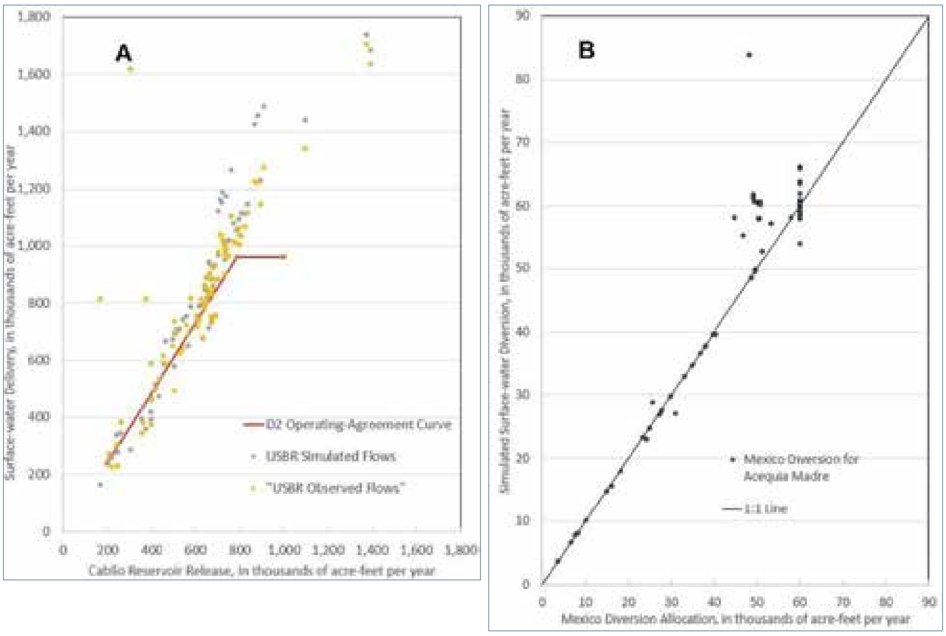
One of the biggest challenges for meaningful modeling that can provide detailed feedback to management and decision makers is identifying all of the inflows and outflows that represent the major stresses of the aquifer and surface-water system. However, as good as these tools (models) can be, the big challenge that still remains along the MX/US border is the scarcity of complete sets of data to feed those models and support decision makers. There are only a limited number of models built for selected TBAs along the MX/US border (Table 1).

Figure 2.
Areas modeled by the Rio Grande Transboundary Integrated Hydrologic model (RGTIHM) in New Mexico, Texas, and Mexico, along with an active hydrologic model grid. The model includes both watersheds and groundwater basins



(Hanson et al., 2020). (©U.S. Geological Survey)

Figure 3.
Graphs showing the (A) Operational Flows versus divertible surface water and related 2008 Operating Agreement delivery curve; and (B) Treaty deliveries to Mexico at Acequia Madre



(modified from Hanson et al., 2020). (©U.S. Geological Survey)

Table 1.
Models built for the TBAs along the MX/US border

TBA Aquifer Number- Name and jurisdictions	Model(s)
9N - Lower Colorado River Basin Baja California Norte/ California-Arizona	A few numerical hydrogeological models built, most on the US-side of the TBA (Reichard and Meadows, 1992; Hill, 1996); or for the Mexican side of the TBA (Ariel, 1968). One Mexicali Valley model was recently developed by Mohammed (2019) using MF-OWHM. Current efforts include building a conceptual model for the entire TBA integrating surface water, groundwater, and transboundary effects, as a first step in a joint scientific assessment (Cital et al., 2021)
14N - Conejos Médanos-Bolsón de la Mesilla and Rincon Valley Chihuahua/ New Mexico-Texas	The Transboundary Rio Grande model was applied to both the US and MX-side of the TBA, The MX part only included the Mexican wellfield south to a nearby bedrock outcrop that subdivides the jurisdictional Conejos-Medanos. The model was set up to be used for management and salinity analysis, but has not yet been used for these purposes (Hanson et al., 2020).
15N - Bolsón de Hueco-Valle de Juárez Chihuahua/Texas	A transboundary hydrogeological model covering both sides of the international boundary. Though the model intention was for El Paso Water Utilities to evaluate strategies for obtaining the most beneficial use of the Hueco Bolson aquifer system (management), it was not used for that purpose (Heywood and Yager, 2003).
18N - Los Mimbres – Las Palmas Chihuahua/New Mexico	The Los Mimbres – Las Palmas TBA model was the first TBA model on the MX/US border and was applied to the entire basin in MX-US TBA (Hanson et al., 1994).
8N - SanDiego-Tijuana Baja California Norte/ California	Initial reconnaissance model of San Diego-Tijuana Transboundary aquifer system (Flint et al., 2012).

(TBA numbers are from UNESCO, 2010)

Governance

Governance not only needs to encompass water rights and distribution of surface water and groundwater but also the monitoring and reporting of the state of the water use and movement. All too often more water is used or not reported, which affect the assessment of water rights and related conjunctive use and sustainability. Combined with no restrictions on the growth of land use as well as the intensification and hardening of demand with increased agriculture, has resulted in a disconnect between management of water rights and water sustainability. This, in turn, results in overexploitation of land and water independent of climate change and droughts that does not have any mechanisms or feedbacks in a governance framework that includes alternate water supplies or constraints on use such as drought contingency or alternative supplies.

We suggest that a clear methodology for shared governance should include permanent monitoring linked to conceptual models continuously reformulated and updated as new information is acquired. In turn, simulation (numerical) models can be adjusted in an iterative process.

Part of the governance challenge in any TBA is the transboundary outreach and consensus-building efforts needed to sustain and manage TBAs as was developed for the San Pedro and Santa Cruz TBAs (Callegary et al., 2018), as communication and cooperation including data and analysis sharing are a fundamental part of the governance framework.

Good practices for shared governance of surface water exist along parts of the border where the Treaty of the Rivers helps manage the shared resources, but none for groundwater. This has negative impacts on the perennity of groundwater and surface-water conveyance for irrigation and treaty obligations. For instance, the requirement of surface-water deliveries can conflict with groundwater uses as shown on the Rio Grande in New Mexico and one of its tributaries, the Rio Conchos in Mexico. The latter are part of the binational delivery Treaties, with increased land use and groundwater use interfering with the conveyance of surface-waters and creating additional supply-and-demand conflicts.

Thus, there is hardly any combined governance on shared groundwater use in the TBAs, which in turns impedes good, shared management of the TBAs along the US/MX border. Yet, comprehensive governance of groundwater resources is critical to preventing and mitigating the aforementioned stresses to groundwater resources. A water crisis is indeed growing across the transboundary aquifers and watersheds as demonstrated by previous litigation in many TBAs and ongoing U.S. Supreme Court litigation in the Lower Rio Grande example of Texas v. New Mexico and Colorado

Summary and conclusions

In light of the short analysis presented here, we conclude that, indeed, a water crisis, lack of shared groundwater governance, and, in some cases, lack of recognition of TBAs continue in the MX/US TBAs. Lack of meaningful data and very scattered to no monitoring of water and land use, as well as the absence of data sharing among jurisdictions, emphasize the groundwater predicament.

Lack of adequate groundwater governance is not only international, many regions with strong local interests (e.g., agriculture) result in lack of governance within the same country. Funding for transboundary monitoring networks is virtually absent. Increased demand for more land use for agriculture, mining, and increased urbanization, further increase the stresses on both groundwater in storage and flowing in the transboundary aquifers along the MX/US border as exemplified by the Lower Rio Grande case study (Hanson et al., 2020).

Further, decreased supply from climate variability (mega-drought), climate change, water exports, environmental flows and habitat restoration exacerbate these combined issues. Thus, competition for water within these regions, as well as exports to outside urban areas, characterize the current TBA conjunctive use of surface water and groundwater.

The examples of interstate litigation described within the USA, continue and could expand as binational conflicts or other transboundary litigations.

As we look forward on the proposed pathway, some progress is developing. For example in the last decade, scientific cooperation and a few governmental initiatives have begun to develop, which include the pulse flow to the Cienega de Santa Clara (Colorado, IBWC, 2010, Minute 316), and binational water scarcity Contingency Plan for the Colorado River Basin (IBWC, 2017, Minute 323), as well as data sharing through IBWC-CILA (TAAP, 2009); and the creation of the Permanent Forum of Binational Waters.

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TOPIC 3/Paper 15

Advances in Geological Knowledge in the Transboundary Outcrop Area of the Guarani Aquifer System, Artigas City and Surroundings, Uruguay.

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Abstract

The Guarani Aquifer System (GAS) is one of the most important transboundary aquifers in the world. Its extension includes part of Argentina, Brazil, Paraguay and Uruguay, where it is used both for human consumption and for agricultural and recreational activities. More specifically in Uruguay, it is found in both unconfined and confined form. In Uruguay, the Guarani Aquifer System consist of Mesozoic sandstones represented by the Tacuarembó and Rivera formations. It is found as an unconfined aquifer in two regions of the territory and, in a confined way when covered by Lower Cretaceous basalts of the Arapey Formation.

This contribution focus on the stratigraphic and structural analysis of the Guarani Aquifer System outcrop located in the easternmost part of the department of Artigas, the Artigas microregion, an area within the Cuareim river Basin that involves an international political boundary with Brazil. Here, groundwater is used as a water source for agricultural activities, and largely for human consumption representing in many cases the only source of drinking water in the area.

The outcrop area of the Guarani Aquifer System constitutes an uplifted block that extends from the Artigas microregion towards the Brazilian territory in a NW-oriented regional structure (Cuareim lineament). The block is bounded by normal faults of N-NE direction in the north of the study area while its outcrop extension is controlled by a E-W strike-slip fault zone in the southern area. Uplift processes allowed erosion of the basalt cover exhuming the sandstones of the uppermost levels of the Guarani Aquifer System and generating the so-called "Window of Artigas".

New geological mapping, stratigraphic correlations and structural modeling allowed us to interpret that in some areas sandstones previously mapped as being part of the GAS are in fact intertraps of the Arapey Formation. Thus, the new data restricts and reduces the extension of the outcropping sandstones of the GAS in the Artigas microregion. In summary, the new geological evidence allowed us to define more precisely the location of the outcropping sandstones of the GAS in the Uruguayan side of the Cuareim River Basin and to establish the structural control of local and regional structures in its distribution. This model will result in a better understanding of the Guarani Aquifer System and its dynamics and, therefore, will provide new tools for the sustainable management of the transboundary aquifer in the Artigas-Quarai area.

Keywords: Guaraní Aquifer System, geology, transboundary

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Introduction

The Guaraní Aquifer System (GAS) is a transboundary aquifer shared by four countries: Argentina, Brazil, Paraguay and Uruguay. In Uruguay, the GAS is developed in its north-northwest region, occupying around 40,000 km^2. It is made up of the Tacuarembó and Rivera formations (Jurassic to Early Cretaceous) occurring in different forms; when confined, the aquifer is covered with up to 1000m of basalts and intertraps of the Arapey Formation. Most of the outcropping GAS develops in the north-central region of Uruguay, in the departments of Tacuarembó and Rivera, along an extensive sub-longitudinal strip structure and adjacent to the basalt cover.

Other locations where the GAS crops are the so-called "windows" that are associated with strong NW structural controls exhibited by the basin in the basaltic region. One of these "windows" is located in the area surrounding the city of Artigas, which is the object of this study. Windows are considered vulnerable areas as they behave as unconfined sedimentary aquifers, susceptible to anthropogenic contamination and climatic variations.

The geological features of the GAS in the study area, a transboundary zone supplying freshwater to the local population as well as resources for the agricultural production, make the existing "window" in the surroundings of the city of Artigas a sensitive area. In order to asses groundwater vulnerability to contamination, more detailed about the distribution, geological and structural features as well as hydrogeological characterization of the GAS in the area is needed. Thus, this works attempts to provide detailed geological mapping and a structural model of the Artigas microregion.

Location of the area

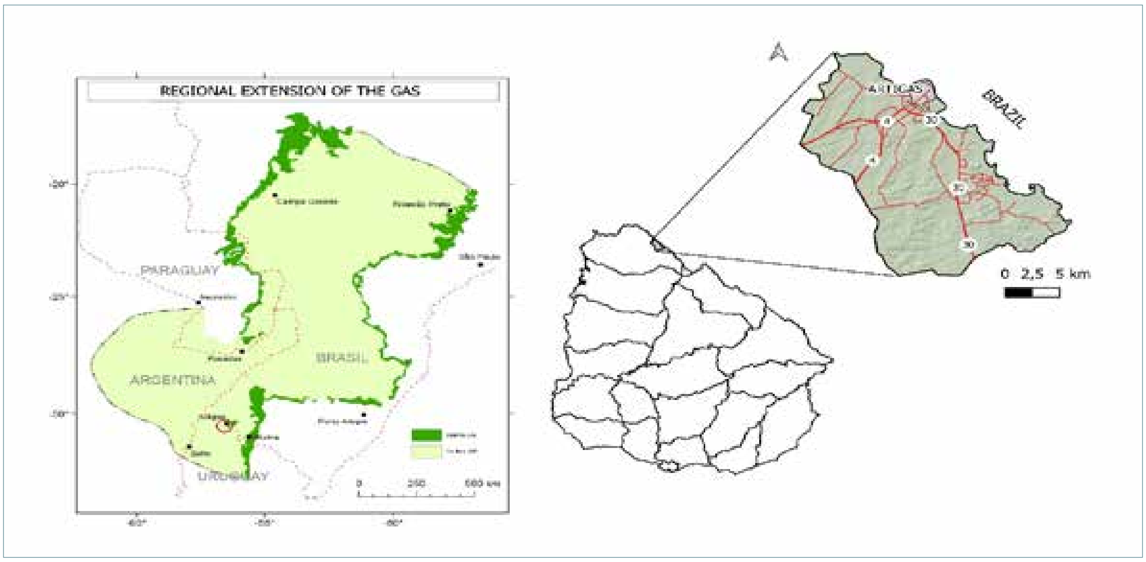
The study area includes the microregion of Artigas, an administrative name defined by the Departmental Administration. It covers an approximate area of 312 km^2 including the Cuareim River as its north-eastern limit, which constitutes the territorial boundary with Brazil (Figure 1). The main city (Artigas) lies along the Cuareim River across from Quaraí city.

The microregion includes vast rural areas, dedicated to agricultural activity particularly associated with tobacco plantation and livestock in a lesser extent.

The GAS and its transboundary aspect in Artigas

The Rivera and Tacuarembó formations (Jurassic-Early Cretaceous), constituents of the GAS, are outcropping in the study area. In Brazil both units correlated with the Botucatú and Guará formations, respectively; however, only the Botucatú formation is found in the Quarai city (Brazil). Thus, the Tacuarembó formation (Uruguay) and its counterpart Botucatú formation (Brazil) are physically separated by the Cuareim river, corroborating the transboundary nature of the aquifer (Figure 2).

Figure 1.
Left: Location of the study area within the extension of the GAS



(modified from Techera et al., 2017). Right: Location of the study area within Uruguay.

Use of groundwater in the area and importance of conservation of quality and quantity

Unconfined aquifers (in this case the outcropping GAS) have greater vulnerability to contamination, being threatened by anthropogenic activities carried out over them. Some activities that can affect the quality of the aquifer are: solid waste disposal, cesspools (in places where there is no sanitation), use of pesticides in agriculture and forestry. Each of these activities generates typical chemical elements, which can be leached and affect the natural quality of groundwater.

In addition to the possible anthropogenic sources of contamination, there is a lack of knowledge of the actual volumes of groundwater extraction, since a large part of the water wells (and their respective flows) are not registered within the government agencies.

The lack of these data makes the management and sustainable use of the aquifer a difficult task.

The area of the outcropping GAS present in the surroundings of the city of Artigas is the object of greater emphasis in this study, as due to its location near the departmental capital there is an intensive use of the land, which generates an extra pressure from the point of view of the water quality (due to its exposure to potential sources of contamination) and quantity of the water (due to the increasing demand). The lack of sanitation in rural areas is a negative point to consider when studying the vulnerabilities of the area.

Groundwater is an essential resource for human and productive supply in the study area. In the city of Artigas, groundwater resources make up 50% of the total volume of water used for public supply, while this percentage increases in the surrounding rural areas where, apart from domestic use, groundwater is used for agricultural production.

Figure 2.
Left: Outcrop on route number 293 located SE of the city of Quaraí (Brazil). Right: Outcrop on a local road south of the city of Artigas (Uruguay)

(© Own Elaboration)

Methodology

The cartographic study was carried out using aerial photos from the Military Geographic Service of Uruguay, and the Digital Terrain Model and images from the Spatial Data Infrastructure of Uruguay (IDEuy). Over 300 water wells were analyzed to check the stratigraphic distribution of the GAS, and the overlying and underlying units in subsurface. Field work was performed to analyze the stratigraphic and structural features of the area and add control points to the subsurface correlation. Geophysical data was also included to control the extent of the GAS in subsurface.

Results and discussion of updated geological mapping

The study area comprises a sector of the Paraná Basin, and three lithostratigraphic units are present which, from base to top, are: the Juro-Cretaceous sandstones that make up the Tacuarembó and Rivera formations and the Early Cretaceous basalts of the Arapey Formation. These basalts are found surrounding the so-called sandstone windows.

In the Tacuarembó Formation (Upper Jurassic-Lower Cretaceous) fine to very fine sandstones predominate, white to whitish, with sub-horizontal to horizontal stratification, with occasional intercalations of pelitic levels. Its fossil content was extensively described by Perea et al. (2009). This unit is interpreted as a succession of fluvial and wind deposits, forming extensive shallow sandy plains associated with ephemeral and/or permanent channels (Bochi de Amarante, 2017).

The Rivera Formation is assigned to the Lower Cretaceous and is made up of medium-fine sandstones, orange to brown in color, showing high-angle cross-stratification and medium grain-size. The sandstone presents a good selection, with a quartz-feldspathic composition and a moderate presence of lithic clasts. It is interpreted as aeolian dune deposits. In the window, the average thickness of the sandstones is 60 m, which coincides with the average depth of the wells in the area, so the thickness can be even greater.

On the other hand, the Arapey Formation is composed of basalts that rest on the sandstones of the Rivera and Tacuarembó formations (Figure 2). The basalts in the study area are generally massive, with different degrees of alteration and colorations ranging from dark gray to reddish. In most cases, in the area of the window they occasionally appear forming small hills, which facilitates their identification.

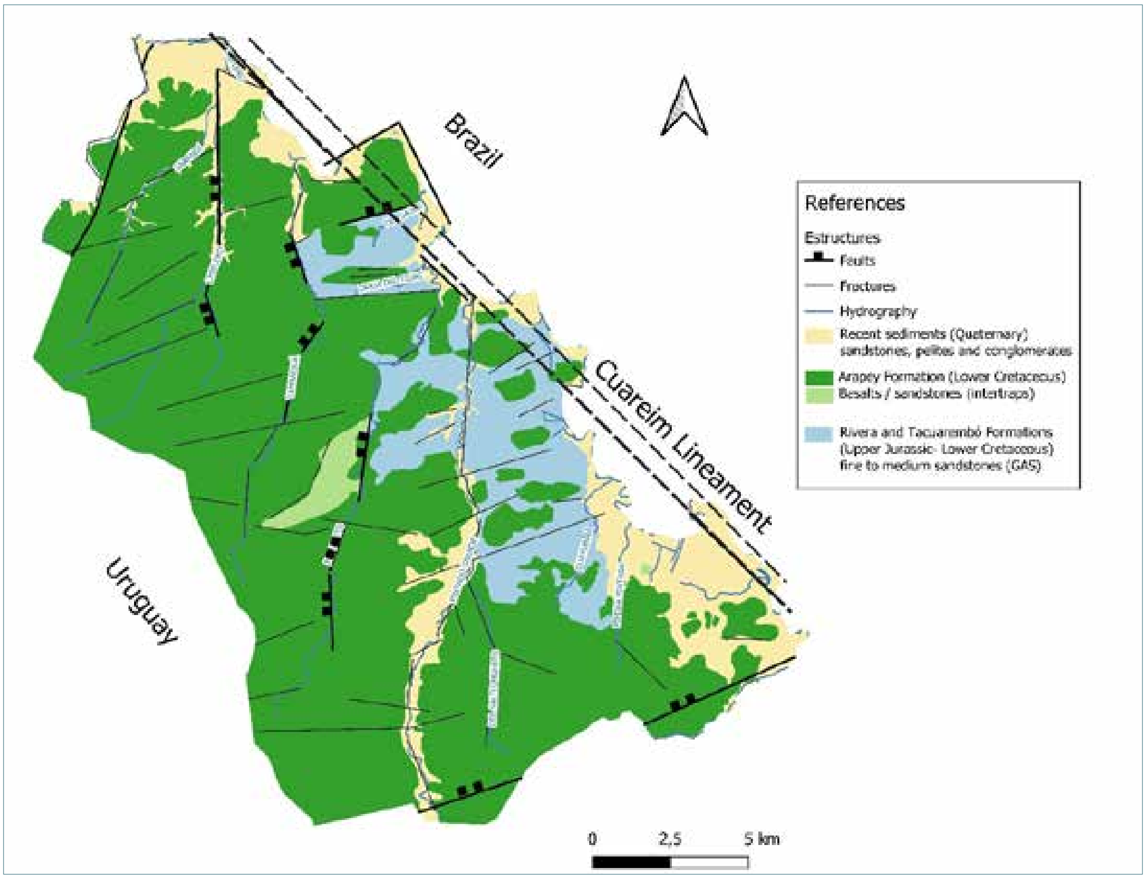
Geophysical surveys carried out in the area allow us to know that the basalts have a thickness of more than 200 m to the east of the microregion (Ramos et al., 2015).

One particular feature of these basalts is that they have sandstone inter-traps that can often be confused with the units belonging to the GAS.

As a result of the geological mapping, the inter-trap sandstones were separated from the GAS units and the main structural features were defined (Figure 3).

Local morpho-structural lineaments control the relief and drainage being several of these features normal faults that compartmentalize the GAS.

Figure 3.
Geological map of the Artigas microregion



(© Open Street Maps, Own Elaboration)

The detailed geological mapping allows us to define that only the outcropping sandstones found in the Central-East sector of the microregion, nearby the Cuareim river boundary are part of the GAS. The rest of the sandstones present in the region correspond to inter-traps and, therefore, are part of the Arapey Formation (light green).

From the analysis of the morpho-structural features, supported by the field and subsurface surveys, two large families of structures with NE and NS orientation have been defined that are associated with regional structural features recognized in the basin. These directions, associated with the NW direction of the Cuareim Lineament, controlled the vertical to subvertical faults that compartmentalized the area and allowed the lifting of a block that controls the development of the GAS window.

These vertical faults, with dislocations that would reach almost 200 m of rejection, are documented in boreholes and magnetotelluric soundings. (Ramos et al., 2015).

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TOPIC 3/Paper 16

Transboundary Aquifers between Mexico and the United States: The Complete MAP

Rosario Sanchez[1] and Laura Rodriguez[2]

Abstract

In 2015, the official number of transboundary aquifers (TBAs) reported between Mexico and the United States of America (U.S.) was 11. However, in 2016, new research indicated that there might be up to 36 aquifers traversing the border between the two countries. In 2018, a more detailed technical study showed that only between Mexico and Texas, there are 33 hydrogeological units (HGUs) identified on the border, of which 15 are considered transboundary aquifers with good to moderate aquifer potential. The most recent study published in 2021 shows that at border-wide scale, there are a total of 72 HGUs from which at least 28 report good aquifer potential and water quality. These 28 HGUs represent 60% of the shareable land between Mexico and the United States. So far there has not been any update on the official numbers of TBAs between the two countries, but groundwater is indeed getting attention and more strategic value as surface water shows its evident exhaustion.

Keywords: Transboundary, Mexico, United States.

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Introduction

In 2015, the International Shared Aquifer Resources Management (ISARM) reported that officially 11 TBAs were traversing the border between Mexico and the U.S. (Rivera et al., 2015). One year later, Sanchez et al. (2016) suggested there might be up to 36 TBAs in the border region. However, this new research only attempted to depict existent aquifers reported on each side of the border without a homogenization effort of criteria used to delineate boundaries among them or to assess its transboundary nature of the different aquifer units across the border. It was not until 2018, when Sanchez et al. (2018) published the first hydrogeological assessment of geological units across the border region between Texas on the U.S. side, and the states of Tamaulipas, Nuevo Leon, Coahuila, and eastern Chihuahua, on the Mexico side. Following the same line of research, in 2021 an additional effort was published to account for the remaining states not covered back in Sanchez et al. (2018). Sanchez & Rodriguez (2021) reported 39 hydrogeological units (HGUs) located between the states of California, Arizona, and New Mexico on the U.S. side, and Baja California, Sonora, and the western part of Chihuahua, on the Mexico side. This latest manuscript is considered the second edition of its predecessor Sanchez et al. (2018), which identified 33 HGUs between the state of Texas in the U.S., and the states of Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas, on the Mexico side. Both publications use the same methodology to assure consistency and coherence among the two assessments, and together comprise the identification, delineation, and classification of all HGUs along the complete border between the two countries. Both studies identify and delineate geological boundaries using surficial geology as the main criterion to perform the geological correlation and structural geology for boundary delineation. Lithological characteristics, hydrogeological features, and topography were used to complement the analysis and strengthen the results.

The combined results of Sanchez et al. (2018) and Sanchez & Rodriguez (2021), as well as Sanchez et al. (2016), are used in this paper as a compilation of findings to offer a synthesized reference of the total number of HGUs in the border between Mexico and the U.S. The complete border area reports 72 HGUs shared between the two countries with an estimate of good aquifer potential and good to moderate water quality in approximately 45% of the land extension covered by the HGUs. As originally reported by Sanchez et al. (2018), the criteria used to define aquifer potential include lithological features, permeability, porosity, hydraulic conductivity, transmissivity, and water yield when available. Water quality parameters are based on the TDS (Total Dissolved Solids) ranges of the Texas Water Development Board (TWDB), as indicated by Sanchez et al. (2018).

What these research findings represent to the current state of knowledge on the border between Mexico and the U.S., is the increasing strategic value of groundwater resources that is shared in the region and that has the potential to become a driver for binational security or an incentive for cooperation. So far, the topic has received limited attention at the binational level and even lesser funding priorities for continued research. Overall, this study reflects two essential realities: half of the border region area has good aquifer conditions, and second, those shared aquifer systems are indiscriminately used by both countries without any legal framework regulating their extraction and management.

The first section of this paper will cover the main findings reported by Sanchez & Rodriguez (2021) and Sanchez et al. (2018) in terms of the number of HGUs, main aquifer units according to their aquifer potential and water quality, and proportions of the extension of land covered by the HGUs over the complete border region and by state. The second part will present an updated list of transboundary aquifers (Table 1) that has the purpose to substitute the one published by Sanchez et al. (2016) and a corresponding updated map (Figure 1) that shows all the identified HGUs. The last section will address final thoughts on what the binational implications can be with this new knowledge in terms of prioritization and attention to the topic, as well as some binational water security considerations.

The current status

As of today, there is no agreement on the number of transboundary aquifers traversing the border between Mexico and the U.S. The latest official report was published in 2015 where 11 aquifers were recognized by both countries (Rivera et. al 2015). Despite new research findings, no official updates have been published by Mexico or the U.S. since then. Additionally, there is not a recognized common methodology at binational or international levels for identifying or delineating the extension of a transboundary aquifer; even the ISARM report from 2015 has no clear criteria for delineating transboundary aquifer boundaries. Furthermore, there is not a formal legal and policy framework at a binational level to address transboundary groundwater management in the Mexico and the U.S. border region.

This reality, along with increasing drought conditions, uncertain climate conditions, population growth, and surface water exhaustion have defined the future of groundwater resources in the border region: an increasingly strategic non-protected natural resource that has the potential to become a security threat to the border region, and therefore to both countries. The development of institutional capacity in the region to cope with water shortages is as limited as the attention to the current conditions of groundwater use and its extraction. Preparedness and leadership as well as willingness to assess and promote binational cooperation efforts, tend to be limited and isolated, driven mainly by surface water needs and concerns associated with the 1944 Water Treaty (IBWC, 1944).

This paper adds to the current state of knowledge, the first complete map of transboundary aquifers between Mexico and the U.S. using a standardized and consistent methodology. Additionally, this study shows two important findings: half of the area of the border region reports good to moderate aquifer potential which makes it even more valuable and strategic; and second, those shared aquifer systems are indiscriminately used by both countries without any legal framework regulating its extraction and management.

HGUs in the Mexico-U.S. border region

Starting from west to east, results indicate that a total of 39 HGUs have been identified on the border between California, Arizona, and New Mexico on the U.S. side, and Baja California, Sonora, and Chihuahua on the Mexico side. This region accounts for an approximate shareable area of 135,000 km^2 (the extension of the land area covered by the HGUs in Figure 1), with both countries sharing approximately half of the total area (69,000 km^2 in the U.S. and

65,000 km^2 in Mexico). From the total shareable area, around 40% indicated good to moderate aquifer potential and good water quality, from which 65% is on the U.S. side and 35% on the Mexico side.

According to Sanchez & Rodriguez (2021), from a border-state perspective, the border region between Baja California and California shows a total of five HGUs, but only three (Tijuana-San Diego Aq., Valle de Mexicali -San Luis Rio Colorado/Yuma-Imperial Valley and a significant portion of the Quaternary deposits of Laguna Salada Aq./Coyote Wells Valley) are considered as good to moderate aquifer potential and generally good to moderate water quality. Available data on water quality varies across the Valle de Mexicali-San Luis Rio Colorado/ Yuma-Imperial Valley from good to poor water quality (limited information is also significant in this area), particularly in the southern portions where saline intrusion has been reported. In the case of the border between Sonora and Arizona, 26 HGUs have been identified, with at least seven HGUs (Nogales-Rio Santa Cruz Aq./ Upper Santa Cruz Basin, Rio San Pedro Aq./ Upper San Pedro Basin, Rio Agua Prieta Aq./ Douglas Basin, Rio Altar Aq., San Simon Wash, Sonoyta-Puerto Peñasco Aq., and La Abra Plain) reporting generally good to moderate aquifer potential and good to moderate water quality conditions. Variability of water quality data in the Sonoyta-Puerto Peñasco Aq., and San Simon Wash is also significant. There are also four HGUs (Cerro Colorado Numero 3 Valley, Lukeville-Sonoyta Valley, The Great Plain, and Arroyo Seco Aq.) that show good to moderate aquifer potential but poor water quality, with also important data gaps on these HGUs. On the border between Chihuahua and New Mexico, good aquifer potential and good water quality are identified in at least three out of the eight HGUs reported. Those HGUs are identified as: Janos Aq./Playas Basin, Ascension Aq./Hachita-Moscos Basin, and Las Palmas Aq./Mimbres Basin (Sanchez & Rodriguez, 2021). See Table 1.

Following the geography to the east, and according to Sanchez et al. (2018), there are 14 (from a total of 33) HGUs identified between Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas on the Mexico side, and Texas in the U.S. side, which report good to moderate aquifer potential and good to moderate water quality (see Table 1). The HGUs classified as good to moderate aquifers are the Edwards Aquifer system (predominantly the Upper Salmon Peak, Edwards Fm., Devils River Limestone), Santa Fe del Pino, Serrania de Burro, Presa la Amistad Aquifers, and the bolsons of Valle de Juarez, Mesilla, Red Light Draw, Green River Valley, Presidio, and Redford. Additionally, the Allende-Piedras Negras Aquifer, Austin Fm., the Carrizo Fm/Carrizo Sand, and part of the Carrizo-Wilcox Aquifer are also in this category, as well as the BRB/Gulf Coast (mainly the Catahoula Fm/Catahoula Fm., Reynosa Fm./Goliad Fm. and Lissie Fm.). From a border-wide perspective, the areas of the bolsons southeast of the Hueco-Tularosa Bolson Aquifer in northern Chihuahua and southwestern Texas, and between the Serrania del Burro and Allende-Piedras Negras Aquifers in southern Texas and northern Coahuila, where the Quaternary and Alluvium deposits are concentrated, appear to be the most important for transboundary aquifer potential. Table 1 shows the compilation of Sanchez et al. (2018) and Sanchez & Rodriguez (2021), which lists the total of HGUs in the border region with good to moderate aquifer potential and good to moderate water quality. They are listed by state on each side of the border. Table 1 only includes the HGUs with good to moderate aquifer potential and water quality for prioritization purposes, therefore they are referred to as transboundary aquifers.

Border-wide, the total number of HGUs between Mexico and the U.S. is 72, covering approximate 315,000 km^2 (180,000 km^2 on the U.S. and 135,000 km^2 on the Mexico side). The total HGUs considered to have good to moderate aquifer potential and good to moderate water quality at a border-wide scale is 28 (referred to as TBAs), which covers an area that ranges between 50 to 55% (of which an approximate 60% is on the U.S. side and the rest in the Mexico side). See Figure 1.

If we compare the original 36 aquifers initially reported by Sanchez et al. (2016) and those HGUs categorized as aquifers according to Sanchez et al. (2018) and Sanchez & Rodriguez (2021), results indicate a more mature analysis and assessment of transboundary aquifers across the region. The 28 transboundary aquifer systems (including the 11 officially reported by ISARM in 2015) have been geologically correlated using the same methods and have been categorized using the same criteria. This contribution by itself, represents the first assessment of this scale between the two countries and the first step towards a more border-wide assessment of transboundary aquifer systems and, at the same time, represents the path towards the refinement of physical features and differences across them. It constitutes a well based platform from which future research can build upon at local, regional, or border-wide scale. This methodology can potentially be replicated at other transboundary aquifers in other world regions and adapted according to data availability. Geological and main hydrological features would be a minimum data required to perform a similar analysis.

Binational security considerations

Results of the three publications referenced above (Sanchez et al., 2016, Sanchez et al., 2018, and Sanchez & Rodriguez, 2021) can be summarized in three main points: first, there are 72 HGUs crossing the border between the U.S. and Mexico, from which at least 28 have good to moderate aquifer potential. Second, the area covered by these 28 HGUs (transboundary aquifers) represents approximately 60% of the shareable land between the two countries. Third, these findings represent the most current state of knowledge on the number, delineation, and categorization of all transboundary aquifers in the border region. Although only 11 have been officially recognized by both countries, as mentioned before.

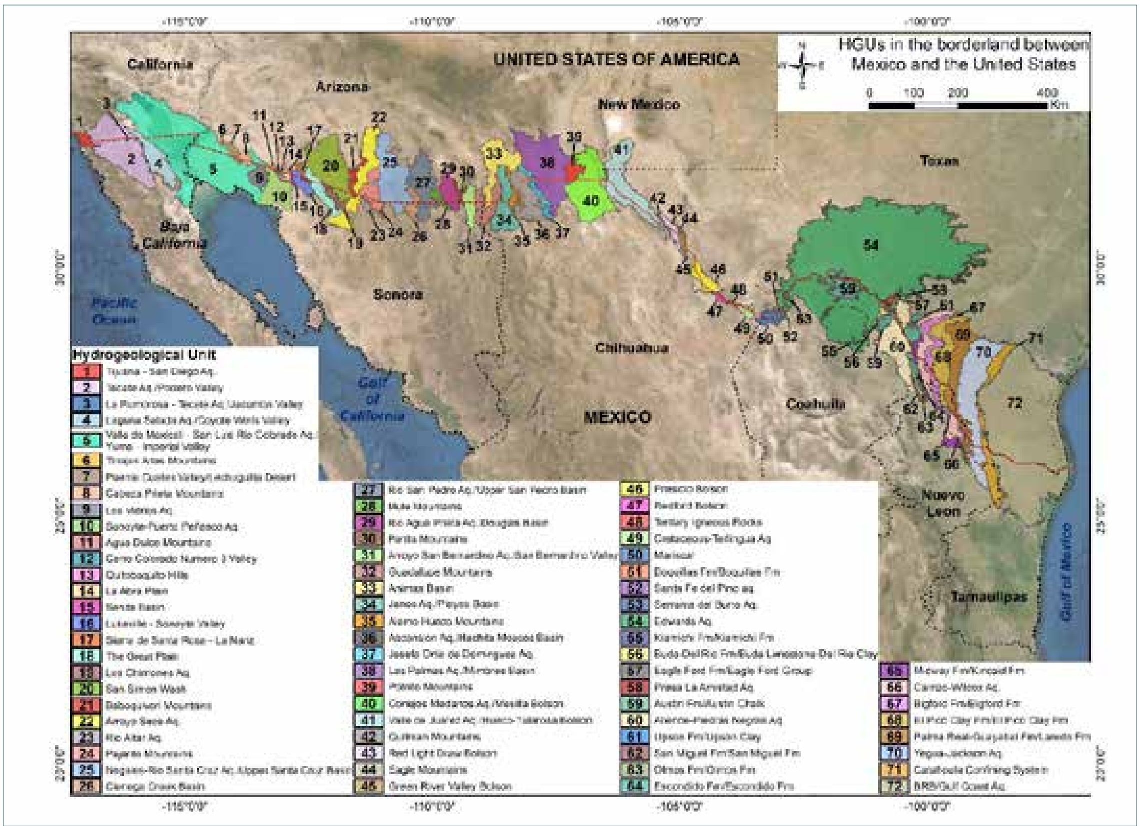
Now, in terms of the implications of this new information to the current legal or policy frameworks in the area, there are several considerations worth mentioning. First, groundwater is rapidly becoming a strategic resource worldwide as surface water becomes scarcer; the Colorado River and Rio Grande binational basins are not the exception. However, the lack of a legal framework that regulates the management of transboundary groundwater resources promotes the unsustainable use and exploitation of the resource. Second, as surface water becomes scarcer in the border, the production of data related to 'new sources' of water such as transboundary aquifers, can potentially speed up the eventual acknowledgment of the strategic value of groundwater at a binational scale.

Table 1.
Transboundary Aquifer (TBA) Systems between Mexico and the U.S.

STATES (MX/U.S.)	TBAs
Baja California/ California	Tijuana-San Diego Aq.
	*Valle de Mexicali-San Luis Rio Colorado/Yuma-Imperial Valley. Laguna Salada Aq./Coyote Wells Valley (Quaternary deposits predominantly)
Sonora/ Arizona	Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin
	Rio San Pedro Aq./Upper San Pedro Basin
	Rio Agua Prieta Aq./Douglas Basin
	Rio Altar Aq.
	La Abra Plain
	*San Simon Wash
	*Sonoyta-Puerto Peñasco Aq.
Chihuahua/New Mexico	Janos Aq./Playas Basin
	Acension Aq./Hachita-Moscos Basin
	Las Palmas Aq./Mimbres Basin
	Potrillo Mountains
Chihuahua/ New Mexico/ Texas	Conejos-Medanos Aq./Mesilla Bolson
Chihuahua/Texas	Valle de Juarez Bolson/Hueco-Tularosa Bolson
	Red Light Draw Bolson
	Green River Valley Bolson
	Presidio Bolson
	Redford Bolson
Coahuila/ Texas	Santa Fe del Pino Aq.
	Serrania del Burro Aq.
	*Edwards Aq. system (predominantly Edwards Fm., Upper Salmon Peak Fm., Devils River Limestone)
	Presa La Amistad Aq.
	*Austin Fm./Austin Chalk
	Allende-Piedras Negras Aq.
Nuevo Leon-Tamaulipas/Texas	Carrizo-Wilcox Aq.
Tamaulipas/Texas	BRB/Gulf Coast Aq. (predominantly Catahoula Fm., Reynosa Fm, Lissie Fm.)
TOTAL	28

(good to moderate aquifer potential and good to regular water quality only).
*Indicates high variability of water quality across the aquifer.

Figure 1.
HGUs in the borderland between Mexico and the United States of America



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Third, Mexico and the U.S. share a water security threat in the border region. Although the sharing concept of a natural resource might sound contradicting to the international principles of sovereignty and self-determination, the conceptualization of a security threat to a border region linked by a natural resource, is really where the pandora box is located. Under the current paradigms of international relations, national security approaches and even water security approaches fail to address the underlying nature of transboundary waters, and more clearly the nature of groundwater resources: the security concern is not conceived nor visualized as a shared threat.

In contrast, the binational water security threat approach is based on recognizing an undisputable sharing condition, into which the security threat operates, but at the same time, the opportunity for cooperation and peace building arises. This recognition can allow for the development of alternative perspectives and strategies to build attention from and prioritization to areas, scopes and issues that might transcend the water topic. This could sound unrealistic in a world ruled by borders and power asymmetries, and we might not be mature enough to invoke it, but at least it offers a potential vision of how nature actually sees and understands water and provides alternative perspectives on the strategic value of our shared waters.

On the optimistic side, this new knowledge along with the recent global trend that focuses on the topic of transboundary aquifers as drivers for peace and cooperation across nations (Walschot and Ribeiro, 2021), can have the potential to elevate the binational conversation into a more formal discussion over shared management of transboundary aquifers.

A more modest expectation is to obtain official recognition by both countries for the existence of at least 28 transboundary aquifers systems in the border region. Additionally, it can help identify priority areas of attention in the short and long term. At the very least, this new research can support the development of subsequent research for more refined case-by-case aquifer conditions and, therefore, more precise local aquifer analysis and assessment approaches.

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TOPIC 3/Paper 17

Hydrogeological Conceptual Model of Transboundary Aquifers with Significant Groundwater Exchange Potential Between Poland and Ukraine

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Abstract

In the Polish-Ukrainian borderland, only the transboundary groundwater reservoir within the Bug River basin has been qualified to the world list of transboundary aquifers (TBAs), published by IGRAC and UNESCO in 2015. As part of the international EU-WATERRES project, the assessment of transboundary groundwater flows and the identification of TBAs had been planned. The aim of this study was to develop a hydrogeological conceptual model of TBAs to assess the dynamics of transboundary groundwater flows in the main usable aquifers between Poland and Ukraine.

For this purpose, two transboundary models were developed: a geological cartographic model, and conceptual hydrogeological model. The cartographic geological model (26.073 km^2) on a scale of 1: 200,000 shows the geological structure of the TBAs area divided into three catchments of the Bug, San and Dniester. The development of this model required harmonization of national stratigraphic nomenclatures and the cross-border determination of the extent of TBAs.

In the conceptual hydrogeological model of TBAs, four transboundary aquifers with high hydraulic conductivity have been identified: 1) alluvial (Qal) aquifer in the valleys of large transboundary rivers; 2) fissure Upper Cretaceous (K2) aquifer commonly occurring within basin of the Bug; 3) local fissure-karst-pore Lower Neogene (N1) aquifer occurring within the south-western border of East European platform and Carpathian Foredeep in the basin of the San; 4) pore Quaternary fluvioglacial (Qf-g) aquifer commonly occurring within basin of the San.

The assumption was made that the model area will be limited to the area where the cross-border connectivity of the main usable aquifers is not disturbed by impermeable barriers to the flow of groundwater, such as draining rivers. Main usable aquifer – is the first usable aquifer from the ground surface, constituting the basic source of water supply. The area identified this way covers the area of approximately 7,150 km^2 and in the catchment division it includes fragments of the catchment areas of the San and Bug rivers in their upper parts. In the Bug basin, the transboundary groundwater flow is directed mainly to Ukraine, while in the San basin - to Poland. The analysis of the individual parameters of the model results showed that more than 1.5 times more groundwater flows from the

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main usable layer from Poland to Ukraine than from Ukraine to Poland. The groundwater balance shows that the groundwater abstraction is negligible and amounts to 3.3% of the TBAs supply, and evapotranspiration in wetlands accounts for approx. 1% of the TBAs recharge. The developed models should lead to more effective joint management of TBAs between Poland and Ukraine.

Keywords: transboundary groundwater flow, hydrodynamic model, hydrogeological databases, joint management

Introduction

Coordinated management of transboundary aquifers (TBAs) is increasingly desirable around the world to minimize adverse transboundary impacts. In addition, due to the increasing global trend of groundwater consumption, the exceeding of sustainable groundwater abstraction in many parts of the world, and to avoid future international disputes and maximize the rational and equitable use of common TBAs, there is a need for an accurate and comprehensive assessment of the development potential of groundwater resources in these layers.

The global identification of TBAs began in 2000 under the coordination of the Internationally Shared Aquifer Resources Management (ISARM) Committee under the UNESCO-IHP International Hydrological Program. According to the results of this assessment, presented by IGRAC (International Groundwater Resources Assessment Center), it is estimated that there are a total of 591 TBAs worldwide, including 72 in Africa, 73 in the Americas, 129 in Asia and Oceania and 317 in Europe (including 226 Transboundary Groundwater Bodies (GWB) as defined in the EU Water Framework Directive).

In the Polish-Ukrainian borderland, only one transboundary groundwater reservoir within the Bug river basin has been qualified to the world list of TBAs (IGRAC, UNESCO, 2015). On the other hand, scientific publications present the premises allowing to justify the hypothesis of the existence of transboundary flows within other catchments apart from the Bug River. Bearing in mind the above statement and the problems related to the intensive extraction of groundwater in the Polish-Ukrainian border zone as a result of mining drainage in the region of Lublin and the Lviv-Volyn Coal Basin, as part of the international EU-WATERRES project, the development of the concept of coordinated management and harmonized monitoring of TBAs was initiated (www.eu-waterres.eu). The aim of this study was to develop a hydrogeological conceptual model of TBAs to assess the dynamics of transboundary groundwater flows in the main usable aquifers between Poland and Ukraine. It should be noted that the TBAs on the Polish-Ukrainian border were the subject of a few studies, all of which were limited by the state border due to the lack of consolidated hydrogeological data between Poland and Ukraine. The above work was initiated in the international project EU-WATERRES (Solovey et al., 2021). In this study, the first comprehensive TBAs study was conducted in the scope of:

Creation of a uniform geological model of TBAs.

The unified model of the geological structure is the first element of an integrated picture of the structure of the aquifer and is a prerequisite for any hydrogeological research.

Development of a conceptual hydrogeological model of TBAs.

A conceptual hydrogeological model is a descriptive and graphical representation of the structure and processes occurring in an aquifer, including contacts with the environment.

Study area

The region of the Polish-Ukrainian borderland is located in the south-eastern part of Poland and the north-western part of Ukraine within the river basins of the Bug, San and Dniester (Fig. 1).

Fig. 1.
Polish-Ukrainian transboundary part of the Bug, San and Dniester River basins

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According to the geographical division, the research area is located on the border of two megaregions - the East European Lowlands and the Carpathian Region. The annual sums of precipitation in the last forty years ranged from 500 mm in the Lowlands to 930 mm in the area of the Outer Carpathians. Field evaporation ranges from 450 mm/y to 520 mm/y (Lorenc, 2005). In the northern part, which is within Polessye, plains dominate and there are many wetlands and lakes here. The largest geomorphological structure is the Bug River valley, up to 4 km wide and 20-30 m deep with distinct terraced levels. The central part of the research area is located in the area of the Volyn Uplands and Roztocze. Its characteristic feature is the alternating occurrence of hills and extensive depressions and valleys. In the south of the area - within the catchment area of the San and Dniester rivers, uplands turn into the Outer Flysch Carpathians.

The hydrography of the region includes the transboundary rivers Bug, San and Dniester with their tributaries and the famous Shatsky lake complex with more than 30 lakes, belonging to the Ramsar protected areas. The Bug and San basins belong to the Baltic Sea basin, while the Dniester basin belongs to the Black Sea.

The geological conditions in the study area are highly diversified due to the presence of three geostructures in the contact zone - the East European Platform (in the north), Carpathian Foredeep (in the center) and the Outer Carpathians (in the south). Within the platform, the cover is formed by Ediacaran, Cambrian, Silurian and Devonian deposits, on which the Carboniferous deposits lie inconsistently. They are covered with Jurassic and Upper Cretaceous sediments and are locally covered by Neogene and Paleogene deposits. Carpathian Foredeep is a young geological structure, constituting a fragment of the Carpathian foreland ditch filled with Miocene molasses (Lower Miocene - Sarmatian). The Outer Carpathians are characterized by presence of flysch on the surface. Their stratigraphic profiles in this region include the Upper Cretaceous, Palaeogene and the lowest Neogene layers. Quaternary cover occurs on the surface of the area in most of the study area.

Methods

The identification and definition of transboundary aquifers began with the harmonization of geological and hydrogeological spatial data between Ukraine and Poland to obtain unified units. The key data are: the spatial variability of aquifer properties, the mapping of the hydroisohypsum and the thickness of the aquifers with an accuracy at least appropriate for a map on a scale of 1: 50,000. The creation of unified maps of the distribution of the above hydrogeological characteristics required the unification of maps supporting the analysis - lithostratigraphic, hydrographic, geomorphological. The definition of the transboundary nature of aquifers was based on hydrogeological cross-sections. On their basis, the lateral extent and vertical structure of aquifers and impermeable layers were determined. Moreover, based on the groundwater level change at observation points, the ways of groundwater flow and the directions of infiltration through hardly permeable layers were interpreted.

The methodology used to develop a conceptual hydrogeological model was based on defining the main components of the structure and processes of the aquifer (Michalak et al., 2011).

Apart from the above maps, the basis for the identification of the model were:

- series of measurements of groundwater levels in 57 monitoring wells (Baza danych, 2019c);
- hydrogeological profiles from 2926 boreholes (Baza danych, 2019a; Fedoseev, 1994);
- hydrogeological measurements in 20 hydrometric stations;
- meteorological data from 10 observation stations;
- documentation of ca. 200 groundwater intakes (Baza danych, 2019b).

Hydrogeological setting

The transboundary part of the Bug basin

The Bug area lies within the East European Platform and is characterized by a significant diversity of the Palaeozoic tectonics. The lowland part of Polessye falls within the Kumów high plain while the upland part - into the Włodawa-Lviv basin (in Ukraine is known as Lviv-Lublin depression).

Within the elevation, on the Proterozoic structures there are Jurassic and Cretaceous deposits and a thin Cenozoic cover. In the depression part, the platform cover is formed by Ediacaran, Cambrian, Silurian and Devonian deposits, on which the Carboniferous deposits lie inconsistently (Paczyński & Sadurski, 2007). They are covered with Jurassic and Upper Cretaceous sediments. Paleogene and Neogen deposits are distributed locally within Roztocze (Fig. 2).

Fig. 2.
Geological map of transboundary part of the Bug river basin

(developed on the basis of State Geological Map of Ukraine (2005) and Szczegółowa Mapa Geologiczna Polski (2019)) (© Open access Maps, Own Elaboration)

The Upper Cretaceous formations outcrop usually on hills and are formed of carbonate and carbonate-silica-clay sediments (marl and writing chalk, occasionally carbonate-silica rock, spongiolites) of the Upper Maastrichtian and Campanian (in the marginal north-eastern part of the basin). The thickness of the Upper Cretaceous carbonate complex reaches 500-700 m.

In most of the Bug area, there is a Quaternary cover on the surface. In the drainage depressions, it is formed of organic formations, in watershed areas - glacial sediments as well as limnic and limnoglacial, glacial muds, in river valleys - sands, gravel, and flooding silts. Eolian sediments are present on the hills (Fig. 2). The thickness of the Quaternary cover is usually 2-10 m, only in the valleys of larger rivers the series of limnic and fluvioglacial sediments reaches 30 m.

In the Bug area *the Upper Cretaceous aquifer* is the main usable one, which is common in Upper Cretaceous sediments. Here this aquifer is used for water supply of large settlements. Within Poland, the aquifer is usually unconfined, in Ukraine, it is mainly confined. The recharge takes place particularly in the elevated areas of Upper Cretaceous sediments outcrops. The main discharge base is the Bug River and its tributaries. The thickness of the aquifer is from the first tens of meters to 100-150 m (within tectonic zones and river valleys). The depth of the groundwater table is set at +1.5-10 m in river valleys, up to 20-40 m - in watersheds (Kamzist & Shevchenko, 2009).

Alluvial Quaternary aquifer is associated with alluvial sandy sediments of river valleys. It is unconfined, up to 15-20 m thick. Waters of this aquifer usually remain in a hydraulic contact with the Upper Cretaceous aquifer.

The Quaternary fluvioglacial aquifer is distributed locally In the Polessye part of the Bug area in sandy formations with a thickness of 5-10 m. It is unconfined, the depth of occurrence is 0-15 m.

Also, within the study region there are several aquifers in Quaternary sediments weakly saturated with water.

The transboundary part of the San basin

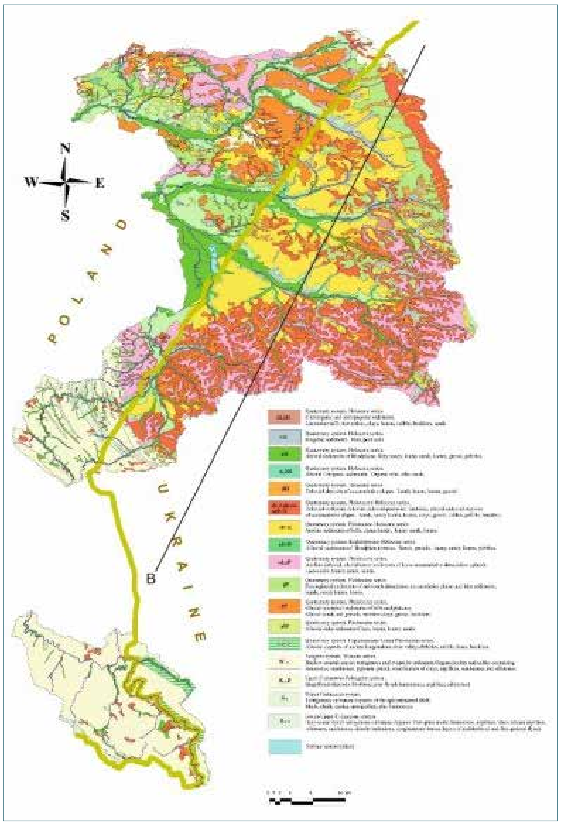
The northern part of the San area is located in Roztocze and the central and southern parts - in the Carpathian region. The Roztocze part of reservoir belongs to the coastal basin, the central part - to the Carpathian Foredeep basin, and the southern part - to the Outer Carpathians.

The Roztocze hills are formed by sands, gypsum and calcareous-lithotamous formations of Lower-Middle Badenian. Upper Cretaceous deposits are widespread (mainly in Poland) in river valleys (Fig. 3).

In the Carpathian Foredeep, the Miocene limestone sediments are covered by a thick layer (up to 3,000 m) of Sarmatian deposits (clays, loams, silts and fine-grained sands). The southern part of the San area (Outer Carpathians) is formed of flysch deposits.

The vast majority of the San area (over 90%) is covered by Quaternary formations of different origin and composition (alluvial, eluvial, diluvial, glacial sediments).

Fig. 3.
Geological map of transboundary part of the San River basin



(developed on the basis of State Geological Map of Ukraine (2005), State Geological Map of Ukraine (2003) and Szczegółowa Mapa Geologiczna Polski (2019)) (© Open access Maps, Own Elaboration)

Upper Cretaceous aquifer in Roztocze is spread mainly in the Polish part of the area. It is fissure reservoir in the carbonate formations and is most often unconfined. The average thickness of the aquifer is 100 m, the averaged filtration coefficient – 3.7 m/d, the well capacity ranges from <10 to 120 m^3/h.

Within the Ukraine part, *the Lower Neogene aquifer* is useable (the main aquifer of the western water intakes of Lviv). The aquifer is firmed by sandy sediments, sandstones, gypsum and calcareous-lithotamous N1b1-2 formations.

The Lower Neogene aquifer recharges in the Roztocze region and discharges in the San River. The waters of the Lower Neogene and Upper Cretaceous aquifers are often in hydraulic contact. The aquifer is mainly confined (drilled at a depth of 11.0 - 46.0 m, the potentiometric surface was at a depth of 5.0-13.0 m below the surface). In Ukraine this aquifer layer is used for balneological purposes.

Quaternary alluvial aquifer is associated with river sediments of the San valley and its tributaries, as well as hydro-glacial formations and sediments (gravel and sand) of old buried structures (the San and Lubaczówka proglacial valleys). The thickness of aquifer in the San valley (the Polish part) is up to 20 meters. The best conditions for infiltration occur within the Holocene terraces of San, Szkło and Lubaczówka, where deposits with high permeability are present. The aquifer is mainly unconfined. The filtration coefficient is usually in the range of 10-30 m/d.

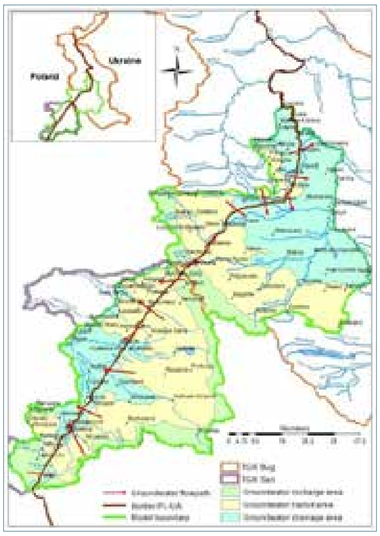
The *Quaternary fluvioglacial aquifer* is mostly useable in the Polish part of the area. The aquifer is associated with fluvioglacial sediments of denudation-accumulation plains and lakes (sand, sandy loams). The thickness of aquifer is 5-8 m, occasionally up to 10-12 m. The aquifer is mostly unconfined, weakly water saturated. The wells capacity is 2-6 m^3/h.

Conceptual hydrogeological model

The developed conceptual model includes the defined boundaries of the transboundary aquifer, separated aquifers and insulating layers, their hydrogeological parameters and an estimated water balance.

The originally assumed model boundaries (Fig. 1) within three catchments - Bug, San and Dniester (26,073 km^2) were narrowed during the analyzes to the area of approx. 7,150 km^2. The reduction of the research area was dictated by the limitation to the area of transboundary layers with a significant potential for groundwater exchange. According to the indicator adopted in this respect - water conductivity of the aquifer, the selection of the appropriate layers was carried out on the basis of the criterion of ^{3} 50 m^2/d. As a result, the Dniester catchment area, the northern and eastern (right-bank) parts of the Bug catchment area and the southern - mountain part of the San catchment area were completely excluded. By separating the aquifer system, efforts were also made to create a situation in which the boundary surface would refer to the hydrodynamic zones that would facilitate the formulation of the boundary conditions. From the north to the east, the border runs along the Bug riverbed to its source. In the south, the boundary surface runs along the European Watershed, the watershed between the Black Sea basin and the Baltic Sea basin. The western border runs perpendicular to the hydroizohips system. The range of the model is shown in Figure 4.

Fig. 4.
Hydrodynamic zones in the model area



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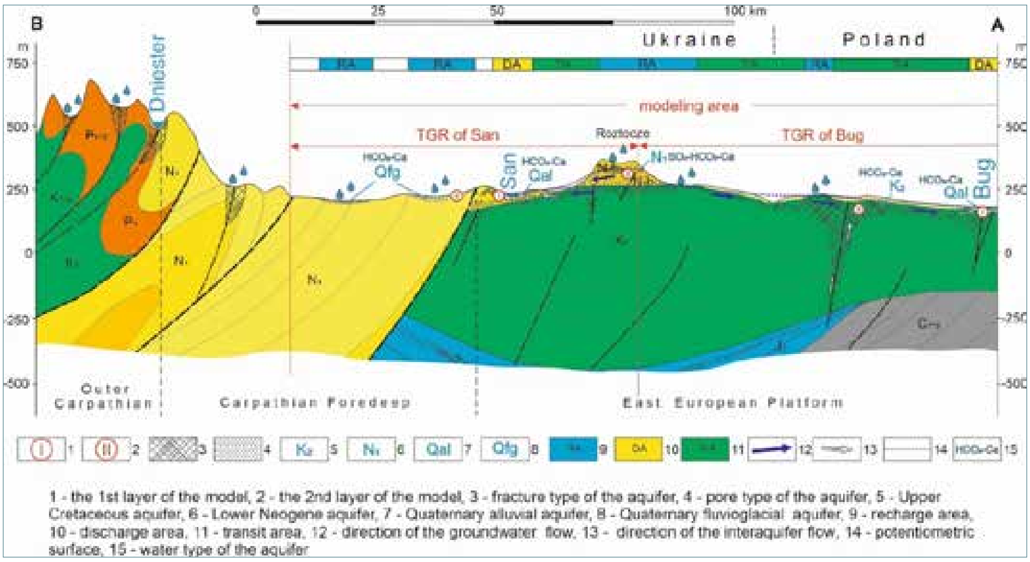
As a result of the schematization of the hydrogeological conditions, it was determined that in the research area, in the active exchange zone, there are two functional water-bearing layers that are often hydraulically connected through semi-permeable formations (Fig. 5):

1. *1st layer* – alluvial (Qal) aquifer in the valleys of large rivers;
2. *2nd layer* is spatially heterogeneous. In the north within the East European platform, it is the Upper Cretaceous (K2) fissure aquifer, in the central part within the south-western border of East European platform and Carpathian Foredeep - the Lower Neogene (N1) fissure-karst-pore aquifer, and in the south within the inner part of Carpathian Foredeep - the Quaternary (Qf-g) pore aquifer.

Fig. 5.
Hydrogeological cross-section of the Bug-San TGR located along the PL-UA border from the south (B axis) to the north (A axis)



Location of the cross-section is shown on Fig. 2-3. (©Own Elaboration)

The 1st layer is in direct contact with the surface water. This layer is recharged mainly by filtration, locally by infiltration of surface waters. The floor of the 2nd layer is confined. The developed conceptual hydrogeological model is therefore a two-layer model. Groundwater generally moves towards the San and Bug rivers, which are the main drainage basis, and locally towards their main tributaries.

The separated water-bearing system is characterized by heterogeneity resulting from the diversified origin of sediments.

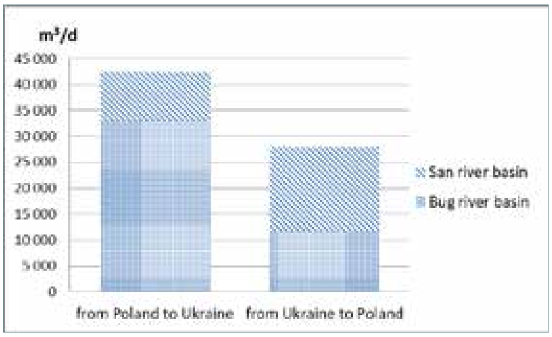
1. The 1st layer is formed of various types of alluvial sand and gravel, therefore the aquifer has good permeability (the filtration coefficient Kf is 0.022-1.7 m/h). As a rule, these are the formations not covered with impermeable sediments, so the aquifer is unconfined. The average thickness of Qal aquifer is 5 m, rarely exceeding 30 m.
2. The 2nd layer - K2 aquifer is of fracture type with generally unconfined groundwater table type in Poland and the confined one in Ukraine. It is built mainly of marls, limestones and chalk. The bottom of the active water exchange zone is located at a depth of 100-150 m below ground level.
3. The 2nd layer - N1 aquifer combines hydrodynamically connected N1b1 and N1b2 water-bearing layers (limestones, sandstones, sands, gypsum). It is a fissure-karst-pore reservoir with a confined groundwater table. Its top is at a depth of 5 to 50 m below ground level. The thickness of the N1 aquifer is approximately 10-40 meters.
4. The 2nd layer - Qf-g aquifer is common in the local and shallow (approx. 2-20 m thick) level of fluvioglacial formations, serving as a usable aquifer in the Carpathian Foredeep on accumulation plains and in river valleys. It is an unconfined groundwater table pore aquifer.

In the concept of the water balance, it was assumed that its positive side consists of infiltration recharge (from precipitation and rivers). The recharge distribution related to the infiltration capacity of surface formations was developed on the basis of the created uniform geological model of the TBAs. The amount of recharge ranges from 0-0.0009 $m^3/d/m^2$, reaching maximum values on the accumulation plains in the San catchment area.

The positive side of the water balance is balanced by three main negative components: evapotranspiration, runoff and groundwater abstraction. The outflow of groundwater from the research area is about 1.5 million m^3/d in total. The average daily intensity of groundwater drainage through water intake is at the level of 46 thousand m^3/d and accounts for 3.3% of the recharge of the TBAs.

The components of the groundwater budget were estimated at the border between Poland and Ukraine, with the aim of assessing the transboundary flows. The total amount of groundwater outflow from Poland to Ukraine is 42,350 m^3/d, 78% of which is in the catchment area of the Bug and 22% of the San (Fig.6). On the other hand, the inflow to Poland from Ukraine amounts to 27,924 m^3/d, 42% of which is in the catchment area of the Bug and 58% - of the San. The highest flow intensity is observed within the transit zone.

**Fig. 6.
Transboundary groundwater flow**



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The developed conceptual model of groundwater flow in transboundary aquifers has some implications for groundwater management. On the basis of the model, the Bug-San transboundary groundwater reservoir (TGR) was determined, the resources of which should be shared internationally. The Bug-San TGR is generally characterized by two transboundary streams flowing from the Roztocze recharge area - the hill embankment running across the PL-UA border. The first stream heads northeast to the Bug River, the second - southwest to the San River. Therefore, it seems right to consider the implementation of joint management of these groundwater resources between Poland and Ukraine.

The Bug-San TGR conceptual model allowed for the determination of appropriate management units and, supported by the numerical model, will enable the formulation of a proposal for an optimal international division of groundwater.

The relevant units for the management of the Bug-San TGR would be the two new cross-border groundwater bodies (GWB), defined on the basis of the boundaries of the conceptual model created:

- Transboundary Bug GWB – northern part of the model area within the Bug catchment;
- Transboundary San GWB – southern part of the model area within the San catchment.

Groundwater abstraction in the indicated areas will have a significant transboundary impact. Therefore, it is necessary to consider the flow system in them as a whole to assess the sustainability of water exploitation in the Bug-San TGR.

Conclusion

A conceptual model of the regional groundwater flow system involving transboundary aquifers (TBAs) in the Bug-San river basin was developed to identify the structure of the aquifer and its processes. The results of this study contribute to the understanding of regional groundwater flow systems and provide concrete data on the sustainable exploitation conditions of the Bug-San TGR.

The proposed two-layer structure of the aquifer system allows for a comprehensive assessment of transboundary flows. This flow was found to occur in four transboundary aquifers: 1) alluvial (Qal) aquifer in the valleys of large transboundary rivers; 2) fissure Upper Cretaceous (K2) aquifer commonly occurring within basin of the Bug; 3) fissure-karst-pore Lower Neogene (N1) aquifer occurring locally within the south-western border of East European platform and Carpathian Foredeep in the basin of the San; 4) pore Quaternary fluvioglacial (Qf-g) aquifer commonly occurring within basin of the San.

The analysis of the individual parameters of the model results showed that more than 1.5 times more groundwater flows from the main usable layer from Poland to Ukraine than from Ukraine to Poland. The groundwater balance shows that the uptake of groundwater is negligible and amounts to 3.3% of the TBAs recharge, and evapotranspiration in wetlands accounts for approximately 1% of the TBAs recharge.

The conceptual model of TBAs also justifies the international management strategy of the Bug-San TGR, especially in the Roztocze area - cross-border elevations.

The conceptual model of TBAs together with the unified geological model will form the basis for the future development of a numerical model of transboundary groundwater flows.

The numerical model will be used to test the conceptual model and will serve as a tool for joint management of groundwater resources between Poland and Ukraine for the sustainable use of resources and the maintenance of the good status of water-dependent ecosystems.

Acknowledgements

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TOPIC 3/Paper 18

Multiscale Approach for Mapping Surface and Groundwater in the Lake Chad Basin

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Abstract

Chad is particularly vulnerable to climate change, while experiencing a strong demographic growth. These factors, combined to the lack of efficient water management policies and the poor knowledge about water resources and aquifer systems, increase the vulnerability of the population and hinders the socio-economic development. The ResEau programme, designed in the framework of the bilateral cooperation between Chad and Switzerland, aims at improving the country's resilience to climate change effects by acquiring knowledge on surface and groundwater through mapping, while building the capacity at a national level and promoting an active management of its water resources.

To understand surface and groundwater interactions in a region covering several million km², often inaccessible and barely monitored from the hydrological and hydrogeological point of view, it is essential to operate at different spatio-temporal scales. The proposed methodology consists of three components, including (i) the collection of hydrogeological/geological data in the field, and the generation of spatio-temporal products gained from satellite data processing, (ii) the mapping of surface lithology and geological structures by taking advantage of the synergistic and multi-scale use of satellite based products, and (iii) the generation of hydrogeological maps, including estimation of groundwater potential in the basement aquifers of Eastern Chad, and the assessment of groundwater dynamics in the Quaternary aquifer of N'Djamena. Groundwater potential maps are produced by establishing associations between explanatory variables and known groundwater through Machine Learning (ML) technique. Groundwater dynamics maps are generated by considering monthly groundwater measurements and ground surface deformations inferred from differential Synthetic Aperture Radar (SAR) interferometry and 3D geological modelling.

This work also shows how remote sensing contributes to produce hydrogeological information when used in a synergistic way with other data sources. Three products examples obtained within the sedimentary and crystalline environments of the Central and Eastern Chad are presented.

Keywords: Hydrogeological maps, remote sensing, Machine Learning

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Introduction

The area currently covered by ResEau (http://reseau-tchad.org/) is located in the East and Centre of Chad. It is characterised by a large population settled in regions where water needs are important and access to water is sometimes limited.

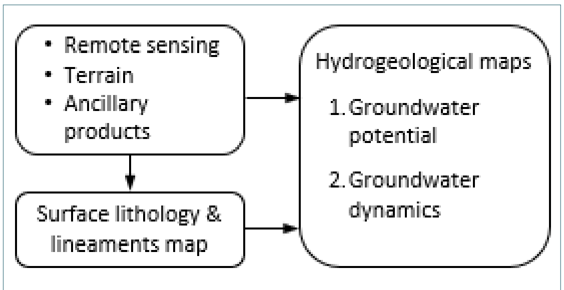
In hydrogeological terms, the area is composed of discontinuous aquifers in the Precambrian basement in the East, and the generalized Lake Chad basin aquifer system in the Centre. In crystalline domains (e.g. Abéché), geological aspects and limited rainfall constrain groundwater occurrence. In the center (e.g. N'Djamena), the high population density and rate of demographic growth produce a constant increase of water resources exploitation. In addition, the capital city N'Djamena repeatedly experiences flood events increasing the risk of groundwater contamination with possible effects on the population health.

The main objective of ResEau, issued by the partnership of the Chadian and Swiss governments, is to map surface and groundwater resources at country level, while building the local capacity and promoting an active management of its water resources. The adopted scale and approach depend on the problem, environment, and data availability. For the crystalline domain, a ML method is used to identify areas of high groundwater potential. For N'Djamena, ground-water dynamics is analyzed by considering monthly hydrogeological surveys, ground surface deformations, and 3D geological modelling. Along with these developments, maps become the tool to communicate between different stakeholders through the involvement of beneficiaries, governmental, non-governmental agents and academic researchers from data collection and analysis to cartographic rendering and hydrogeologic interpretation.

Methodology

The methodology is illustrated in Figure 1.

Figure 1.
The three components



It consists of three components: the first two comprise the generation of essential static and seasonal products, which, in turn, are used to produce hydrogeological maps for the specific environments.

Remote sensing, terrain, and ancillary products

To understand surface and groundwater interactions in a region covering several million km², it is essential to operate at different spatio-temporal scales. For this purpose, products from diverse sources are generated and exploited.

Satellite products

Multi-temporal Landsat-8 and Sentinel-2 optical, and Sentinel-1 SAR data are used to generate seasonal (October-May and June-September) products. For this end, a customized software solution is employed to process time-series and to exploit the synergistic use of the various data sets. The main products are land cover (sparse and dense vegetation, bare soil, agriculture, rangeland, surface water, water pond, settlement, rocky area) and soil moisture; for the dry season only, a Landsat-8 Sultan lithological product (Sultan et al., 1987) is produced. In addition, for the specific environment of N'Djamena, a subsidence map is generated through a multi-temporal interferometric technique, the Small BAseline Subset (SBAS) using Sentinel-1 ascending and descending data.

Monthly and seasonal rates of precipitation, temperature, and evapotranspiration are derived from daily Meteosat Second Generation (MSG) TAMSAT.

Slope, river network, catchment area, distance to major channels, Topographic Wetness Index (TWI), and Topographic Position Index (TPI) are derived from GLO-30 Digital Elevation Model, an enhanced DEM based on the integration of different public domain remote sensing DEMs.

Terrain products

It consists of piezometric measurements (monthly/seasonal) of existing boreholes/wells and geological surveys.

Ancillary products

It includes data collected from other works, among others, lithostratigraphic logs.

Surface lithology and geological structures

Mapping of surface lithology and geological structures is indispensable for the delineation of groundwater potential zones. For this purpose, it is required to operate (a) at regional scale to identify the landscape units and sedimentary processes; (b) at larger scale to determine the surface lithology and lineaments within each unit. In terms of data processing, this is realized by applying the hierarchical image representations multi-source approach proposed by Cui et at. (2017), where the object content is optimized through the synergistic use of multi-scale data.

Landscape units and sedimentary processes (a) characterised by the same geomorphic features and roughness are derived from topographic data. These units are subsequently categorized in terms of surface lithology by using Landsat-8 Sultan lithological product, and seasonal land covers (b).

Faults and fractures are derived from GLO-30 DEM. This is achieved by assessing the most frequent tectonic azimuth, and, thereafter, generating an optimum DEM shading (Akram et al., 2019). Tectonic lineaments and fractured zones are extracted by exploiting specific contours and lines detection algorithms on the shaded DEM.

For the assignment of the appropriate lithological units and verification of the tectonic lineaments and fractured zones, geological/hydrogeological surveys and related local knowledge are required. The available lithostratigraphic logs are used to complete and verify the final map.

Hydrogeological maps

Groundwater potential

Martínez-Santos and Renard (2019) propose to use Machine Learning techniques to find combinations of explanatory variables to produce a groundwater potential map. Prerequisite is the availability of geolocated water points and the categorization in positive or negative based on water availability. MLMapper uses a selection of ML algorithms providing a series of hydrogeological potential maps. This is achieved by training ML algorithms with 60% of the verified boreholes/wells, while the remaining 40% are utilized to test the result by scoring. The maps with the highest scoring are retained and the consistency of the different potential maps is assessed on the basis of the local knowledge. A hydro-geological potential map is subsequently generated for the reference area. Once validated, the explanatory variables and related algorithm are then applied to a larger area within the same landscape, hence enabling to produce a hydrogeological potential map where boreholes/wells are absent or inaccessible.

Groundwater dynamics

To assess groundwater resources in the urban environment of N'Djamena, monthly piezometric measurements, selected satellite products (such as land subsidence, surface lithology, land cover/change map, and daily precipitations), and 3D ground modelling are used.

Ground surface deformations are derived by exploiting the SBAS approach retrieved from Sentinel-1 data over the period October 2016 to June 2021. The evolution of displacements is calculated with respect to the first acquisition over the analysed period, and the deformations – which describe and quantify soil compaction – are projected along the vertical direction.

Lithological descriptions from 93 borehole logs ranging in depth from 25m to 80m are simplified into four lithological classes: clay, sandy clay, sand, and clayey sand which are used to construct a 3D geological model using RockWorks 2020. For the topographic surface, GLO-30 DEM is utilized. Interpolations of strata's upper and lower limits are performed by the lateral-blending method.

Map Examples

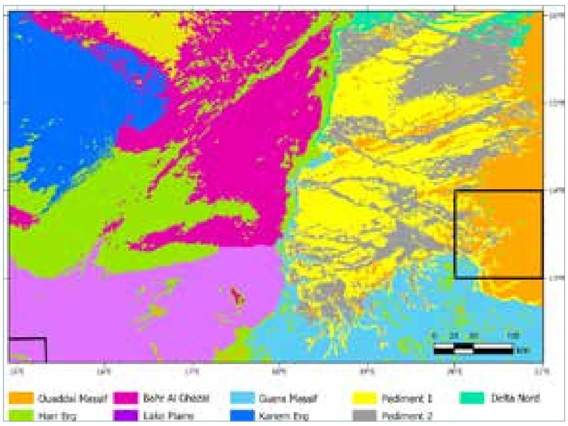
Surface lithology and geological structures in Lake Chad basin

Within the sedimentary cover of the Lake Chad basin formations, certain morphological features of the sedimentary systems can be indicators of groundwater availability. Moreover, geological structures such as faults and dykes play a crucial role on groundwater flow-paths in the basement area.

Geomorphic and roughness features along with the Mega Lake Chad level 325 masl (the maximum elevation in the Holocene) are derived from GLO-30 DEM to delineate the landscape units, as illustrated in Figure 2. For each unit, an analysis of the elevation, as proposed by Davis and DeWiest (1966) is performed. This allows to assess the erosion/deposition environments, hence the landform, and to refine the unit itself.

It should be stressed that most of existing public domain DEMs are not suitable for the purpose of this work, mainly due to major artifacts and/or elevation errors precluding the generation of reliable morphological and structural information.

Figure 2.
Landscape units at regional scale. The boxes represent N'Djamena (left) and Abéché (right)



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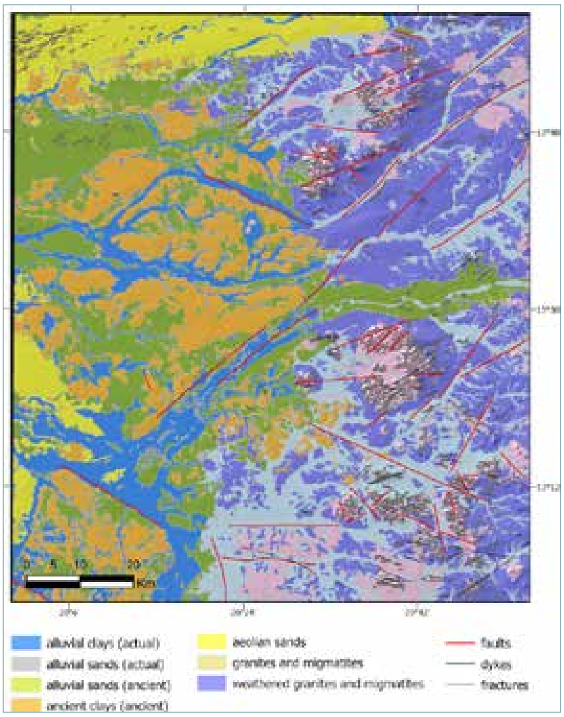
The landscape units are afterwards used to characterize the sedimentary deposition and, when coupled with the Landsat-8 Sultan product and the seasonal land cover, the surface lithology. To properly characterize the lithological map of the basement region of Abéché derived from Landsat-8 Sultan product, 88 sites are visited during a geological/ hydrogeological survey over an area of 27,000 km^2. In addition, the availability of 37 lithostratigraphic logs in Abéché shows that the surface lithology map accuracy is 97%, encouraging performance for the classification of areas with similar characteristics.

Geological structures derived from GLO-30 DEM following the methodology described in Section 2.2 are visited for validation as well. It is worth mentioning that, while the automatic generation of lineaments is well performing in outcrops, geological knowledge/interpretation is necessary for major visible or buried tectonic lineaments.

Figure 3 illustrates the resulting lithological and structural map for the region of Abéché.

Figure 3.
Surface lithology and geological structures map of Abéché



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Groundwater potential in basement aquifer

For the crystalline region of the Eastern Lake Chad Basin where groundwater is the primary source for drinking, agriculture and pastoral uses, geological aspects and limited rainfall constrain its occurrence. For this critical region, a groundwater potential map is therefore crucial to identify suitable areas where wells should be constructed.

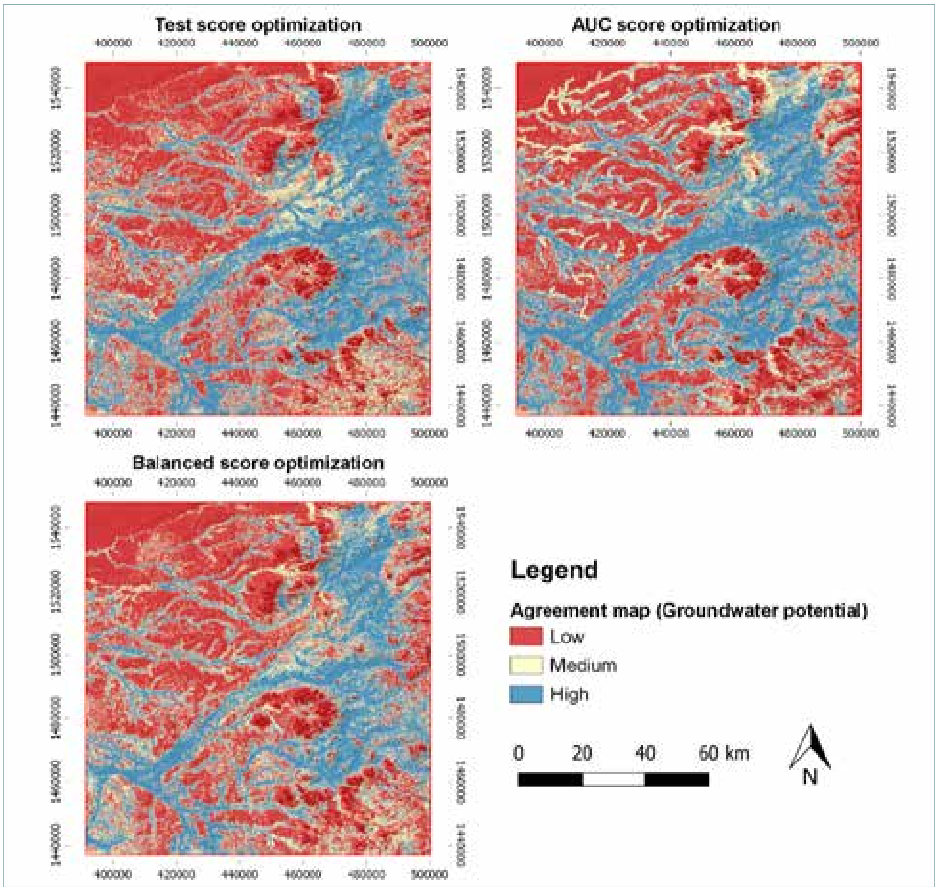
A selection of explanatory variables, identified from a thorough survey of literature (Díaz-Alcaide and Martínez-Santos, 2019), are derived from satellite-based products and field measurements. These include surface lithology and geological structures, slope, TWI, distance to major channels, land cover, seasonal vegetation and moisture indices, SAR coherence, precipitation, and groundwater depths. Twenty supervised classification algorithms are trained to establish meaningful associations between the selected variables and 60% of the existing 488 boreholes/wells in this region.

Algorithm performance is assessed as per several metrics. In this case, these include Area Under the Curve (AUC) scores, test scores and balanced score metrics. Random Forest (RF) and Extra Tree (ET) classifiers show a better performance than the other algorithms, with AUC in excess of 0.87 and test scores in excess of 0.80. Figure 4 shows the outcomes of the ensemble map for test score, AUC and balanced score as optimization metrics. Fracture density, slope, SAR coherence, TWI, basement depth, distance to ephemeral channels, and slope aspect are identified as the most significant explanatory variables, although the algorithms also relied on variables such as precipitation, the interpolated hydraulic heads and saturated thickness, among others.

From a hydrogeological perspective, the maps show higher groundwater potentials within the wadi's alluvial systems and in the piedmonts area, while basement outcrops and the areas around surface water divides within the sedimentary sector are characterized by a lower groundwater potential.

From a methodological standpoint, this first ML attempt highlights the advantages of using a large number of supervised classification methods in order to identify the best performers. Prerequisite is the availability of precisely geolocated water points, the categorization into positive or negative based on water availability, and a large set of explanatory variables, static as well as dynamic/seasonal. Once validated, the most significate explanatory variables and best performers algorithms are used to predict the potential groundwater of neighboring regions where groundwater conditions are expected to be similar.

Figure 4.
Groundwater potential maps of Abéché. The maps represent the ensemble mean of the two best-performing algorithms, i.e., RF and ET



The top left map shows the result obtained when maximizing test score, while the top right one illustrates the result of maximizing AUC scores. The bottom map represents the optimization of the balanced score metric. Pixel scores are computed as the simple arithmetic mean between the ETC and RFC outcomes. Blue pixels mean that both algorithms agreed on a positive groundwater potential (arithmetic mean = 1). Conversely, red zones represent those pixels where both algorithms agreed on a negative groundwater potential (0). Yellow represents disagreement between RFC and ETC outcomes (0.5). (©Own Elaboration)

Groundwater dynamics in Quaternary aquifer

N'Djamena experiences constant increase of water resources exploitation due to high population and urban growth. In addition, the city rises at the confluence of the Chari-Logone rivers and, in the recent years, has repeatedly experienced flood events increasing the risk of groundwater contamination. Understanding groundwater dynamics in this urban context is particularly beneficial to improve the water resource management in this sensitive environment.

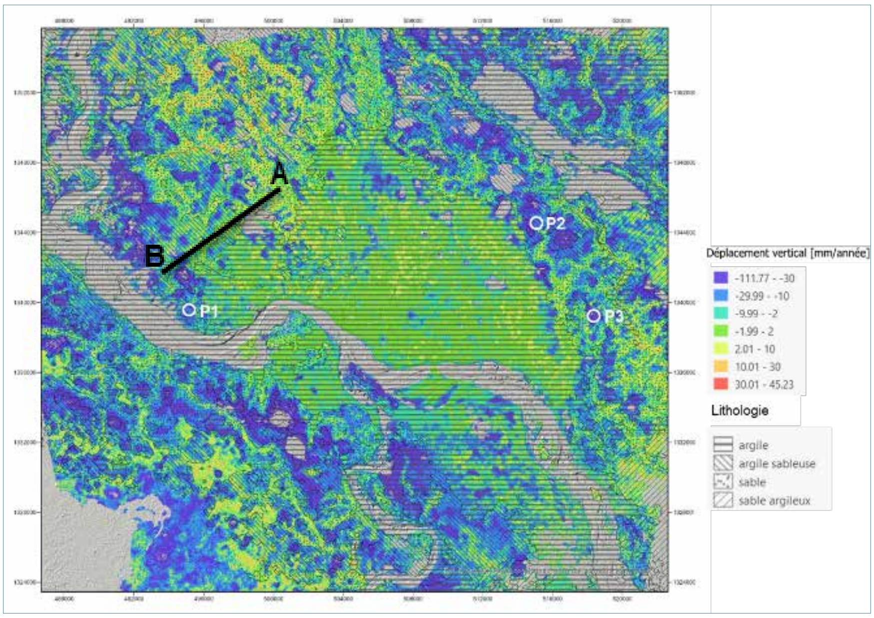
Groundwater dynamics is analysed and assessed by means of monthly piezometric measurements coupled to multi-temporal differential SAR interferometry. Moreover, surface lithology and the available 93 stratigraphic boreholes logs are used to develop a 3D model of the Quaternary aquifer layers, the most exploited aquifer of the city.

Monthly ground surveys are carried out to gather periodical measurements of the groundwater level, define the groundwater flow (direction, gradients) and its dynamics. This allows to identify possible seasonal behaviour and correlation with the stratigraphy. The groundwater surveys show a minimum groundwater level in June and a maximum in November, with a maximum variation of approximately 6m, close to the river. These periodical measurements confirm that the water levels of the Chari-Logone River assure a continuous hydraulic load throughout the year, resulting in a north-northeast flow direction. Moreover, they demonstrate that the effect of direct recharge from the river is not detectable beyond a few kilometres from the shorelines.

Figure 5 presents the mean rate of vertical deformation referred to the period October 2016 – June 2021 and the surface lithologies, obtained according to the methodology described in Section 2.1.1. The light blue, blue and purple areas are compacting with a deformation rate up to 110 mm/year, while green areas are stable.

The subsidence map shows that the area of the city centre is not affected by vertical deformation, although corresponding to the areas of highest groundwater extraction. The areas most affected by deformation are mainly located outside the urban area, often in correspondence to clay surfaces or lithologies having a clay component (clay sand, sandy clay). These areas are also the most prone to temporary surface water coverage during the rainy season. Inversely, the city centre benefits of a network of canals allowing the evacuation of surface water. In essence, the observed vertical deformation in N'Djamena and its surroundings is strongly related to surface water management and lithological properties of the surface.

Figure 5.
SBAS land subsidence map generated from Sentinel-1 data. The map shows the mean rate of vertical deformations, shown in light blue, blue and purple, while green areas are stable. For the segment AB, refer to Figure 6



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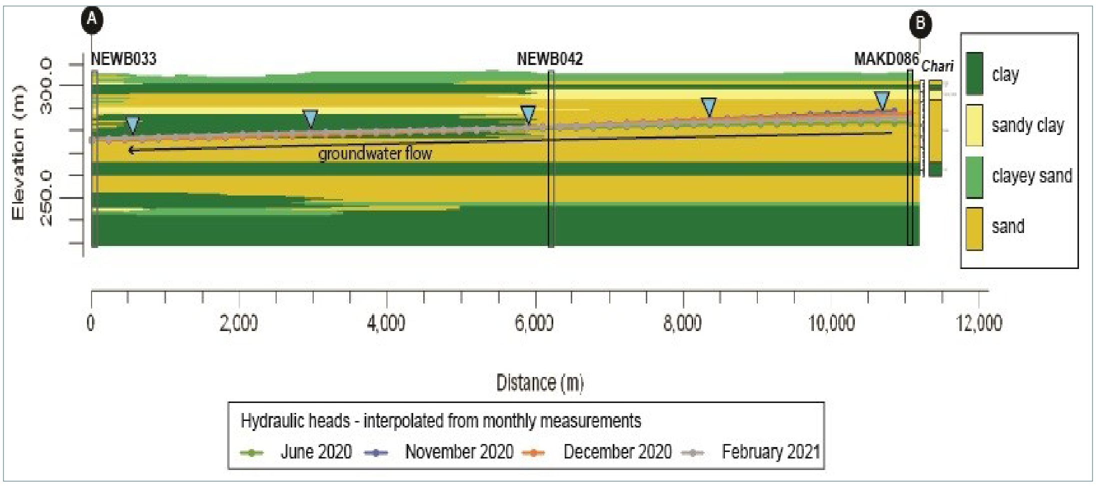
To assess the subsidence potential and improve the hydrogeological knowledge of the aquifer system underlying the city, a 3D geological model is developed allowing to delineate the thickness, extent, and distribution of the Quaternary sediments.

Figure 6 shows an example of profile (refer to Figure 5) extracted from the geological model, to which are superimposed the groundwater levels and their seasonal fluctuations. The profile shows larger fluctuations and hydraulic gradients close to the river where sandy layers are predominant, while a few kilometres from the shoreline, the fluctuations become undetectable and hydraulic gradients flatten in correspondence to clay layers at depth.

Figure 6.
An example of profile issued from the geological model to which groundwater levels and seasonal variations are superimposed



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Moreover, the resulting lithologic model demonstrates the structural complexity of the Quaternary aquifer system. The base of the Quaternary aquifer corresponds to the upper limit of the Mio-Pliocene, a thick clay layer (estimated at 200 masl for N'Djamena) deposited during the Mega Lake Chad period (between 6.7 to 2.4 Ma). This limit varies between 48 and 68m depth under the city of N'Djamena. Generally, the Quaternary layers are composed by two sandy levels (4 to 32m thickness for the shallow layer, 6 to 42m thickness for the deeper layer), separated by a layer of clay (2 to 28m thickness). The clay layer can sometimes be absent. For the built area of the city, the upper layer is characterized by clays up to 17m thickness. In the bed of the Logone and the canal this thickness can reach 40 to 52m.

At present time, more in-depth analysis is ongoing to assess possible correlations between groundwater behaviour, water extraction, and subsidence rates.

Conclusions

The proposed methodology and related map examples highlight the importance to operate at different spatio-temporal scales, as well as the value to combine point/profile field data with satellite based spatial products to produce surface lithology, geological structures and hydrogeological maps. Nevertheless, the local geological and hydrogeological knowledge/expertise to correctly interpret and refine the digital products is fundamental. Following main conclusions are made:

1. Remote sensing, terrain, and ancillary products: The synergistic use of the various time-series datasets contribute to the development of hydrogeological information.
2. Surface lithology and geological structures: A multi-scale approach maximizes the map content, if remote sensing products are coupled with local geological expertise.
3. Groundwater potential: Precisely geolocated water points and a large set of explanatory variables are essential. The derived explanatory variables and related algorithms allow to upscale to larger areas within similar landscapes.
4. Groundwater dynamics: The use of piezometric regular temporal measurements and 3D geological modelling enhances the under-standing of the complex relationship between the Chari-Logone River and the Quaternary aquifer of the Lake Chad basin.
5. New insights to the geology and hydrogeology of the Chadian sector of the Lake Chad basin are brought through the proposed approach, which is moreover relevant to other areas and countries sharing the resources of this vast aquifer system. Finally, the understanding of the groundwater dynamics and its relationship with the surface water is fundamental to transboundary water resources management.

Acknowledgments

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Conclusions

by Rosario Sanchez

The main lesson over the last two decades and based on current research presented during the Conference on this topic, is that there is no recipe for identifying nor for assessing transboundary aquifers. There is no *size fits all*, but the good news is that there is no need to. Shared aquifers do not only share waters, but they also share history, localities, priorities, culture. Funding capabilities, institutional differences and specific physical and social complexities play a definite role on the way one aquifer assessment differ from another. There are conditions that can be hardly replicated. We can indeed learn from the techniques, the principles, the processes, but the outcomes will only be a result of the specific socio, economic and political needs of their own aquifer-sharing communities. This is important to understand, because we tend to idealize and look for a global harmonization of processes and regulations that might not be necessary after all. Whether the assessments are based on whole aquifer approaches, zoning, hot spots, transboundary corridors, or effective transboundary aquifer areas, if the sharing countries agree on the approach they want to use and the fundamental principles of cooperation and collaboration are the main outcomes, then the biggest challenges have been already achieved.

Transboundary aquifer assessments seem to be truly the result of the convergence of scientific assessments, social interactions, networking development and capacity building at a local level. It requires enough flexibility for adaptation to specific priorities, and financial capabilities of the sharing communities. As complex as this may sound, this reality is in fact an optimistic scenario as it has opened the door for alternative techniques, protocols, tools, approaches, assessments on the way we address and understand shared groundwater resources. We have learned there are multiple and diverse technologies used all over the world to represent the transboundary nature of aquifers and their current conditions, all of them with the purpose to inform sound transboundary groundwater management. We have acknowledged all these converging elements are necessary to pave the road towards effective transboundary aquifer assessment and management, unfortunately this necessary convergence condition still has a long way to go.

For the future, there is the need to think pragmatically. Groundwater science is a very complex topic. If we add the transboundary, social, economic, and political elements, it becomes an overwhelming issue hardly addressed at that scope. Numerical models have been developed and are being used more often now all around the world, along with advanced remote sensing and digital processes, but the lack of data, financial support, and expertise is still the main obstacle. Trust and commitment that allows for effective data sharing protocols across countries is also limiting the advancement capabilities of technical efforts. There is the need to work with what is available: either data, funding, community capacity or institutional support. It is a process that requires perseverance, patience and permanent communication with decision-makers and stakeholders, and there are no shortcuts.

Step one will always be to strengthen communication channels across borders to effectively share needs and jointly decide the way forward. We are not discovering magic solutions. On the contrary, we are realizing that the transboundary aquifer topic offers an opportunity for creativity not just in the development of science-driven approaches for mapping, delineating, and assessing shared aquifers, but also in the management possibilities. The is an opportunity to be creative, to propose, to imagine, to learn from each other, to respect differences, but above all, to finally understand that the groundwater sharing notion is not limited to water.

TOPIC 4

Governance of TBAs: Strengthening cooperation

Introduction

by Stefano Burchi

Cooperation among the concerned countries is critical to the sustainable, long-term management and shared benefits of transboundary aquifers and to effective governance arrangements. Against the backdrop of a handful of known formal arrangements on record for the governance of transboundary aquifers, and of the apparent desirability to expand and strengthen cooperation, the available record will be explored, including the available legal frameworks at the global and aquifer-specific level. Lessons and pointers will also be drawn aimed at informing more arrangements to come on stream for the effective governance of transboundary aquifers, resting on strengthened cooperation among the concerned countries and on robust legal frameworks.

Cooperation between and among States that have a transboundary aquifer in common is key to governance arrangements for the aquifer enabling the sustainable development and use of the precious groundwater in it, and that are also sustainable through time. The papers that are included in this selection suggest that cooperation thrives in an environment that encourages synergistic dynamics across the spectrum that goes from the legal foundations of cooperation to the relevant governmental institutions, and from the science/policy divide to the multiple spatial dimensions of cooperation.

TOPIC 4/Paper 19

Conjunctive Management of Water Resources and Governance of Transboundary Aquifers of Iullemeden-Taoudeni / Tanezrouft (ITTAS)

(Algeria, Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Mauritania, Niger, Nigeria)

Abdel Kader Dodo[1], Mohamed Baba Sy[2], and Joël Tossou[3]

Abstract

The transboundary Iullemeden Aquifers System (IAS) and the Taoudeni / Tanezrouft Aquifers System (TTAS), located in West Africa contain significant water reserves (~15,000 billion m^3). The two systems are connected and together form the Iullemeden-Taoudeni / Tanezrouft Aquifer System (ITTAS). The ITTAS groundwater resources, interconnected with those of the Niger River, are shared between eleven countries: Algeria, Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Guinea, Mali, Mauritania, Niger, Nigeria.

These water bodies are subject to various threats, mainly overexploitation (localized), pollution from various sources and the effects of climate change. Under the effect of climate change, for example, the Niger River has undergone substantial reductions in its flow volumes in all its compartments due to (i) decreased rainfall, (ii) increased evaporation and (iii) reduction of groundwater recharge.

To support countries concerned with mastering or even simply reducing the impacts of these threats on water resources and to meet the water demands of neighboring populations, the ITTAS project was financed by the GEF[4] and is implemented by the Niger Basin Authority, OSS, UNIDO[5] and UNESCO. The project aims to support governance and administration of the aquifer system based on an ecosystem approach for joint management of the global strategic resource and for the sustainable development of the concerned sub-region. Such management requires a better understanding of the dynamics of this hydraulic assembly and its relationship with its environment.

The project will also make it possible to implement the collective governance of the ITTAS aquifer system that has already been initiated through a memorandum of understanding signed by four countries for the creation of a Consultation Mechanism.

This article describes a mechanism for collaboration in progress, to set up concerted governance for management of interconnected groundwater and surface water resources that are shared by eleven countries, some of which are concerned only with surface water (Cameroon, Chad, Côte d'Ivoire, Guinea), others by groundwaters, and others by both.

The article highlights the various interventions and achievements that effectively operationalized the conjunctive management of the water resources of the aquifer system of ITTAS and those of the Niger River.

Keywords: transboundary aquifers; Governance; Concertation.

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Introduction

The Sahara and Sahel Observatory (OSS) supports countries and member organizations in producing, managing, sharing and disseminating information for sustainable natural resource management, focusing on the priority issues of land and water degradation.

The regional project " Improving IWRM[6], and governance based on knowledge of the Niger Basin and the Iullemeden-Taoudéni/Tanezrouft Aquifer System " (NB-ITTAS[7]) involving eleven countries, is financed by GEF, implemented by UNDP and UNEP, and executed by the Niger Basin Authority (NBA), OSS, UNIDO, and UNESCO. Within the framework of this project, OSS is responsible for, among other things, elaborating the hydrogeological model of the transboundary groundwater of the Iullemeden-Taoudéni/Tanezrouft Aquifer System and developing the Transboundary Diagnostic Analysis (TDA) and the Strategic Action Programme (SAP) recommended by GEF for International Waters.

The Iullemeden and Taoudéni/Tanezrouft basins cover an area of more than 2.5 million km^2 between longitudes 10° West and 10° East and latitudes 10° and 27° North. The two sedimentary basins of Taoudéni/Tanezrouft and Iullemeden cover an area of 2 000 000 km^2 and 500 000 km^2 respectively. The basins consist of vast collapsed tectonic structures in which several thousand meters of detrital sediments, mainly of continental origin, have accumulated from the Paleozoic to the Tertiary with marine or lagoon episodes.

Most of the modelled area is located in the arid to semi-arid climatic zones of the sub-Saharan and Sahelian type. The Sahel is a semi-arid tropical transition zone, characterized by a dry season of 7 to 8 months without rain, running from October-November to April-May, and a wet season of 4 to 5 months. The area is subject to a strong annual rainfall gradient, positive from north to south. Rainfall is violent and stormy and lasts less than a few hours. In fact, the Sahel is one of the regions of the world where interannual rainfall variability is the most marked (Pfeffer 2011, Booth et al. 2010). Mean annual potential evapotranspiration can reach 2500 mm with daily temperatures ranging from 20 to 40 °C.

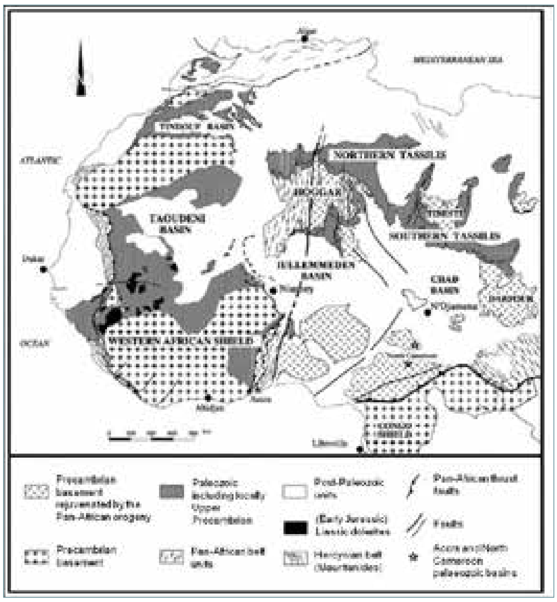
The Iullemeden and Taoudéni/Tanezrouft aquifer system are closely hydraulically connected to the Niger River, which crosses the study basin over more than 2300 km, i.e. a little more than half of its course. In the Iullemeden basin, downstream of the "Gao Gap", i.e. between Ansongo and the confluence of the Dallol Bosso far downstream of Niamey, the Niger River flows over the underlying basement formations and becomes disconnected from the Iullemeden aquifers.

Hydrogeological framework

The Iullemeden, Taoudeni/Tanezrouft aquifer system (ITTAS) comprises two main aquifer formations: the Intercalary Continental (CI) and the Terminal Continental (CT). It also includes the underlying Paleozoic sedimentary formations, some infracambrian formations and the generalized limestone or dolomitic formations that are hydraulically continuous with the CI and CT.

6. Integrated Water Resources Management
7. NB = Niger Basin. ITTAS= Iullemeden, Taoudeni/Tanezrouft Aquifer System with 11 countries: Algeria, Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Mauritania, Niger and Nigeria.

Fig. 1.
General geology of West Africa



(Pfeffer 2011, Massuel 2005 , Konaté et al. 2003) (© Open Access)

Approximate water balance of ITTAS

The water balance of the Iullemeden (SAI), calculated in 1970 before its exploitation, had established the natural contributions to be 4.9 m³/s (OSS, 2011), of which 3.84 m³/s is ensured by direct infiltration of precipitation at a rate of 86% on the CT and 14% on the CI, 0.29m³ /s corresponds to the recharge of the CI by the infiltration of runoff water from the reliefs of the northern edge and 0.77 m³/s comes from the Rima River and infiltrates at the level of CI. At the level of the SAI, the natural discharges are through the drainage of the CT by the Dallols (0.45 m³/s), and by the Rima River (0.35m³/s) and through the drainage of the CT and the CI by the Niger River, which are estimated respectively at 2.5 and 1.6 m³/s.

However, the global model of the SAI (OSS 2017b) developed within the framework of the GICRESAIT[8] project estimates the total recharge of the SAI at 243 m³/s, of which 229 m³ /s would come from direct recharge and 14 m³/s from rivers. As for the Taoudeni / Tanezrouft (SAT), natural inputs that are orders of magnitude different from one another have been cited in the literature: 7.9 m³/s (UNESCO/OSS 2005) and 355 m³/s (OSS 2017b). Thus, the global model of the ITTAS (OSS 2017b) estimates the natural inputs to the entire system at 598 m³/s, of which 523 m³/s would come from direct recharge, 12 m ³/s from the border relief and 63 m³/s from the rivers, mainly the Niger River.

Analysis of all the data shows that the plausible order of magnitude for the total recharge of the ITTAS would be in the range of 13 to 30 m³/s. The calibration of the hydrodynamic model, currently underway, will make it possible to establish the water balance of the ITTAS with acceptable accuracy.

Initial estimates of the calculated water balance, as part of the current study, indicate that the renewable resources of the aquifer system amount to 22.3 m³/s. The recharge by infiltration of rainfall including direct infiltration and infiltration of runoff water from the edge reliefs totals 21 m³/s. The contribution of the Niger River to the recharge of the aquifers is equal to 1.3 m³/s. The direct recharge by rain infiltration is equal to 9.8 m³/s, it takes place mainly at the level of the CT (9.5 m³ /s). The recharge flow is equal to 0.3 mm/year on the major part of the SAT and 0.9mm/year on the level of the SAI. Recharge by infiltration of runoff water coming down from the CI edge reliefs amounts to 11.2 m³/s. Recharge by rainfall is distributed between 62% and 38% respectively in the Iullemeden and Taoudéni/Tanezrouft basins and is more important in the SAI.

Leakage from natural outlets totaling 22.3 m³/s includes evapotranspiration (2.9 m³/s), drainage from the Niger River (13.9 m³/s), the Rima River (2 m³ /s) and other rivers south of the SAT (2.5 m³/s), the Dallols (0.95 m³/s), and springs in Burkina Faso (0.12 m³/s). The vertical exchange

8. Project "Integrated and concerted management of the Iullemeden, Taoudeni/Tanezrouft aquifer system": Algeria, Benin, Burkina Faso, Mali, Mauritania, Niger, Nigeria.

between the two aquifers is mainly upward (11 m^3/s) from the CI to the CT.

It should be noted that the infiltration of rainwater and runoff through streams and ephemeral water bodies is important. Totaling 21 m^3/s, it constitutes 94% of the renewable resources of the ITTAS. On the other hand, the contribution of perennial watercourses is low. The Niger River feeds the CT and CI aquifers by 1.3 m^3/s. The exchange between the aquifers and other perennial rivers such as the Rima River is exclusively from the aquifer to the river. Indeed, the total drainage by the hydrographic network is 18.4 m^3/s, with 13.9 m^3/s by the Niger River, 2 m^3/s by the Rima River and 2.5 m^3/s by the tributaries of the Niger located south of the SAT.

Transboundary diagnostic analysis (TDA)

The Niger River Basin is currently facing several types of threats to its environment and ecosystems. The TDA of the Niger River Basin (NBA, 2009) as well as that of the SAI (OSS, 2011) have already been carried out. These studies, complemented by the TDA in the Taoudéni basin, have revealed the following results:

- Climate change is both a threat and an underlying cause. It is a threat because the trend of increasing aridity is reducing the overall water content of the system, through decreased precipitation, increased evaporation and reduced groundwater recharge. As a cause, these changes put pressure on human health, food security and overall livelihoods and/or resilience.
- Land degradation and land use change are also threats; surface and groundwater linkages are well illustrated in the basin by the impacts of land degradation. Deforestation and poor agricultural practices, coupled with degradation of protected areas, particularly in the recharge regions, have resulted in lower rainfall retention rates. This leads to rapid runoff and reduced groundwater recharge, reduced base flows during the dry season, and increased magnitude of flooding events. Sediment loads are also increased.
- Changes in the hydrological regime, have negative impacts on the basin and are the result of a combination of climate variability and climate change, increasing the demand for consumptive water, land degradation and land use change.
- Water quality and pollution, through the constant increase of industrial and mining activities but also tanneries, agriculture, and other activities, have increased the total pollution load with risks in some specific locations. Several pollution problems have been identified: (i) Industrial pollution; (ii) Mining pollution; (iii) Oil pollution; (iv) Anthropogenic and agricultural pollution; (v) Infestations of invasive aquatic plants.

These problems have been identified by the national TDAs already carried out. The national TDAs will lead to a regional TDA that will propose solutions to address these cross-border problems. On the basis of this regional TDA, a Strategic Action Programme (SAP) will be defined for adoption by the countries.

Pollution control

A study entitled "Introduction of Systematic and Integrated Approaches to Industrial Competitiveness and Environmental and Social Responsibility to Reduce Wastewater Discharges and Pollution Loads in the Niger River" was carried out, which has a goal to reduce the pollution load in the Niger Basin water system in partnership with the private sector active in the basin. The integrated approach used is the Transfer of Environmentally Sound Technologies (TEST) developed by the United Nations Industrial Development Organization

(UNIDO) and successfully tested elsewhere in the world, including some African countries, which has been selected as a pilot test method in the basin. This approach aims to increase the productivity, environmental performance and social responsibility of polluting companies in the basin.

Collaboration mechanism

Pollution problems have been identified in this project. To address these hydrogeological and environmental risks, and to reduce or even mitigate the degradation of water quality, the project promotes conjunctive management of groundwater and surface water resources. Thus, following the ministerial declaration signed in 2009 (Mali, Niger, Nigeria) and the one signed in 2014 within the framework of the GICRESAIT project, a memorandum of understanding has been drawn up in this sense.

Four out of seven countries have already signed the Memorandum of Understanding establishing the ITTAS Consultation Mechanism. Actions are underway to ensure that "National policies and institutions and civil society platforms support ecosystem-based management of the Niger River".

In this regard, close collaboration and coordination is being established between OSS/ UNESCO, the technical advisory body that has been assisting the ITTAS countries in developing one or more appropriate governance options, and the Niger Basin Authority, the long-established intergovernmental body mandated for the sustainable management of water resources in the Niger River Basin on behalf of and in the best transboundary interest of the Niger River Basin States, with support from UNDP and UNEP as GEF agencies.

On this basis, reviews are conducted on the realistic synergies to be found between the institutions concerned (in terms of leadership, contribution, and budget) in order to carry out the activities aimed at setting up this consultation framework.

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TOPIC 4/Paper 20

Characterizing Legal Implications for the Use of Transboundary Aquifers

Gabriel Eckstein[1]

Abstract

Groundwater resources that traverse political boundaries are becoming increasingly important sources of freshwater in international and intranational arenas worldwide. This is a direct extension of the growing need for new sources of freshwater, as well as the impact that excessive extraction, pollution, climate change, and other anthropogenic activities have had on surface waters. It is also a function of the growing realization that groundwater respects no political boundaries, and that aquifers traverse jurisdictional lines at all levels of political geography.

Due to this growing awareness, questions pertaining to responsibility and liability are now being raised in relation to the use, management, exploitation, and governance of cross-border aquifers by stakeholders and policymakers who want to maximize their access to subsurface freshwater, as well as minimize their legal vulnerability and exposure. This is occurring both at the international level where two or more sovereign nations, and at the domestic level where two or more subnational political units, overlay a common aquifer.

The law applicable to transboundary groundwater resources at both levels of governance is presently quite primitive and inadequate. Moreover, the relationship of groundwater law to surface water law is often absent from treaties as well as national laws and regulations. While a few promising trends appear to be emerging in the international realm, clear rules and regulations addressing questions of responsibility and liability in relation to the use, management, exploitation, and administration of transboundary groundwater remains elusive at all level of governance.

To provide a foundation for the development of such norms, this paper explores circumstances under which the use, management, exploitation, or administration of a transboundary groundwater body might cause harm to a neighboring political unit—either to their territory, or to important economic, societal, or other interests—and, thereby, result in legal responsibility and/or liability. It assesses cause and effect relationships with reference to conceptual models of transboundary aquifers developed by Eckstein & Eckstein (2005) and Eckstein (2017). Notions of gaining and losing stream relationships, recharging and non-recharging aquifers, groundwater flow direction, the impact of groundwater pumping, anthropogenic contamination, and other concepts are utilized to describe scenarios in which harm could traverse a political boundary. The paper then translates that analysis into notions of responsibility and liability that are common to the legal realm. This research area is novel and has only marginally been addressed in the domestic interstate context of the United States (Hall & Regalia 2016).

Keywords: International Law, Transboundary Aquifers, Liability

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The Quandary of Mixing Groundwater and Law

Boundaries demarcating the territorial lines of sovereign states and subnational political units typically serve as the basis for claims of right to solid natural resources found within each jurisdiction. For example, rights to coal, uranium, and other mineral deposits that traverse political frontiers are typically divided in relation to geographic boundaries with each state's or sub-state unit's entitlement directly related to those resources physically found within its territory.

Divvying up fluidic resources, like groundwater, flowing between two or more jurisdictions, however, presents unique challenges. Groundwater flows do not respect political boundaries or other artificially drawn demarcation. Rather, groundwater courses toward and through the path of least resistance as a function of gradient, permeability, porosity, pressure, and other geophysical and natural factors (Heath, 1987). As a result, groundwater flows can traverse international and intranational administrative boundaries, thereby making national and subnational political units "riparian" to the same groundwater system.

The challenge, in terms of law, sovereignty, and ownership claims for groundwater resources, lies in determining the particular quantities or benefits, or rights thereto, that should accrue to each riparian. The situation, however, is further complicated by the fact that groundwater flows occur unseen underground and do not typically move in a linear fashion—not like rivers, but rather in a 3-dimensional spatial context—thereby making it difficult to measure accurately. Thus, for purposes of allocating legal ownership or usufructuary rights to groundwater resources, it is impracticable even to attempt to attach a point of origin to any drop of water, or to predict the precise moment that a particular droplet in a transboundary aquifer crosses a political frontier.

In addition, with the possible exception of fossil and connate groundwater resources, most aquifers are hydrologically linked to the water cycle, and regularly receive water from and transmit water to other components of the system. As a result, an aquifer may be subject to fluctuations in both water quantity and quality in relation to recharge, discharge, precipitation, evaporation, and other changes in and impacts on the system. This, in turn, further complicates designation of sovereign and other rights related to transboundary subsurface freshwater resources, and requires a holistic understanding of the science of groundwater when assessing the legal implications stemming from the use of transboundary groundwater resources.

Under what circumstances might groundwater or an aquifer raise transboundary legal implications at either the international level or among subnational political units? What conditions might trigger adverse cross-border consequences, and under what scenarios might they be negated? These queries, and others, are the types of questions now being asked by sovereigns at the national and sub-national levels, and that necessitate further scrutiny. This article addresses these particular issues and seeks to enhance understanding of the legal dimension of transboundary groundwater and aquifers grounded in the science of hydrogeology.

Background

In Eckstein & Eckstein (2005) and Eckstein (2017), the authors highlight basic definitions and concepts of hydrogeology that are essential to understanding how groundwater flows and interacts with surface water systems, and what effects extraction through wells can have on both. Among others, these include the influent (or losing) and effluent (or gaining) relationships that often exist between surface waterbodies and aquifers, aquifer recharge and discharge processes and zones, recharging and non-recharging aquifers, groundwater flow direction, and the impact of groundwater pumping and pollution. The publications present six simple conceptual models of aquifers whose use and exploitation could have transboundary effects with legal implications. Building on these publications, this article identifies the circumstances in which the use, management, exploitation, or administration of groundwater in a transboundary aquifer might infringe on the legal rights of a neighboring political unit and, thereby, result in legal responsibility and/or liability.

Before discussing these legal implications, it is necessary first to identify what rights aquifer riparians typically enjoy. At the national intrastate level, the law applicable to such cross-jurisdictional resources necessarily depends on the domestic laws of the country in which the resource is found. In federal systems, where subnational units have some measure of sovereignty over resources and activities occurring within their borders—like those of the United States, India, Brazil, and Australia—the law hinges on the legal relationship between the federal and state governments, as well as the intrastate jurisprudence that may exist in the country. Thus, for example, in the United States, disputes over interstate waters are resolved by the United States Supreme Court under the doctrine of equitable apportionment. That venerable Court, in fact, recently adjudicated its first case involving interstate groundwater resources ruling that equitable apportionment applies equally to disputes involving transboundary groundwater resources as it does for those involving cross-border surface water bodies (Mississippi v. Tennessee, 2021). Other nations' high courts have never, or only marginally, addressed intrastate groundwater disputes. As a result, there is a dearth of experience and jurisprudence from which responsibility and liability for cross-border impacts can be derived.

In the international realm, the situation is not much better. The international law of transboundary groundwater resources is still in its infancy and the rights of countries to such resources have yet to be fully defined (Eckstein 2017). The most significant attempt to formulate legal norms for the use, management, exploitation, and administration of groundwater traversing international frontiers was undertaken from 2002-2008 by the UN International Law Commission in its Draft Articles on the Law of Transboundary Aquifers. That work product was submitted to the UN General Assembly for its consideration and has been on the Assembly's agenda in 2008, 2011, 2013, 2016, and 2019. Each time, however, the subject matter was commended to the attention of UN Member States and further considerations tabled for a future meeting (UNGA, 2019). The Draft Articles are slated again for the Assembly's agenda in 2022.

Other relevant global instruments include the 1992 UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes, and the 1997 UN Convention on the Law of the Non-navigational Uses of International Watercourses. Both include various principles that are applicable generally to transboundary watercourses and, ostensibly thereby, to cross-border groundwater resources that are part of the watercourse regime. In both cases, though, groundwater is a secondary concern to rivers and lakes and most of the precedence underpinning the instruments are grounded in disputes and practices related to the governance of transboundary rivers and lakes. Accordingly, while the two conventions are purported to codify the customary international law for transboundary watercourses (McCaffrey 2019), it is questionable whether they equally represent the codification of customary norms for transboundary groundwater and aquifers.

As a matter of substantive international law, based on the Draft Articles, the two global watercourse conventions, and the handful of treaties formulated for specific transboundary aquifers globally, the most that can be said today is that: (1) an aquifer riparian has some yet-to-be fully defined rights to use and enjoy groundwater from an aquifer that underlays both its territory and that of a neighboring jurisdiction; and (2) when that use and enjoyment interferes with the equivalent rights of the neighboring aquifer riparian to use and enjoy the groundwater underlying its own territory, such rights may be subject to restrictions and possible liability (Eckstein 2017). Whether the conflicting rights are grounded in the two cornerstone principles of international water law—equitable and reasonable use, and no significant harm—has yet to be established.

As a result, there are no broadly accepted substantive international legal rules governing the management or allocation of groundwater flowing through an international transboundary formation, or of benefits that may be derived from that groundwater. In terms of procedural rights and obligations, however, four principles appear to be trending toward customary legal acceptance. These include the obligations to: (a) regularly exchange data and information about the transboundary aquifer; (b) monitor and generate supplemental data and information about the transboundary aquifer; (c) provide prior notice of planned activities that may adversely affect either the territory of another aquifer riparian or the transboundary aquifer itself; and (d) create an institutional mechanism to facilitate or implement the above obligations (Eckstein 2017).

Given that the rights and obligations of aquifer riparians are still in their early development and remain inconclusive, the scrutiny that follows is somewhat crude in that it simply considers various scenarios of cross-border interference with the potential legal rights of neighboring political units. Despite its simplistic approach, the analysis offers some insight into when legal responsibility and/or liability might arise from the use, management, exploitation, or administration of groundwater from a transboundary aquifer.

Transboundary Legal Implications of Aquifers

As suggested above, legal responsibility and/or liability might arise when one aquifer riparian's utilization of groundwater from a transboundary aquifer within its territory interferes with a neighboring aquifer riparian's equivalent right to use the same aquifer. In the context of a cross-border aquifer, such interference will manifest as either depletion or contamination, or both, of the groundwater found beneath a neighboring riparian's territory.

Generally speaking, though, not all negative impacts on the rights or interests of a neighboring riparian are actionable under law. A *de minimis* or insignificant impact is unlikely to be deemed unlawful. Rather, the impact has to be significant enough to result in an appreciable (non-*de minimis*) infringement of the neighboring riparian's ability to use the groundwater from the shared aquifer, or possibly a hydrologically related river or lake, on its side of the political boundary (McCaffrey 2019). However, whereas substantive rights in transboundary groundwater resources have yet to be defined under international law, the threshold for harm—between non-actionable (de minimis) and actionable (non-*de minimis*) impacts—remains unclear. Absent such an impact, and at a level above the threshold for unlawful conduct, it is unlikely that the neighboring riparian could have any legal grounds to raise against the acting aquifer riparian's activities in relation to the aquifer, regardless of the aquifer's transboundary geology and geography.

Circumstances that could result in transboundary legal implications pertain to the extent to which one aquifer riparian takes action in relation to a transboundary aquifer and thereby negatively impacts the ability of a neighboring riparian to use the aquifer. Such impacts can be both quantitative and qualitative in nature and can be related to activities that change the natural flow direction, volume, or quality of the groundwater within a specific portion or the entirety of the aquifer. Among other causes, such impacts could result from extraction of groundwater from the aquifer, land use practices that result in diffuse pollution, injection of fluids and gases into the formation, deposition or burial of wastes over or within the formation, diminution or increase of the natural recharge into the aquifer, diminution or increase of the natural discharge out of the aquifer, mining of the aquifer matrix, and other activities that have a detrimental impact on the functioning of the aquifer.

One example of such cross-border harm might occur where one aquifer riparian pumps groundwater from a transboundary aquifer in the vicinity of the border causing a cone of depression (in an unconfined aquifer) or reduction of the pressure head (in a confined aquifer) to expand toward that boundary. In the simplest case, where the aquifer in the immediate border region has no hydrologic connections to any transboundary surface water bodies, such as found in Model C in Eckstein (2017), the cross-border impact will occur strictly through the aquifer. Where the cone of depression crosses underneath the artificial political line, it will affect the natural flow of the aquifer beneath the neighboring riparian's territory within the cone's radius of influence. The extent to which that artificial alteration affects the ability of the neighboring riparian to use and enjoy the aquifer will determine whether the impact on the affected riparian is greater than the *de minimis* threshold and, therefore, whether that riparian might have a cause of action against the acting riparian.

In a more complicated example, the aquifer in the immediate vicinity of the border region could have a hydrologic connection with either a contiguous transboundary river (where the surface water body forms the border, as depicted in Model A in Eckstein (2017)) or a successive transboundary river (where the river flows across a frontier from one political jurisdiction and into another, as shown in Model B in Eckstein (2017)). In such cases, the hydrologic connection creates additional complexities in which the aquifer riparian pumping from the aquifer could cause negative impacts to be felt across the border. Moreover, those complexities will be further muddled depending on whether the aquifer-river relationship is an influent or effluent one, as well as whether excessive pumping changes an effluent relationship to an influent one.

For example, where one aquifer riparian extracts groundwater from a transboundary aquifer with an effluent relationship to an adjacent contiguous river, the pumping could affect the water in the river. Where pumping substantially exceeds the aquifer's natural capacity to replenish, thereby causing the well's cones of depression to extend to the river, the artificial extraction could change the aquifer-river effluent relationship to one that is influent within the cone of depression. Referred to as "streamflow depletion" or "capture" (Barlow & Leake 2012), this conduct could cause water in the river to be pulled into the aquifer and toward the well on the pumping riparian's side of the border. To the extent that this appreciably impacts the non-pumping riparian's ability to use or enjoy an equitable and reasonable share—the recognized standard for the right to utilize surface waters from a transboundary watercourse under international law (McCaffrey 2019)—of the water from the transboundary river, the latter riparian may have a claim against the pumping riparian.

It is noteworthy, though, that in this scenario, the cone of depression was described as only reaching the river and not the aquifer segment located in the territory of the non-pumping riparian. If pumping was increased and the cone of depression were to extend into the neighboring territory (and if the *de minimis* threshold was crossed), that riparian's claim for harm could pertain both to the impact on the contiguous river as well as to the aquifer segment underneath its territory. Moreover, while the latter claim would be limited geographically to the radius of influence of the cone of depression reaching into the neighboring riparian's territory, the geographic scope of the claim related to the river could be much larger since the impact on a flowing river can be felt downstream beyond the geographic contours of a cone of depression.

Although the above addresses the potential transboundary consequences to water quantity, a transboundary aquifer hydrologically linked in an effluent relationship to a transboundary contiguous river also could cause negative, cross-border water quality concerns. For example, a naturally flowing effluent, contiguous river bisecting an unconfined aquifer, under homogeneous and "text-book" conditions, will impede pollutants and other negative traits on one side of the aquifer from crossing over to the opposing sides by drawing them into the river. Thus, if one of the riparian jurisdictions introduces any pollutants into the river, because of the effluent relationship of the river to the aquifer, the aquifer is unlikely to be contaminated. Of course, the riparian introducing the pollution may be responsible for consequences in and to the river, as well as to other riparians utilizing the river downstream from the point of contamination. Similarly, if one of the riparians introduces a pollutant into the aquifer that is drawn into the effluent river, that riparian could be liable for harming its neighboring and other downstream riparians by diminishing the water quality of the river.

In another distinct scenario involving water quality, one aquifer riparian might artificially introduce contaminants into its own section of a transboundary aquifer, which then migrate across the border into the aquifer portion of a neighboring riparian as a result of the latter riparian's substantial pumping activities (Burke, et.al., 1999). The assignment of responsibility and/or liability to the polluting riparian would not be automatic and would depend on additional circumstances. For example, if the natural flow of the aquifer was from the polluting aquifer riparian toward the neighboring jurisdiction, responsibility and/or liability might be applicable if the *de minimis* threshold of harm to the neighboring riparian was surmounted. However, if the contamination migrates across the border because the neighboring riparian was pumping from the aquifer and its cone of depression "pulled" the contaminants across the political frontier, the polluting jurisdiction might avoid liability and responsibility. It would depend on a variety of additional factors, such as whether or not the riparian extracting the groundwater knew about the contamination across the border prior to engaging in its pumping activities, whether the polluting riparian provided adequate notification to the pumping riparian about the contamination and its potential to flow across the border, whether the contamination would have migrated across the frontier regardless of the pumping riparian's extraction activities, and whether the pumping riparian's extraction activities accelerated or amplified the cross-border flow of groundwater along with the contamination.

While the above examples focused on an effluent aquifer-river relationship where the river is contiguous, similar scenarios could be crafted where the hydrologic relationship is an influent one and where the river is successive across the neighboring jurisdictions. Moreover, adding a further dose of reality, and thereby complexity, it is entirely possible for a river's hydrologic relationship to an underlying aquifer to alternate between effluent and influent as it courses toward its terminus. This can depend on a host of factors ranging from geology, topography, permeability, and other physical characteristics that are often very unique to each river and aquifer basin, as well as changes in precipitation and climatic events. Moreover, some rivers can be contiguous between neighboring political units and then successive with the same or other bordering jurisdictions.

The Special Case of Non-Renewable Groundwater

One area that may require special consideration involves fossil and connate groundwater and aquifers, as depicted in Model F in Eckstein (2017). These non-renewable resources are uniquely vulnerable to depletion since in the absence of recharge, any withdrawal will result in the mining of the resource. Likewise, they are distinctively susceptible to pollution because the lack of significant recharge and flow reduces their ability to naturally attenuate contaminants.

Consider, for example, where one jurisdiction begins to extract groundwater from a fossil aquifer that traverses the political boundary of its neighboring jurisdiction. Since the aquifer has no contemporary source of recharge (or, only *de minimis* recharge), the pumping eventually will begin to lower the water table, or pressure head, beneath the neighboring riparian's territory. Yet, because a non-recharging aquifer, by definition, cannot be pumped sustainably, it may seem unreasonable to assign liability merely for the depletion. Otherwise, neither state would be permitted to withdraw any water from the aquifer.

As for harm arising from the anthropogenic contamination of the aquifer, assigning liability also would be complicated. If none of the riparians was actively withdrawing or planned to withdraw groundwater from the aquifer, the pollution would be unlikely to migrate far from the point of contamination. This is because fossil and connate aquifers usually have little or no flow. However, if one of the overlying aquifer riparians started to extract groundwater, it would create an artificial flow in the direction of the well's intake, which would cause the contaminants to migrate across the frontier. Whether liability might arise in such a scenario would depend on a variety of criteria, including many of the same factors identified earlier for pollution migrating underneath the border into the aquifer portion of a neighboring riparian. Yet, because of the lack of recharge, flow, and discharge in a non-recharging aquifer, which prevent it from naturally cleaning itself, it may be reasonable to heighten the liability, and possibly further lower the threshold for harm, for such contamination.

Some scholars have drawn comparisons between fossil and connate aquifers to other non-renewable, depletable natural resources, like oil and gas deposits, and suggest applying similar legal regimes to non-renewable groundwater resources (Caponera, 1992; Jarvis, 2014). Such rules, however, typically focus on maximizing the exploitation of the resource rather than on the uses to which groundwater can and should be put. As a result, ownership rights for oil and gas deposits are divided *vis a vis* negotiated and agreed-upon volumes, or in relation to the pumpers capacity to extract the resource. Moreover, liability for cross-border harm or interference with rights to subsurface, transboundary oil and gas resources arises primarily in the context of contract violations, and occasionally for allegations of intentional theft of resources.

While the exploitation-focus of this approach may not negate its relevance and applicability to transboundary groundwater resources, it must be recognized that groundwater, whether recharging or non-recharging, has qualities that are distinctly unique from those of oil and gas deposits. For one, the hydrocarbon development regime is not designed to account for the human right and environmental benefits aspects of groundwater resources. It also cannot compensate for the reality that while energy resources like oil and gas have alternatives (e.g., solar, wind, hydro, etc.), water does not. In addition, non-recharging aquifers can be recharged through artificial means, by injection or infiltration pools, from excess surface runoff, return flows, and treated wastewaters. Thus, the life of such resources can be extended in ways that oil and gas deposits cannot, and managed in ways that would be uneconomical in the hydrocarbon sector.

The lack of experience in managing non-renewable resources in an interstate or intrastate manner have hampered the emergence of relevant principles and rules for their governance. Thus, the similarities to oil and gas deposits does present appealing possibilities. Nevertheless, given the disparities noted above, it may be reasonable to suggest that responsibility and liability for transboundary fossil and connate groundwater depletion or contamination should probably be broader in scope to account for the non-economic aspects of groundwater. In addition, the regime should have a threshold for harm and interference that is lower than that applied to cross-border oil and gas deposits.

Conclusion

Transboundary groundwater and aquifers at both the national and international levels are becoming increasingly critical sources of freshwater for communities worldwide. Simultaneously, excessive extraction, pollution, climate change, and other anthropogenic activities are placing many of these resources in jeopardy. As a result, policymakers and stakeholders at various levels of civil society are now seeking rules and norms for their governance in order to safeguard the resources into the future. In particular, many seek to understand the responsibilities and possible liabilities that may arise from transboundary impacts resulting from the use and exploitation, and even careless protection, of these subsurface treasures. This is occurring both at the international level among two or more sovereign nations that overlay a common aquifer, as well as at the domestic level between two or more subnational political units.

The reality, however, is that the law applicable to transboundary groundwater resources at both levels of governance is at a very nascent stage.

Moreover, establishing responsibility and liability in the context of transboundary groundwater resources can be a rather complex endeavor that requires specialized knowledge of the science of groundwater resources. This article sought to provide a foundation for the development of such laws and regulations by exploring circumstances under which the use, exploitation, protection, management, and administration of cross-border groundwater resources might result in harm to a neighboring political unit. As nations and subnational political units continue to expand their reliance on transboundary groundwater resources, they will need to develop principles and norms that are both grounded in sound science and built on an understanding of the distinct value of groundwater for people and the environment.

Lastly, it is worth stating that this article is far from comprehensive and leaves numerous issues and challenges unaddressed. As the field evolves, additional research will be needed to fill in the many gaps on responsibility and liability related to such topics as: the surface water-groundwater interface; harmful impacts that become evident only after years or decades; challenges in establishing causation and identifying wrongdoers; and land uses in recharge areas.

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TOPIC 4/Paper 21

The Role of 'Convergence' in Clarifying the Boundaries of International Law on Transboundary Aquifers

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Abstract

Given the relative dearth of established State practice regarding the emerging rules of international groundwater law, and the spectre of "fragmentation" impacting the rules applying to transboundary aquifers and those applying to transboundary rivers and lakes, the phenomenon of "convergence" may have a role in informing critical elements of both complementary fields of international law. This is particularly likely to be the case in relation certain objectives of international groundwater law, which are becoming increasingly important, such as sustainable management of water-dependent ecosystems and equitable realization of water-related human rights entitlements.

The phenomenon of convergence can be understood as a systemic response to concerns regarding the fragmentation of international law, which promotes greater uniformity and congruence in approach across different sectors and sub-sectors in the application of relevant rules and principles of international law. It is becoming sufficiently prevalent for commentators to note that 'convergence and unity are becoming more dominating features of international law discourse than the claims to autonomy and specificity of different regimes and disciplines which previously dominated' (Andenas, 2015). Such convergence has substantive, procedural, institutional and methodological elements, and is readily apparent in the recent development of international water law, where it occurs through a range of mutually complementary mechanisms, including:

- Creative judicial interpretation of treaties and customary international law;
- Inter-regime institutional collaboration and cooperative elaboration of treaty regimes;
- Codification initiatives taking account of developments in related fields; and
- Increasing prominence and pervasiveness of human rights-related and environmental requirements.

It is worth noting, for example, that ecosystems obligations arising under international law applying to both transboundary surface waters and groundwaters will be profoundly influenced by increasingly sophisticated technical methodologies elaborated under the auspices of the Ramsar and CBD Conventions, while inter-State cooperation regarding both classes of transboundary water resources is to be measured and reported against a single global benchmark in SDG Indicator 6.5.2. In the light of concerns regarding the fragmentation of international watercourses and groundwater law expressed after the adoption of the ILC's 2008 Draft Articles on the Law of Transboundary Aquifers, it is helpful to focus on the mechanisms by means of which these closely interrelated fields might be reconciled and rendered more coherent and complementary.

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Introduction

At the first ISARM Conference, several international water law experts, including the present author, took the opportunity to express concern regarding the risk of normative fragmentation in the rapidly evolving field of international water law, especially regarding the risk of divergence between the rules applying to the management of shared surface waters and those applying to transboundary groundwaters. The primary source of such concern was the 2008 adoption by the International Law Commission (ILC) of a set of Draft Articles on the Law of Transboundary Aquifers, which appeared likely to guide the development of international groundwater law in a direction somewhat different to that of general international water law (McIntyre, 2010). While the latter body of rules has largely evolved on the basis of practice relating to surface waters and did not therefore take full account of the distinct hydrogeological characteristics of groundwater, of its relative importance in satisfying human needs, or of its environmental significance and vulnerability, the threat of fragmentation appeared to threaten the field with legal uncertainty and confusion.

Ten years on, the situation appears less worrying, largely due to greater understanding of the phenomenon of convergence in international law, by means of which this ever-expanding and increasingly complex system of rules somehow manages to maintain its overall unity and essential coherence. Convergence provides a counterbalance to the risk of fragmentation that inevitably attends a continually expanding and increasingly specialized body of rules, which is administered and shaped by a growing array of specialized inter-governmental and judicial institutions. The phenomenon of convergence is facilitated by a range of procedural and institutional practices in the elaboration of international rules, several of which can be observed driving convergence between the law relating to shared surface and groundwaters.

Before proceeding to explore the phenomenon of convergence further, and the processes by means of which it occurs in respect of international water resources law, it is helpful briefly to recount the precise risk of legal fragmentation presented by the ILC's 2008 Draft Articles.

ILC Draft Articles on Transboundary Aquifers

As has been extensively reported (McCaffrey, 2009; McIntyre, 2011) the approach adopted by the ILC, the UN body charged with 'the progressive development of international law and its codification' (UN Charter, 1945, Art. 13), in elaborating its 2008 Draft Articles differed from that employed in general international water law in several important respects. Indeed, by excluding a preambular reference to any of the seminal instruments codifying general international water law, such as the International Law Association's 1966 Helsinki Rules or the 1997 UN Watercourses Convention, the 2008 Draft Articles appears actively to seek to distance the emerging field of international groundwater law from the previously codified and more firmly established rules of general international water law.

The first difficulty with the 2008 Draft Articles concerns their scope of application, which appears somewhat confused - overlapping in some respects with that of the 1997 UN Watercourses Convention whilst also allowing lacunae to remain in terms of their coverage. Whereas the 1997 Convention includes within its coverage groundwaters (whether transboundary in character or located within the territory of a single State) having a 'physical relationship' with transboundary surface waters, the 2008 Draft

Articles purport to cover any transboundary aquifer whether or not connected to surface waters. Therefore, the Draft Articles cover so-called "confined" aquifers as long as they run across or straddle a State boundary, thereby overlapping in this regard with the Convention. However, they fail to include an aquifer situated entirely within one State, but which contributes to the flow of an international watercourse (which would of course be covered by the Convention). Though the latter example avoids the potential simultaneous applicability of two sets of rules presented by the former, it nevertheless 'exempts an important constellation from their *lex specialis* rules, so that only more general rules of international law apply' (Mechlem, 2009).

Of course, overlapping application of the Convention (representing the general rules of international water law) and of the Draft Articles (representing *lex specialis* rules for international groundwaters) would matter little if both sets of rules broadly corresponded. Recognizing the importance of such coherence, the ILC's 1994 Draft Articles on Non-Navigational Uses of International Watercourses, on which the UN Watercourses Convention is based, were accompanied on their adoption by a Resolution on Confined Groundwaters, which urged States to be guided where appropriate by the principles contained in the 1994 Draft Articles (and subsequently in the Convention). Unfortunately, the 2008 Draft Articles on Transboundary Aquifers depart in several important respects from the general legal regime codified in the 1997 UN Watercourses Convention and several other water instruments.

Most notably, the reaffirmation of State sovereignty over transboundary aquifers contained in Draft Article 3, when read in conjunction with the definition of "aquifer" set out in Draft Article 2(a), marks a dramatic reassertion of sovereign control over shared water resources. Because the definition includes both the 'geological formation', over which exclusive sovereign control could never be in doubt, and the 'water contained in the saturated zone of the formation', in which one would expect there instead to exist a 'community of interest' in the parlance of general international water law (Gjørtz Howden, 2020), the Draft Articles represent a 'potentially regressive' shift in international water resources law practice (McCaffrey, 2009). Generally established practice has never recognized a State's exclusive sovereignty over transitory international water resources, as suggested by Draft Article 3 and related commentary, but merely its sovereign right to utilize such waters having regard to the corresponding sovereign rights of other basin or aquifer States. The respective rights of each State would be determined by means of the process of equitable balancing of needs and benefits inherent to the cardinal international water law principle of equitable and reasonable utilization. Thus, Draft Articles 3 and 2(a) mark (at least potentially) a significant retreat from the entire historical and conceptual arc of development of the most fundamental principle of international water law, which can be understood as a means of limiting, on the basis of the sovereign equality of States, the application of absolute and uncompromising theories of territorial sovereignty to shared water resources. Recognizing humanity's unique and total dependence upon water, the international community has historically fostered inter-State engagement over the use of shared water resources based on distributive equity rather than strict sovereign entitlements informed by geophysical factors (Fuentes, 1996).

A stark illustration of the potentially regressive implications of the reassertion of sovereignty under the 2008 Draft Articles is provided by the 2010 Guarani Aquifer Agreement, inspired to a significant degree by the ILC's work. Though the Agreement defines the "Guarani Aquifer System" in strictly water-related terms as 'a transboundary water resource', it asserts that '[e]ach Party exercises *sovereign territorial* *control* over their respective portions' after identifying the four aquifer State parties as 'the *sole owners* of this resource'. The Commission's conclusion, contained in the commentary to the 2008 Draft Articles, that 'groundwaters must be regarded as belonging to the States where they are located, along the lines of oil and natural gas' marks a considerable departure from the established paradigms of distributive equitable sharing of benefits derived from, and intensive inter-State cooperative management of, shared water resources. Rather, the emphasis on sovereignty suggests a shift towards the narrow and short-term self-interest of States sharing vital groundwater resources.

The Draft Articles diverge from the established rules of general international water law in number of other respects, often quite subtle but almost always related to the Commission's emphasis on sovereignty as a key guiding value. For example, they appear to give considerable weight to geophysical or hydrological factors in any determination of an equitable share of the groundwater resources, by emphasizing 'contribution to the formation and recharge of the aquifer' as a factor relevant to equitable and reasonable utilization. The relevant ILC commentary explains that this 'means the comparative size of the aquifer in each aquifer State and the comparative importance of the recharge process in each State where the recharge zone is located'. This is at odds with established practice in general international water law (Fuentes, 1996) and suggests that equitable and reasonable utilization under the Draft Articles may be less distributive in that it is less concerned with human needs and dependence. Similarly, the Draft Articles provide considerably less detail on, and thus appear to place less emphasis upon, the critically important obligations of inter-State procedural engagement. Of course, intense procedural engagement is particularly associated with the identification of each State's legitimate interests in the resource, as required for any distributive equitable allocation of uses, benefits or quantum share (McIntyre, 2007). Surprisingly, given the inherent vulnerability of groundwater resources, Draft Article 12 on prevention, reduction and control of pollution appears rather underdeveloped in comparison to the corresponding Article 21 of the 1997 UN Watercourses Convention, which suggests specific measures on which watercourse States might cooperate in order to address pollution.

Of course, the Draft Articles also introduce several welcome modifications to the established normative pattern, some of which are specifically relevant to the management of aquifers, while others represent progressive development of general international water law. Among the former, the factors identified in Draft Article 5 as relevant to equitable and reasonable utilization highlight the vulnerability and exhaustibility of many aquifers by emphasizing consideration of alternative sources of water supply and, in addition, 'the role of the aquifer … in the related ecosystem'. Among the latter, Draft Article 1 describes the scope of the instrument in a helpfully broad manner to cover, in addition to utilization and protection of aquifers, other activities likely to impact upon aquifers. Similarly, Draft Article 4, the core provision setting out the principle of equitable and reasonable utilization, emphasizes long-term benefits rather than utilization, thereby permitting broader consideration of relevant factors leading to more efficient use of resources and optimization of human benefits. The Draft Articles also stress the importance of 'vital human needs', both as relevant to determination of equitable and reasonable utilization and to the management of emergency situations. Whilst such innovative features mark a departure from the established patterns of international water law, thus risking further legal fragmentation, they also present an opportunity for the latter's progressive evolution.

Phenomenon of Convergence in International Law

In response to the fragmentation of international law due to its continuing expansion and diversification, and the related development of increasingly autonomous sub-regimes, a counteracting integrative process of convergence is occurring due to 'the gradual interpenetration and cross-fertilization of previously somewhat compartmentalized areas of international law' (Cassese, 2001). Both phenomena may be viewed as interdependent processes necessitated by an increasingly extensive, sophisticated and specialized legal system (Craven, 2002). Fragmentation may be viewed as indicative of the success of the system of international law in addressing the problems of increasingly sophisticated inter-State interactions in an increasingly complex world, while convergence serves to restrain international law's disintegration in order to preserve the requisite degree of systemic unity.

Convergence is facilitated and supported by several centrally important institutions, by the continuing evolution and growing prominence of certain specialist sub-fields of international law, and by certain established processes employed in the formation of international rules. Most notable amongst the institutional drivers are the universalist instincts of the International Court of Justice (ICJ) in its role as the pre-eminent adjudicatory body concerned with the determination and application of international rules. Commentators note the Court's recent contributions to customary international law on human rights and environmental law, and development of the doctrines of *erga omnes* and *jus cogens* as illustrative of a transformation in its approach, which now acts 'as a force binding international subsystems "within a minimal communal sphere"' (Crawford, 2014; Paulus, 2005). Others suggest that '[t]he development of customary international law by the ICJ is now more likely to include human rights law, international trade law, environmental law, and other fields of international law which until recently seemed to fragment into autonomous regimes' (Andenas, 2015).

In addition, the ILC generally displays a tendency towards the identification and promotion of generally accepted normative positions in its central role in the codification and progressive development of international law, where ILC pronouncements 'carry unusual normative force and may help to resolve difficult legal issues' (Crawford, 2014). This assists in "nudging" international law in the direction of universality. Though this paper highlights above striking examples of where the ILC's codification efforts in respect of transboundary aquifers depart from its earlier work on international watercourses (ILC, 1994), most aspects of the Commission's codification work in both areas are complementary and mutually supportive. Crawford highlights the Commission's seminal work on State responsibility, where the proposed rules are elevated 'to a higher level of generality – from "primary" to "secondary" rules' (Crawford, 2014), which has contributed to wide-spread acceptance of the resulting Draft Articles on State Responsibility (ILC, 2001).

As regards law-making processes, the general use of codification initiatives as a key means of informing rational development of important and emerging areas of legal activity, even by learned societies and other bodies enjoying no law-making mandate formally conferred by States, further contributes to incremental progressive convergence around key legal values in many fields. In addition, other quasi-constitutional systemic processes embedded into the fabric of international law promote convergence, including the principle of "systemic integration" applying to the interpretation of treaties pursuant to Article 33(1)(c) of the Vienna Convention on the Law of Treaties, which has facilitated such 'interpenetration and cross-fertilization', notably between the sub-fields of international environmental law and water resources law (PCA, 2013).

As regards the growing prominence and pervasiveness of certain sub-fields of international law, the universal character of many human rights values may also contribute to the tendency towards convergence. Clearly, it would be difficult to include any provision in a modern water law instrument, applying either to groundwaters or surface waters, which might in any circumstances permit violation of a non-derogable obligation associated with the human right to water (UN CESCR, 2002). Similarly, the increasingly urgent relevance of environmental values, especially regarding biodiversity conservation and climate change mitigation and adaptation, impacts upon different sub-fields in a uniform manner. It is quite clear, that technical guidance and other practice developed under the Convention on Biological Diversity (*e.g.* on the 'ecosystem approach') and the Ramsar Convention (*e.g.* on the 'Wise Use of Wetlands') will exert considerable influence on the application of international rules relating to both groundwaters and surface waters.

Convergence and International Water Law

Despite the obvious scope for fragmentation in international water law, where no two shared basins are remotely similar hydrologically, environmentally, economically or socially, in its recent development it interacts intensively with other sub-fields of international law. As the most litigated aspect of recent international environmental and natural resources disputes, tribunals pronouncing on international water resources disputes have readily borrowed and assimilated values from related complexes of primary substantive rules including in particular international environmental and human rights law.

Despite the risk of fragmentation presented by the ILC's Draft Articles, over time the practice of international law appears to promote unity in the management of groundwater and surface water resources. This trend is illustrated by the 2017 decision of the Ministerial Forum of the Parties of the Orange-Senqu River Commission (ORASECOM) - a river basin organization (RBO) established between Botswana, Lesotho, Namibia and South Africa - to establish a Multi-Country Cooperation Mechanism for the Stampriet Transboundary Aquifer System (STAS MCCM), which lies within the basin. The STAS MCCM will facilitate joint management of the resources of the aquifer and coordination of the requirements applying to surface waters and groundwater resources. For example, ORASECOM will now have responsibility for activities related to the STAS, which have been incorporated into ORASECOM's 10-year IWRM Plan, running from 2015-2024. This is not an isolated example of the incorporation of groundwater within the activities of RBOs. In Southern Africa alone, similar initiatives have recently been adopted in the context of the Limpopo and Zambezi basins. In the context of the second cycle of national reporting on SDG indicator 6.5.2, on 'progress on transboundary water cooperation', the Danube States report that groundwater bodies of basin-wide importance are incorporated into the river basin management plan of the International Commission for the Protection of the Danube River (ICPDR). Highlighting the potential unifying role of such paradigms as the SDGs, the Second Report on SDG Indicator 6.5.2 suggests that '[i]n other instances, it may be necessary to update older [transboundary cooperation] arrangements in order to integrate principles

… which account for both surface water and groundwater' (UNECE/UNESCO, 2021).

Through international water law's dynamic and intensive interactions with other sub-fields, it typifies the processes of 'interpenetration' and 'cross-fertilization'. Evolving practice in the field demonstrates each of the key means of addressing normative incompatibility (Craven, 2002). For example, 'rules of hierarchy' appear to be emerging, under which human rights values take priority, followed increasingly closely by ecological values. The human rights values correspond with international water law's traditional emphasis on providing for "vital human needs" and are increasingly informed normatively by the global discourse on the human rights of access to adequate water and sanitation, and by the elaborate implementation framework developed for realization of Sustainable Development Goal (SDG) 6. In turn, the ecological values correspond with increasing recognition of the imperative of protecting water-related ecosystems and maintaining the ecosystem services and human benefits provided thereby. Such 'environmentalization' of International Water Law' (Canelas de Castro, 2015) has resulted in many key imperatives of international environmental law becoming central features of international water law. In the celebrated *Pulp Mills* case, for example, the ICJ recognized the customary status and universal applicability of the requirement to conduct environmental impact assessment (EIA) of a major project potentially impacting a shared watercourse (ICJ, 2010), and hence its critically important role in discharging the core duty, contained in all water resources instruments, whether concerned with groundwaters of surface waters, to notify other aquifer or watercourse States of such planned measures. Further, 'machinery for institutional dialogue' plays an increasingly important role in ensuring such 'permeation' and 'cross-fertilization'. For example, the Conferences of the Parties and Secretariats of the Convention on Biological Diversity and the Ramsar Convention on Wetlands continue to elaborate detailed guidance on the integration into international water law instruments and practice of ecosystems obligations arising under each of these flagship global environmental conventions.

As regards the most egregious form of fragmentation, that of secondary or "structural" rules, including rules relating to 'the source of obligation, the identity of relevant actors, the method by which competing interests are to be weighed, or the basis for responsibility – that seems to call into question the integrity of the whole' (Craven, 2002), international water law similarly demonstrates the operation of convergence, thereby contributing to the systemic integrity of international law more generally. As regards 'the source of obligation', for example, foundational cases in the area have turned upon determination of the respective limits of States' rights and duties emanating from territorial sovereignty (*Lac Lanoux*, 1957) or upon radical approaches to the general rules of treaty interpretation, including the contextually informed principle of 'contemporaneity' (ICJ, 1997) and pioneering application of the principle of 'systemic integration' (PCA, 2013). Other cases have focused upon the role and character of intergovernmental institutions in the discharge of procedural obligations and elements of due diligence conduct (ICJ, 2010). As regards 'the identity of relevant actors', international water law works within the traditional confines of international law to adapt to emerging requirements to facilitate participation of relevant stakeholders or the wider public, with the 1992 UNECE Water Convention regarded as 'arguably leading the charge on producing instruments which strengthen joint institutions and stakeholder participation' (Moynihan, 2017). Possibly no other sub-field of international law is so concerned with elaborating 'the method by which competing interests are to be weighed', since such a process comprises the core of equitable and reasonable utilization, the overarching cardinal principle of international water law. As regards the 'basis for responsibility', a recent case saw the ICJ extend the application of secondary rules on State responsibility to a new class of transboundary harm, *i.e.* the loss by one State of the beneficial enjoyment of water-related ecosystem services due to ecological damage caused by another (ICJ, 2015/2018). Thus, despite its specialized, context-specific character, international water law appears to counteract threatened fragmentation of the 'systemic rules' of international law through resort to the universally applicable general rules and institutions of international law. Indeed, it might be understood to address the unavoidable complexity of its subject-matter by employing context sensitivity in the application of general rules, typified by the overarching principle of equitable and reasonable utilization.

Conclusion

There is every reason to believe that legitimate concerns regarding the risk of fragmentation of the rules of international water resources law, presented by aspects of the ILC's 2008 Draft Articles, may largely be obviated by higher order forces operating to maintain the systemic integrity of international law more generally. Thankfully, the systemic nature of international law endows it with greater unity of vision and greater clarity and singularity of purpose than those institutions sometimes charged with the elaboration and development of its constituent parts.

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TOPIC 4/Paper 22

Transboundary Groundwater in International Law

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Abstract

The strategic importance of groundwater is on the rise due to a variety of factors, most notably climate variability. Of the 366 documented transboundary aquifers and 226 transboundary "groundwater bodies", only seven are covered by a formal agreement. This research traces the steps that have led to the recognition of groundwater in the agreements among States. The UN Draft Articles on the Law of Transboundary Aquifers (2008) receives special attention in view of its importance as a reference for States. The analysis of the Draft Articles is complemented by the analysis of the handful formal agreements on record regarding specific aquifers. A few arrangements on record are also canvassed as well as global soft-law instruments. The analysis reveals that State practice in the matter is evolving, and that a binding agreement at the global level is desirable.

Keywords: transboundary aquifers, groundwater, international law

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Introduction

Unsustainable freshwater exploitation patterns, water pollution, and climate variability have all been contributing to groundwater's growing strategic importance. Groundwater represents 97% of total freshwater on the Planet, and it is stocked in geological formations known as aquifers, a number of which are common to two or more States.

It is worth highlighting and clarifying at the outset that international water law draws a distinction between groundwater and aquifers, even though no such difference seems to exist *prima facie*. In particular, "groundwater" is the water found in the subsurface within a saturated geologic formation; therefore, water that is found beneath the surface, but not within a "saturated formation" will not be defined as groundwater (Eckstein, 2017). An aquifer is found underground and includes two elements: a geological formation capable, because of its characteristics, of "water bearing" and groundwater itself. It is precisely such double profile that has implications from an international law perspective, in the sense that international law canvasses not only the rights and obligations related to the management of the fluid element of an aquifer (groundwater), but also those related to the management of the combination of the fluid and the static (geologic formation) components of an aquifer (Sindico, 2020).

In this connection, it has been argued (by Rivera 2021) that when a new agreement is being contemplated, a preliminary question to ask is: should such agreement be about just groundwater, or should it reach out to the aquifer, i.e., groundwater and the geologic formation where groundwater is found?

When groundwater and/or an aquifer traverse two or more jurisdictions the scale of the dynamics of groundwater flow or storage, must be considered, along with the specific conditions and local circumstances of a particular aquifer. The implication is that for simpler locally based groundwater scenarios, it would be possible to define effective TBA areas by identifying the priority areas of an aquifer using pumping hot spots (Sanchez et al., 2020). Management of groundwater at the scale closer to the jurisdictional boundaries seems preferable to management of the full aquifer, but at the same time improved shared governance of the full aquifer is desirable to avoid aquifer misuse (Rivera, 2021).

In particular, and with reference to agreements among States regarding transboundary aquifers, it bears emphasizing that State practice is under development, and that there is no legally binding global legal instrument to-date. Of the 366 known transboundary aquifers (TBAs) (UN-IGRAC, 2021), seven are covered by formal agreements, while five are covered by other kinds of arrangements.

Towards the full recognition of the transboundary nature of aquifers in the relevant agreements among States

By the mid-20th century, transboundary groundwater had attracted attention, however marginal relative to the focus of water treaties (Eckstein, 2017). In parallel, the full recognition of the link between surface water and groundwater has emerged in many a surface water treaty made in the last decades. The growing awareness of the importance of preserving these vital resources from over-exploitation and from pollution has led some authoritative observers to conclude that the importance of cooperation among the countries concerned must not be under-estimated (Stephan, 2009).

The Draft Articles on the Law of Transboundary Aquifers

The most important international instrument, however non-binding, for transboundary aquifers is the Draft Articles on the Law of Transboundary Aquifers (Draft). The Draft originated from the UN International Law Commission (2002-2008), and it was eventually appended to UNGA Resolution 63/124 of December 2008, as a non-binding instrument for the guidance of States in the negotiation of agreements on transboundary aquifers.

The Draft is patterned after the 1997 UN Convention on the Law of the Non-navigational Uses of International Watercourses (UNWC), with adjustments due to the vulnerability of aquifers to pollution and to over-exploitation (Quadri, 2022). Although the Draft Articles are not a legally binding instrument, a few "core" substantive and procedural norms in the Draft reflect customary international law. It is worth emphasizing in this connection that these few customary norms are legally binding universally, regardless.

An aquifer under the Draft consists of the rock formation underground and the water that is contained in it (Sindico, 2020). In addition to "uses" of the aquifer, the Draft includes all activities that can harm it. The Draft carries two key substantive rules: the first acknowledges the right of States to the equitable and reasonable utilization of transboundary aquifers and obligates States to maximize the long-term benefits from the use of such aquifers. The second rule inhibits States from causing significant cross-border harm. The procedural norms regard to monitoring, the exchange of data and information among States, and the duty of States to provide prior notice of planned measures that can have a cross-border impact.

The environment protection norms of the Draft assume a particular importance in view of the vulnerability of aquifers (Eckstein, 2017). States are to take all appropriate measures to protect and preserve the ecosystems within or dependent upon a transboundary aquifer, and to ensure adequate recharge and discharge flows. Pollution prevention and minimization obligations, that are of particular importance to the natural recharge of aquifers, reflect the same kind of concerns. These norms combined aim to respect the entire ecosystem, and to safeguard the ecosystem support function of transboundary aquifers (Burchi, 2009).

The principle of limited sovereignty

The limited sovereignty of States over transboundary aquifers enables good neighbourly relations among aquifer States, based on a community of interests (Rieu-Clarke et al., 2012). Such community of interests is the outcome of a convergence of state interests, bringing them together and rooted in the shared nature of the resource. The principles underlying the limited sovereignty theory and the Draft Articles as a whole respond to the need to safeguard the political, social and economic equilibrium of states in the management of shared water resources.

The limited sovereignty principle is enshrined in Article 3 of the ILC Draft Articles, whereby each state has sovereignty over the portion of a transboundary aquifer situated in its territory.

At the same time, however, the exercise of such sovereignty is qualified by the rules of general international law, and by those posited in the Draft Articles, to the effect that: 'Each State has sovereignty over the portion of a transboundary aquifer or aquifer system located within its territory. It shall exercise its sovereignty in accordance with international law and the present articles'. The second sentence bears out the limited sovereignty concept, as sovereignty must be exercised in conformity with international law and the Draft Articles. In good substance, states have sovereignty over the portion of a shared aquifer situated in their respective territory; however, sovereignty is relative, or attenuated by the principle of equitable and reasonable utilisation posited by Article 4, by the duty not to cause harm according to Article 6, and by the balance of the Draft Articles.

Professor McCaffrey is of a different opinion, however, arguing that Article 3 suggests an absolute sovereignty principle (McCaffrey, 2009).

He argues that while nations may have sovereignty over "the rock", they cannot have sovereignty over the water contained within the formation. A State simply cannot have the exclusive ownership that sovereignty implies in something that is shared with another State (McCaffrey, 2011). He argues that the provision is contrary to customary international law applicable to international watercourses.

Today, the theories of absolute sovereignty (Rieu-Clarke et al., 2012) as well as those of the absolute integrity of riparian states to a shared watercourse, have been largely superseded by customary international water law, as reflected in the Draft Articles and in the New York Convention from where it is derived. The equitable and reasonable utilisation principle, embedded as it is in the community of interests of the states concerned, is the natural spin-off of the irreconcilable theories about sovereignty.

Agreements and arrangements concerning transboundary aquifers

Seven known formal agreements are on record. The Agreement on the Genevese Aquifer (1977, renegotiated in 2007), was made by French and Swiss local authorities on the two sides of the border. It is a complex instrument providing for technical mechanisms for the joint management of the aquifer, and for a permanent bi-lateral Commission with consultative status (De los Cobos, 2018).

Three agreements were made by Chad, Egypt, Libya and Sudan for the Nubian Sandstone Aquifer System (NSAS), the first (1992) providing for a Joint Authority, the other two – made in 2000 – on monitoring and data and information sharing (Quadri, 2019).

A Consultation Mechanism for the joint management of the North-Western Sahara Aquifer System (NWSAS or SASS, for its French acronym) emerged as a result of intense cooperation among the countries concerned, i.e., Algeria, Libya and Tunisia, that climaxed in 2002 in a Coordination Unit assisted by National Focal Points, hosted by the Sahara-Sahel Observatory (OSS). A Council of Water Ministers, a Permanent Technical Committee and National Committees were added in 2006. The Consultation Mechanism manages the data base, promotes monitoring and research, and keeps the aquifer model up to date. A Protocol was drafted in 2015 to further strengthen cooperation among the aquifer countries (Taibi, 2017).

A MoU was made in 2014 by the countries that share the Iullemeden and the Taoudeni/Tanezrouft Aquifer System (the two aquifers combined known as ITTAS) - Algeria, Benin, Burkina Faso, Mauritania, Mali, Niger, and Nigeria. The MoU replaced a prior MoU on the Iullemeden Aquifer System alone, made in 2009 by Niger, Nigeria and Mali (Burchi, 2018).

The ITTAS MoU added a Permanent Technical Scientific Committee and a Coordination Unit and elaborated on the substantive and the procedural norms that were codified in the 2009 MoU. The new MoU is quite an advanced instrument; however, it is not in effect as yet as three of the ITTAS States have failed to sign in to-date (Eckstein, 2017).

The 2010 Guaraní Aquifer Agreement sealed cooperation among Argentina, Brazil, Paraguay and Uruguay that had been underway since the early 2000's for the survey and monitoring of the giant aquifer. The agreement came into effect in 2020 and carries substantive and procedural principles that are patterned after the Draft Articles reviewed earlier and provides for a Commission that coordinates cooperation and oversees the implementation of the agreement (Sindico et al., 2018).

In 2015, Jordan and Saudi Arabia signed an agreement for the controlled exploitation of the Al-Sag/Al-Disi aquifer. A five-year moratorium was agreed on extractions of groundwater from a Protected Area, while extractions from a wider Management Area are restricted to domestic use. Polluting activities in the latter area are banned.

A Joint Technical Committee oversees the implementation of the agreement, monitoring and the exchange of information (Eckstein, 015).

Other known arrangements on record range from the 1996 MoU between Canada's British Columbia and the US Washington State regarding the Abbotsford-Sumas aquifer to the 1999 MoU between the cities of Ciudad Juarez, Mexico and El Paso, Texas, regarding the Hueco Bolson aquifer. Others more recent such as the 2017 MoU between the municipalities of Concordia (Argentina) and Salto (Uruguay) regarding the Guaraní Aquifer, the Stampriet Aquifer System (STAS) countries – Botswana, Namibia, South Africa – which has the objective to nest a Cooperation Mechanism for the aquifer within the Orange-Senqu River Commission (2017), and the Statement of Intent committing stakeholders from El Salvador and from Honduras to cooperation in respect of the transboundary Ocotepeque - Citalá Aquifer (2019).

These kinds of arrangements, ranging from formal MOUs and from the official decision of an intergovernmental body to a much less formal Statement of Intent, seem to point in the direction of alternative models for the management of transboundary aquifers. Another notable example is the Ramotswa Project, that generated in 2019 a joint Strategic Action Plan (SAP). In this case, the management of the aquifer has been subsumed in the existing Limpopo Watercourse Commission (LIMCOM) (Sindico, 2020). In the specifics, a Groundwater Sub-Committee has been created within LIMCOM, for the coordination of aquifer-related activities among the four countries that have it in common, i.e., Botswana, Mozambique, South Africa and Zimbabwe, all four being LIMCOM member States.

Another example is the arrangement model developed by the Protection and Sustainable Use of the Dinaric Karst Transboundary Aquifer System – DIKTAS, shared by Albania, Bosnia-Herzegovina, Croatia and Montenegro (2010-2014), which pioneered the integrated and sustainable management of a karstic aquifer in a transboundary context. In particular, the relevant arrangement consisted of a two-tier mechanism comprised of National Interministerial Committees (NICs) and a regional-level Groundwater Committee (Sindico, 2020).

Soft law instruments: UNECE Model Provisions on Transboundary Groundwater

The "Model Provisions on Transboundary Groundwater", adopted in 2012 by the Parties to the UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes, are in the nature of a soft law instrument for the guidance of the Parties to the Convention with specific regard to transboundary groundwater, and with a view to facilitating the implementation of the Convention in that regard (Tanzi, 2015). Based on the UN Draft Articles, the Model Provisions carry also norms of customary international water law that are binding universally.

Conclusions

The following conclusions can be drawn from the foregoing analysis. Despite the growing recognition of the importance of groundwater in several international instruments, state practice in the matter of cooperation regarding transboundary aquifers is scanty. Specific mention and references to groundwater have begun appearing only recently, and the relevant international law is under development and evolving. This is mainly due to the scarce information, knowledge, and experience regarding this "hidden" resource, that have resulted in less than appropriate and sustainable management approaches. Lack of knowledge has been an obstacle to the development of specific management models at the regional and universal scale. It has also impeded regular resource monitoring, which is critical to the assessment of aquifer change over time, notably regarding groundwater levels, extractions, and recharge. All these factors have contributed to slowing down cooperation over transboundary aquifers. Still, it is a fact that these have attracted increasing attention in the last two decades as a result of the growing demand for water, and of the increasing awareness of the international community and of governments of the urgency to protect an increasingly scarcer and vital natural resource.

Given the lack of a legally binding global instrument governing transboundary aquifers, for the time being, the UN Draft Articles remain the most authoritative reference for States on a global scale. The guidance value of the Draft Articles in the negotiation of future transboundary aquifer agreements is crystallized in the UN General Assembly resolutions regarding the Draft Articles. With due allowance for their being in a *soft law* instrument, the Draft Articles mark a significant step forward in the development of international law in the matter of transboundary aquifers. Upgrading the entire Draft Articles, and all the several norms of inter-State behaviour to the status of a legally binding instrument of universal application, including rules for the settlement of disputes among States, would be a desirable further step forward in that direction. Such upgrading would crystallize the emergence of norms for the international community to be bound, that could be precise enough to ensure the protection and sustainable development of transboundary aquifers. In this connection, this author hopes that a global consensus around this course will form in view of the next round of discussions on the format and status of the Draft Articles, that is scheduled on the occasion of the 2024 regular session of the UN General Assembly.

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TOPIC 4/Paper 23

A 30 Year Evaluation of JA-NSAS as a Pioneer Regional Organization for the Management of Transboundary Aquifers

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Abstract

The Nubian Sandstone Aquifer System (NSAS) is one of the largest aquifer systems in the world, covering approximately 2.2 million km^2 in Northeast Africa. It extends for over 1,500 km in the East-West direction and 1800 km in the North-South direction across Chad, Egypt, Libya, and Sudan. Near the oasis of Kufra, NSAS reaches a maximum thickness of more than 4000 m. The hydraulic head ranges from 570 m above sea level west of Darfur to 78 m in the Qattara depression. The total volume of freshwater stored in the NSAS was estimated at 450,000 km^3, of which around 14,000 km^3 are recoverable.

Thirty years ago, the four NSAS countries laid the building blocks for cooperation in managing the shared aquifer system. Egypt and Libya started the process in the early 1980s and culminated in 1991 with the establishment of the Joint Authority for the Study and Development of NSAS (JA-NSAS). The constitution of the Joint Authority was adopted in 1992. Sudan joined the Joint Authority in 1996, and Chad followed suit in 1999, making all riparian states members of JA-NSAS and abiding by the principles of the joint management of this important transboundary basin.

The functions of JA-NSAS include the periodic collection of field data, carrying out supplementary studies on the state of the aquifer, preparing plans for water resource development, proposing and implementing joint policies for the rational utilization of water resources, and assessing their environmental impacts at the national and regional levels, and organizing training courses and capacity building.

Over the past 30 years, more than 30 meetings of the Board of Directors have been held to set general policies and follow up the activities of the subsidiary offices in the Member States. International and regional organizations such as IFAD, UNESCO, IAEA, IDB, GEF were approached for funding regional hydrogeological studies and devising strategies for the sustainable exploitation of the shared aquifers, elaborating socio-economic studies, updating the mathematical model and database, and preparing a Strategic Action Program.

Major steps have been taken thus far to enhance institutional capacity and secure the flow of technical information. They include establishing a common network of production and monitoring wells, developing mathematical models capable of simulating various exploitation scenarios, and signing a protocol for monitoring and exchanging groundwater information. Data on annual extraction, water quality, and water levels from the regional monitoring network, as well as the socio-economic and environmental data and drilling results, are systematically entered into the Nubian Aquifer Regional Information System (NARIS).

Keywords: Nubian Sandstone Aquifer System, Joint Authority, Transboundary Aquifers.

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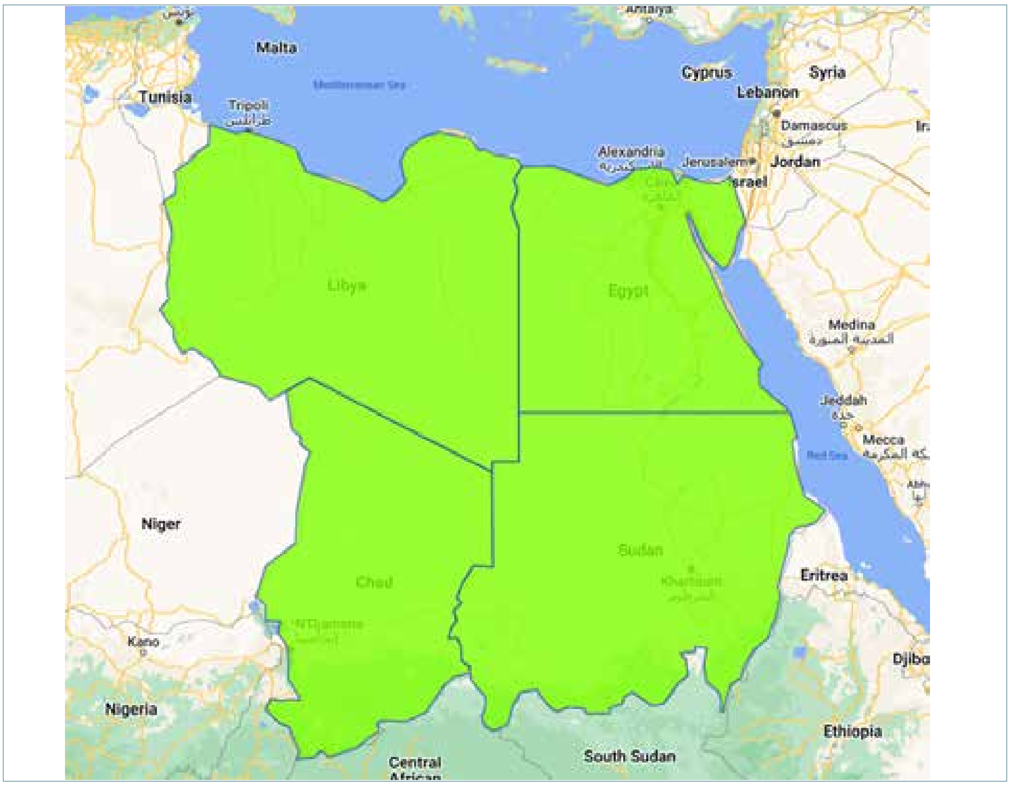
Introduction

The Nubian Sandstone Aquifer System (NSAS) is one of the largest groundwater basins in the world, covering approximately 2.2 million km^2 of the eastern part of the Sahara Desert in the four riparian countries of Chad, Egypt, Libya, and Sudan. The bulk of the NSAS is located within Egypt and Libya at 828,000 km^2 and 760,000 km^2 respectively while Sudan and Chad share relatively smaller portions of 376,000 km^2 and 235,000 km^2 respectively (Fig. 1).

Figure 1.
Location map of the NSAS



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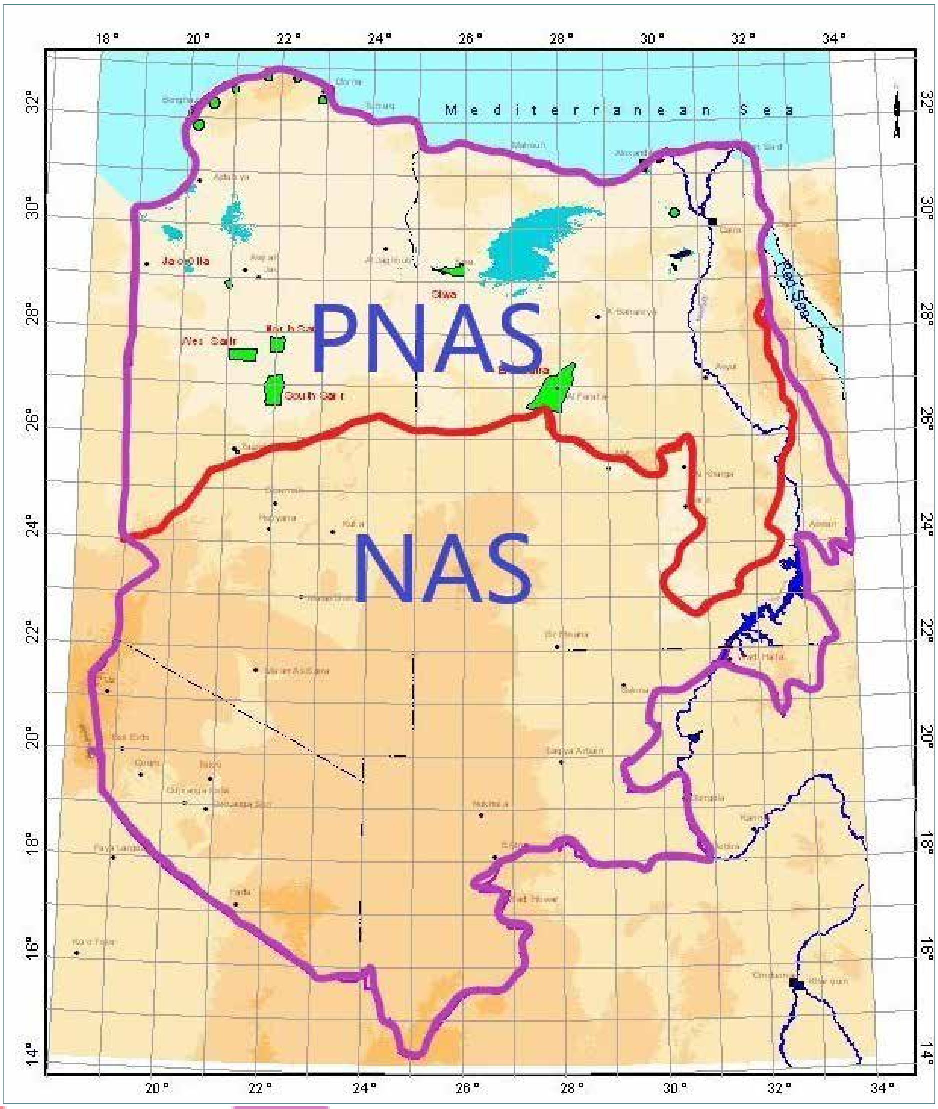
General Characteristics of the NSAS

Two sub-basins are known to form the NSAS: the Nubian Aquifer System (NAS) and the Post-Nubian Aquifer System (PNAS) (Fig. 2). The former is a multi-layered aquifer system ranging in age from Cambrian to Lower Cretaceous with a thickness ranging from 500 to more than 4000 m at the center. It underlies the whole area of NSAS in the four states. However, north of latitude 26° N in Libya and Egypt, it occurs at great depths under the PNAS and loses importance due to poor hydraulic properties and high salinity. South of latitude 26° N, NAS is unconfined for the Mesozoic upper aquifer to semi-confined or confined for the Palaeozoic deep aquifers. In general, it consists of thick sandstone layers with intercalations of clay. The upper unconfined part of the NAS is widely exploited in the four countries for agricultural and domestic purposes. Transmissivity values for the total thickness of the NAS range from 100 m2/d near basement outcrops to over 10,000 m2/d at the central and northeastern parts where the thickness exceeds 3000 m while storativity falls between 7x10-5 and 2.7x10-2 for the confined and semi-confined conditions respectively. The water quality of the unconfined NAS ranges from a TDS of less than 500 mg/l to 1000 mg/l. In the confined part, however, water quality deteriorates rapidly northward in the deep Paleozoic aquifer to exceed 10,000 mg/l, while the upper part (Mesozoic) maintains relatively fresh water with TDS of less than 2000 mg/l.

The PNAS overlies the NAS north of latitude 26° N within Egypt and Libya and consists of a number of sandstone and carbonate aquifers ranging in age from Upper Cretaceous to Quaternary. PNAS aquifers are mostly confined and have relatively inferior properties compared to NAS. They are mainly exploited for local community development and for the irrigation of large-scale agricultural projects, and in Libya, as a source for water transfer to northern regions through the Great Man-Made River Project.

Figure 2.
Boundary of the NAS/PNAS



NAS/PNAS Boundary

Boundary of the NSAS

NSAS has undergone several studies in the past few decades with a particular focus on its ability to meet growing long-term demand. Regional and local mathematical models were used to simulate the future behavior of the aquifers in response to different production scenarios. The volume of freshwater stored in the NSAS is very high. One study estimated it to be about 457 thousand cubic kilometers, of which only 14 thousand cubic kilometers are exploitable. These figures may represent a theoretical upper bound, but they do reflect the enormous size of groundwater reserves in this transboundary aquifer system.

The direction of groundwater flow in the NSAS is from the southwest to the north and northeast towards the natural depressions, coastal sabkhas, and the Mediterranean Sea. The hyper aridity of the Sahara implies that groundwater in the Nubian Basin is very old with little or no modern recharge.

The Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System

Large-scale development of the NSAS started in the early 1960s in the western desert of Egypt in the oases of Dakhla, Kharga, Farafra, and Bahareya and more recently in Siwa and East Oweynat. Ten years later, Libya launched new irrigation projects in Kufra, Tazirbu, Sarir, and Jalu, and at a later stage the Man-Made River project to transfer water to coastal areas.

As a result, total groundwater abstraction from the NSAS including northern Sudan jumped from 197 Mm3 in 1960 to 1375 Mm^3 in 1998. On the other hand, abstraction from the PNAS in Libya and Egypt also witnessed an increase from 94 Mm3 in 1960 to 911 Mm^3 in 1998 (Table 1). Systematic monitoring of drawdown in the areas of intense exploitation revealed a gradual expansion of the cones of depression. Drawdown contour maps of 1998 reveal a progressive increase in water level decline ranging from 20 to 60 m at the center of the wellfields in the NAS and from 4 to 7 m in the PNAS (in Libya) but fading out within a few kilometers outward.

Table 1.
Groundwater abstraction (Mm3/y)

	Year	1960	1970	1980	1990	1998
NAS	Egypt	195.40	331.32	350.70	519.10	683.24
	Libya	2.00	39.20	209.28	250.90	285.55
	Sudan					406.74*
	Total	197.40	370.52	559.98	770.00	1375.53
PNAS	Egypt	66.75	66.70	66.68	235.73	346.01
	Libya	27.50	75.35	310.13	571.64	565.35
	Total	94.25	142.05	376.81	807.37	911.36

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*Mostly from the Nile Nubian Basin which is not considered part of NSAS

Given that groundwater is the only source of development in the desert region and taking into account the steady population growth and future water demand, Egypt and Libya decided to establish close coordination between their authorities responsible for the management of this shared aquifer system.

Accordingly, the establishment of the Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System (JA-NSAS) was declared in Tobruk (Libya) during a summit meeting on 17 October 1989. The establishment protocol was subsequently signed by the respective Ministers in Tripoli in October 1992 during the third round of the Libyan-Egyptian Joint High Committee chaired by the two Prime Ministers. The protocol stipulates that the city of Tripoli hosts the headquarters of the JA. Members of the Board of the JA were then nominated from both sides. The remaining countries sharing the NSAS were invited to become full-fledged members of the JA. Both Sudan and Chad were admitted to the JA during the second Board meeting in April 1995 and the fourth Board meeting in March 1999 respectively.

Objectives and functions of the Joint Authority

The JA was entrusted with the following tasks:

- Collection, analysis, integration, and dissemination of data and studies from member states;
- Conducting complementary hydrogeological studies;
- Planning for the development of water resources according to agreed exploitation policies at national and regional levels;
- Implementing joint capacity building programs and exchange of experiences;
- Ensuring rational use of the NSAS water;
- Assessing the environmental impact of water development with a focus on combating desertification and the use of renewable energies;
- Organizing scientific workshops and seminars related to the aquifer system;
- Consolidating ties with corresponding regional and international organizations.

The administrative structure

The JA is managed by a Board of Directors consisting of (12) members, three from each country, and chaired alternately among the member countries for a term of two years. A full-time Executive Director is appointed by the Board to carry out executive tasks such as implementing the decisions and recommendations of the Board, following up on technical studies and training programs, preparing meeting minutes, and supervising the administrative and financial staff.

The Board of Directors holds two meetings each year at its headquarters or in one of the member states. A quorum is reached by the presence of two-thirds of the members from each side. Decisions are taken by consensus among the attendees, and in case of differing views, the matter is referred to higher authorities in each country for consideration. JA maintains national offices in each of the capitals of the member states.

Funding sources

The annual budget of the Authority, after its approval by the Board of Directors, is financed from the contributions of member states in equal shares. The Authority also receives financial support from relevant international organizations such as the International Fund for Agricultural Development (IFAD), the International Atomic Energy Agency (IAEA), and the Global Environment Facility (GEF) to finance some key studies.

Key studies

The JA has carried out several studies on the state of water resources of NSAS and its rational management for sustainable development. The key studies include:

1. *The Regional Strategy for the Utilization of the Nubian Sandstone Aquifer System (2001).* The study was launched in 1998, funded by IFAD, and executed by the Center for Environment & Development for the Arab Region and Europe (CEDARE). The main objective of the study was to "formulate a regional groundwater development strategy aimed at optimizing levels of groundwater withdrawal from the Nubian Sandstone Aquifer System in each country in order to avoid any negative reciprocal externalities". The study included:

- Compilation and synthesis of existing data and information in the fields of geography, geomorphology, hydrography, geology, and hydrogeology.
- Development of a regional mathematical model to simulate the aquifer response to future water abstraction scenarios.
- Capacity building of national institutions and technical staff.
- Development of a database known as the Nubian Aquifer Regional Information System (NARIS) to fulfill the following tasks:
- store, search and retrieve information about the NSAS such as water levels, drawdowns, stratigraphy, hydraulic parameters, water quality, extractions, etc.;
- Provide an integrated regional information system among the riparian countries thus ensuring the sharing, exchange, and flow of information;
- Assist the decision-makers by providing relevant and accurate information about the status of NSAS;
- Provide a standardized method for data collection and entry;
- Identify data gaps and overlaps;
- Prepare the input parameters for the groundwater model.

A mechanism for data entry, data update, and data transfer is available for each country, in accordance with a regional mechanism for data sharing and exchange agreed by the four countries in October 2000, where data is stored in a server and accessed only by the four countries through the internet. NARIS is managed by JA Headquarters and consists of two components: the groundwater component, and the bibliographic database component. Initially, the groundwater component comprises 2018 wells (732 observation wells, 1088 production wells, and 198 exploration wells), while the bibliographic component comprises 843 references from previous studies. A second phase of the project covered the socio-economic component and was financed by the Islamic Development Bank (IDB).

2. *The Formation of an Action Programme for the Integrated Management of the Shared Nubian Aquifer (2010).* The study was launched in 2005 and was funded by GEF and IAEA with UNDP as the implementing agency and IAEA as the executing agency. The immediate objectives of the study are to:

- Prepare and agree on a Shared Aquifer Diagnostic Analysis (SADA);
- Address key methodological, data, and capacity gaps needed for strategic planning decisions;
- Prepare a Strategic Action Programme (SAP) to outline the necessary legal, policy, and institutional reforms;
- Establish an agreed legal and institutional mechanism toward an NSAS convention for joint four-partite management and rational use of the shared NSAS System.
- The study included an updated mathematical model and a comprehensive isotope hydrology survey.
- The agreed Strategic Action Programme (SAP) was endorsed by the Water Resources Ministers of the riparian countries at a meeting held at IAEA headquarters in Vienna on 18 September 2013.

3. *Enabling implementation of the Regional SAP for the rational and equitable management of the Nubian Sandstone Aquifer System (NSAS).* An updated and finalized version of the SAP project document was approved by the Board of Directors on 26 August 2021. Preparations are underway to launch the project which will be funded by GEF, implemented by UNDP, and executed by UNESCO. The project will in particular:

- Address gaps in knowledge on the NSAS resources and dependent ecosystems;
- Support capacity development at local, national, and regional levels;
- Facilitate national reforms on policies necessary to successfully implement the SAP and support the formulation of National Action Plans linked to the SAP;
- Utilize the results from four pilot actions to demonstrate improved management approaches at the national and local levels;
- Identify future financing options to assist in the longer-term implementation of the agreed SAP.

The project will therefore complement the previous study projects and will enhance the capacity of the JA to better manage the NSAS resources. Furthermore, the project will ensure regular monitoring of aquifers' response to local pumping plans and revitalization of the Regional Database (NARIS).

Shortcomings

In the year 2000, two agreements were signed on the establishment of a regional monitoring network for monitoring changes in water quality and water levels in the NAS and the PNAS, in addition to groundwater abstractions, and the exchange of gathered information through (NARIS). However, despite the efforts made by the JA and the National Offices in organizing data collection campaigns, there remain clear gaps and discontinuities, especially with regard to water quality and groundwater abstraction. As a result, the processing and dissemination of data using NARIS is irregular or even absent in recent years. The JA and the National Offices are also understaffed and financially under-resourced.

Population growth will lead to increased abstraction with excessive water level decline and increased salinity which will inevitably damage the natural ecosystem. Detailed hydrogeological studies are therefore urgently needed to avoid an environmental catastrophe.

The lack of periodic updating of the regional model or the development of detailed local models impedes making strategic decisions about the pattern and distribution of exploitation in the threatened areas of the basin.

The absence of a binding legal framework that addresses aspects related to the nature of transboundary waters also impedes the rational and sustainable collective management of these vital resources for the benefit of all states.

Accordingly, the JA is required to achieve the objectives stipulated in its establishment decree and to activate all agreements related to monitoring and information exchange.

Conclusion

The JA-NSAS is one of the leading organizations in the field of transboundary basin management with over three decades of continuous operation. Notable achievements in the form of conducting major regional studies and developing long-term strategies have been made mainly through external funding by international organizations. However, in recent years, JA has faced some difficulties that hindered moving forward in achieving its set goals. Among such difficulties are:

- Political instability, insecurity, and frequent replacements of board members;
- Interruptions in collecting field data needed to feed the NARIS data exchange system;
- Delay of financial contributions by member states;
- Cancellation of meetings and training programs due to the COVID-19 pandemic.

The JA will soon begin implementing the Strategic Action Plan (SAP) through which several priority issues will be addressed, including strengthening institutional, regulatory, and legal frameworks, raising the capabilities and performance of JA and its national offices, as well as intensifying field data collection campaigns and activating databases and mathematical models.

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TOPIC 4/Paper 24

Governance of the Guarani Aquifer: Creating a Commission

Catherine Tinker[1]

Abstract

The Guarani Aquifer Agreement of 2010 was ratified by late November 2020 by all four states containing portions of the vast Guarani Aquifer. Argentina, Brazil, Paraguay and Uruguay accepted binding legal duties with the objective to "promote conservation and environmental protection of the Guarani Aquifer so as to ensure multiple, reasonable, sustainable and equitable use" of its water resources" (GAA, Article 4) and the duty not to cause "significant harm" to the other parties or to the environment (GAA, Art. 6). Monitoring and management are left to each state over that part of the aquifer within their territory, the great majority of which is in Brazil. The treaty establishes obligations of cooperation among the four states, including sharing of information and scientific data on the aquifer; notification of planned measures; consultation, negotiation, and mediation; and referral of disputes to the Commission for recommendations. The treaty's substantive and procedural obligations are also found in other international and regional treaties, customary international law, and soft law declarations such as the United Nations International Law Commission Draft Articles on Transboundary Aquifers adopted by the General Assembly in 2008. The institutional mechanism established in the treaty is a Commission, which has not yet met or adopted its rules. This paper recommends that the Commission create a Secretariat and a Scientific and Technical Body to assist and advise the Commission on research and coordination, as in other regional and multilateral environmental agreements. Protection and conservation of the Guarani Aquifer System and its groundwater requires cooperation, continuing scientific and technical research, and education through an activated Commission working together with the relevant states party to the Guarani Aquifer Agreement as water demand grows and droughts recur in the region. Availability of sufficient fresh water for present and future generations depends on compliance with the treaty's rules, Commission procedures once adopted, and subsidiary governance mechanisms established with the flexibility to respond to new scientific or technical discoveries, the effects of climate change, local needs, and future legal developments.

Keywords: groundwater, governance, Guarani Aquifer

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Introduction: The Guarani Aquifer Agreement and International Law

A nascent governance framework was created for the Guarani Aquifer, a confined transboundary aquifer, with the signing of the Guarani Aquifer Agreement in 2010 by Brazil, Argentina, Paraguay and Uruguay. By 26 November 2020, the Guarani Aquifer Agreement (the Agreement or GAA) entered into force after ratification by all four states (Sindico, 2021), but the Commission designed as the institutional mechanism in the treaty has not yet begun to act. The Agreement is intended to foster cooperation regarding the aquifer system and requires sharing scientific research and data and exchange of information among the four states containing the Guarani Aquifer System and an earlier Strategic Action Plan (Hirata, Kirchheim & Manganelli, 2020; IGRAC Transboundary Aquifers of the World Map, 2021).

The treaty's objective is that *"states shall promote conservation and environmental protection of the Guarani Aquifer so as to ensure multiple, reasonable, sustainable, and equitable use of its water resources."* Conservation and sustainable, reasonable and equitable use of non-renewable natural resources are foundational principles of international environmental and water law applicable to transboundary aquifers. These norms are found in treaties such as the UN ECE Water Convention and multilateral treaties on climate change and loss of biodiversity; customary international environmental law principles of "no-harm" and sustainable development from oft-repeated UN documents over 50 years; and soft law such as United Nations resolutions (Sindico, 2020).

A cardinal international law principle elaborated in the GAA is the duty to avoid "*significant harm*" to the territory of other states or to the environment (GAA, Art. 3, 6). If such harm does occur, there is a duty to mitigate the damage (GAA, Art. 7). Territorial sovereignty of each of the four states over portions of the Guarani Aquifer is affirmed in the GAA, with states' authority to monitor and manage the portions of the aquifer located in their state subject to "*reasonable and sustainable uses criteria*" (GAA, Art. 3). One important limitation on sovereignty in the treaty is that states must act in agreement with *"the principles and norms of international law."* (GAA, Art. 2, 5, and 13). Another widely adopted set of legal principles found in the Guarani Aquifer Agreement (Art. 8-13 and 16-18) involve established procedural duties or norms of notification, consultation, negotiation and mediation; exchange of information and conduct of EIAs; and institutional mechanisms (Eckstein, 2017). These procedures are typically included in bilateral and multilateral environmental agreements to promote the overall objective of cooperation (GAA, Art. 5 and 12-14) in the prevention of environmental harm or conflicts over natural resources. The support system for states and society envisioned in the treaty is an institutional entity, the Guarani Aquifer Commission (GAA, Art. 15).

Governance Mechanisms: The Guarani Aquifer Commission and Subsidiary Bodies

The Commission is the decision-making body of the GAA, similar to a conference of the parties (COP) to a number of multilateral environmental agreements that meet annually or regularly on subjects such as climate change, biodiversity, wetlands, trade in endangered species, and others. Each of the four states party to the GAA is represented on the Commission, and individuals from the ministries of foreign relations or from sectoral ministries are likely to be represented. The Commission will meet within the framework of the Treaty on the La Plata River Basin (Villar, Ribeiro & Sant'Anna, 2018), a relationship which will be defined and evolve over time.

Procedures that foreseeably may be adopted by the Commission once they meet include rules on frequency and location of meetings, voting (whether by majority or by consensus), presence and participation of observers (including accredited non-governmental organizations and the public), and appointment and funding of a permanent Secretariat for administration and a Scientific and Technical Body to coordinate research and information-sharing. In the event of a request for an inquiry by states after exhaustion of the other steps provided in the treaty for resolution of a dispute, the Commission could be expected to develop criteria for analysis and the scope of its possible recommendations to states.

A Secretariat, assuming one will be created by the Commission once it begins to work, may initially serve mainly as a "post office" to deliver communications among two or more states, schedule and organize meetings of the Commission, and provide notification of shared scientific research, data and reports. The Secretariat's mandate may be expected to expand as future needs are recognized, particularly once the Commission is requested to act as an intermediary in a dispute between states.

A formal Scientific and Technical Body (STB) could be established to coordinate and initiate research and studies and situate the professional scientific and technical work within the GAA beyond current epistemic communities that may share information or conduct joint research. A focus on new discoveries about the physical, geological, chemical and other characteristics of the Guarani Aquifer and the social effects of the use or availability of its groundwater may require more flexible and effective governance to meet the objectives of the treaty to protect and use the water in the Guarani Aquifer reasonably, sustainably and equitably.

Implementation of the Guarani Aquifer Agreement by States Aided by the Commission

The Guarani Aquifer Agreement affirms territorial sovereignty and control by states, including monitoring of that part of the Guarani Aquifer located within each of the four states. This sovereignty is subject to international law (GAA, Art. 2, 3 and 13; Sindico, 2021). States will interpret the meaning of terms and duties of "multiple, reasonable, sustainable and equitable use" and avoidance of "significant harm" in light of customary international law, the way the terms are commonly used in multilateral environmental treaties, or in other agreements made through international or regional bodies of which they are members, according to the rules on treaty interpretation in the Vienna Convention on the Law of Treaties (VCLT). There is no direct monitoring or management of the aquifer by the Guarani Aquifer Commission or any subsidiary body explicitly authorized in the GAA. Some coordination, collection, and analysis of information by the Commission might be envisioned in the future for protecting the Guarani Aquifer and assuring availability of water to meet anticipated growth in demand. As states begin fulfilling their legal duties in Art. 4 of the treaty on protection and use of the water, some may find it useful to use the GAA framework and determine to expand the Commission's mandate in the future.

The Commission and Secretariat's ability to support or encourage states' compliance with the treaty depend on the political will of the four states and adequate financing for research projects and administration. Currently little evidence of interest or impetus to make this a priority is apparent (Hirata et al, 2020). Several possible scenarios can be imagined consistent with state practice under other relevant treaties to which the Guarani states are party, best practices, and obligations accepted by the states in multilateral treaties, customary law or soft law declarations and resolutions on a variety of environmental and sustainable development principles.

To begin, the Commission at its first meeting will need to adopt its own rules and procedures, as suggested above, and consider creation of subsidiary bodies under the GAA. Questions to be determined are the extent of transparency in sharing data or studies with other organizations and the public, and participation by observers in the meetings. Another question is how to coordinate scientific and technical studies, research, and results among the four states and with other regional or global aquifer entities.

The Secretariat will initially serve a weak administrative function. This might involve coordinating Commission meetings as requested by the governments, or simply forwarding information from one state to another when a state requests utilization of the procedures in the Agreement. Such tasks require minimal staff and budget and is the most likely first step. Much more active coordination functions could develop, establishing and maintaining relations and exchange of information and best practices with other similar treaty bodies and their Secretariats or with intergovernmental organizations and agencies. Education about the Guarani Aquifer and groundwater for affected local communities and indigenous peoples in the aquifer area and for the general public through publications, webinars and other media could become a task of the Secretariat. Outreach to existing programs that already fulfill some of these roles could be part of the Secretariat's mandate with Commission approval. This includes the UN Global Environment Facility (GEF) Transboundary Water Assessment Program (TWAP); UNESCO's Intergovernmental Hydrological Program (IHP) and ISARM Americas Program (with the OAS); and the Regional Center for the Management of Groundwater (CeReGas) in Uruguay. The GAA Secretariat (and the Scientific and Technical Body proposed below) could utilize the resources of these other programs to identify gaps; access their studies, analyses and publications; and collaborate on further research and projects concerning the Guarani Aquifer System.

A Scientific and Technical Body (STB) could be created to plan and conduct shared scientific research, generate reports and provide advice to the Commission. It could highlight critical transboundary areas of the Guarani Aquifer (Art. 14) (Manganelli, 2020) and suggest actions to specifically prevent significant harm in these areas. Many other treaties have a scientific and technical body that advises the COP, the decision-making body analogous to the Commission on the Guarani Aquifer, such as the UN Convention on Biological Diversity (Subsidiary Body on Scientific, Technical and Technological Advice, or SBSTTA) and the UN Framework Convention on Climate Change (Subsidiary Body on Scientific and Technical Advice, or SBSTA). Given the emphasis in the GAA on shared scientific information, it seems appropriate to establish an STB to identify new areas for research and provide a framework or platform for sharing information beyond *ad hoc* or informal communications among scientists or technical experts. In the case of a Commission inquiry on an unresolved issue between states, independent scientific or technical evidence would be especially helpful in interpretation of data on the degree or risk of significant harm from a proposed activity by a state sufficient to trigger the treaty's procedural obligations. The advice of an STB could aid the Commission in making recommendations in the case of a dispute states cannot otherwise resolve, a key role of the Commission explicitly delineated in the GAA.

The Commission could adopt an inclusive and transparent approach to governance, with public access to information and public participation in decision-making. This is consistent with existing international environmental law; policy in the 2030 Agenda for Sustainable Development and its SDG 6 on water and sanitation; and trends in transboundary aquifer and groundwater law (Tinker, 2016).

The Commission's application of a human rights approach to groundwater in the Guarani Aquifer could focus on equitable principles applied to the human right to water (Salman, 2014) and protection of the aquifer for the needs of present and future generations. Inclusion of traditional knowledge from indigenous and local communities on the aquifer and its groundwater could complement and strengthen scientific research and recommendations under the GAA, addressing civil and political rights, economic, social, cultural and environmental human rights, and the rights of nature.

In the future, the Commission could become proactive in aiding or inspiring implementation of the GAA by states and could even spur interest in integrated water resources management of the Guarani Aquifer System (Sindico, Hirata and Manganelli, 2018). Fragile recharge areas of the aquifer along a border between two Guarani Aquifer states could become jointly established protected areas with shared monitoring of any pumping of groundwater, and integrated management to prevent pollution of the aquifer. Other forms of cooperation within the water basin could be developed as appropriate.

Finally, the Commission could take the lead in the progressive development of new international law on transboundary aquifers and groundwater tailored to the Guarani region. An active Commission, with a Secretariat and STB as suggested above, and involvement of stakeholders could protect this important natural resource, provide sufficient fresh water for future needs, and develop the right to a clean and healthy environment for all. Failure to realize this potential could lead to scarcity of water for agricultural and drinking water needs as the effects of climate change continue to disrupt weather patterns, crops and communities, causing displacement and loss.

Conclusion

The GAA will begin to be operationalized when there is political will to meet as a Commission and establish procedures and any subsidiary bodies deemed necessary. Until activation of the Commission becomes a priority for the Guarani states, each state is obligated not to violate the object and purpose of the GAA under general treaty rules. Common practices and interpretation of key terms in other environmental and water law treaties or customary international law already adopted by the four states provide a basis for compliance with the Guarani Aquifer Agreement, but the treaty's formal cooperation and coordination on the aquifer is currently lacking. The absence of current conflicts between or among states in the region or immediate threats to depletion of the groundwater in the Guarani Aquifer should be seen not as justification for delay, but rather as an opportunity for careful development of the institutional mechanisms for the GAA, including creation of a Commission with a Secretariat and a Scientific and Technical Body (STB). Facilitating cooperation among the four states and ensuring the uses of the groundwater in the manner permitted in the Guarani Aquifer Agreement will require imagination, education, transparency, and a process that promotes legitimacy and participation in decisions by the Commission. New initiatives may emerge naturally with further research about the hydrogeology of the Guarani Aquifer System and its scientific characteristics; patterns of use of the groundwater; advances in global groundwater law and policy; mitigation measures or adaptation to climate change; and consideration of other environmental factors and social conditions affecting the Guarani Aquifer and the needs of all stakeholders. The governance tools suggested above and the growing body of international law and best practices on transboundary aquifers and groundwater could contribute to establishment of a flexible framework to prevent harm to the Guarani Aquifer and ensure the multiple, reasonable, sustainable and equitable use of fresh water by present and future generations.

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Related regional organizations:

CeReGas, Regional Center on the Guarani Aquifer System, Uruguay and UNESCO, https://www.ceregas.org/.

ISARM-Americas (UNESCO and the International Association of Hydrogeologists (AIH)), https://isarm-americas.org/.

Transboundary Water Assessment Program (TWAP), Global Environment Facility, http://www.geftwap.org/.

TOPIC 4/Paper 25

Transboundary Groundwater and Aquifer Governance in the Context of Transfrontier Conservation Areas - An Opportunity for Synergy in Southern African

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Abstract

Transfrontier conservation areas (TFCAs) are established with the aim of collaboratively managing shared natural and cultural resources across international boundaries for improved biodiversity conservation and socioeconomic development. Southern Arica has one of the highest concentrations of TFCAs in the world. It encompasses18 TFCAs in the Southern African Development Community (SADC), accounting for 15% of the aggregated area of TFCAs globally, while itself only covering 6.5% of the global land mass. Naturally, many of these TFCAs overlap with transboundary aquifers (TBAs). Hence, it is important to develop joint institutional frameworks addressing water and natural resources management in these contexts while harnessing the synergies that such opportunities present. This paper outlines and discusses the recent progress in terms of assessing and managing transboundary aquifers and associated groundwater resources that geographically intersect TFCAs in SADC, in particular the development of a novel transfrontier groundwater management framework. Such knowledge and framework will enhance integration and streamlining of TBA and groundwater governance into broader natural resources governance frameworks in the region, critically supporting development goals around water security, environmental integrity, and climate resilience. The Kavango Zambezi Transfrontier Conservation Area (KAZA TFCA) is the largest terrestrial TFCA in SADC as well as globally, representing unique natural systems, supporting interlinked watercourses, and encompassing immense biodiversity. It includes parts of the Okavango-Cubango and Zambezi River Basins, importantly the associated iconic inland Okavango Delta, and also numerous declared protected areas. The five Partner States sharing KAZA TFCA (Angola, Botswana, Namibia, Zambia and Zimbabwe) are undergoing rapid economic growth as well as significant population growth, especially in upstream countries like Angola with an annual population growth rate of 3%. Challenges such as water scarcity, climate change, inadequate water and other infrastructure, growing human-wildlife, and land use conflicts call for more proactive natural and water resources management and transboundary cooperation to ensure the resilience of communities, wildlife, and the ecosystems on which they rely, while simultaneously supporting sustainable economic growth.

Keywords: Kavango Zambezi Transfrontier Conservation Area, Transfrontier Groundwater Management Framework, Southern African Development Community

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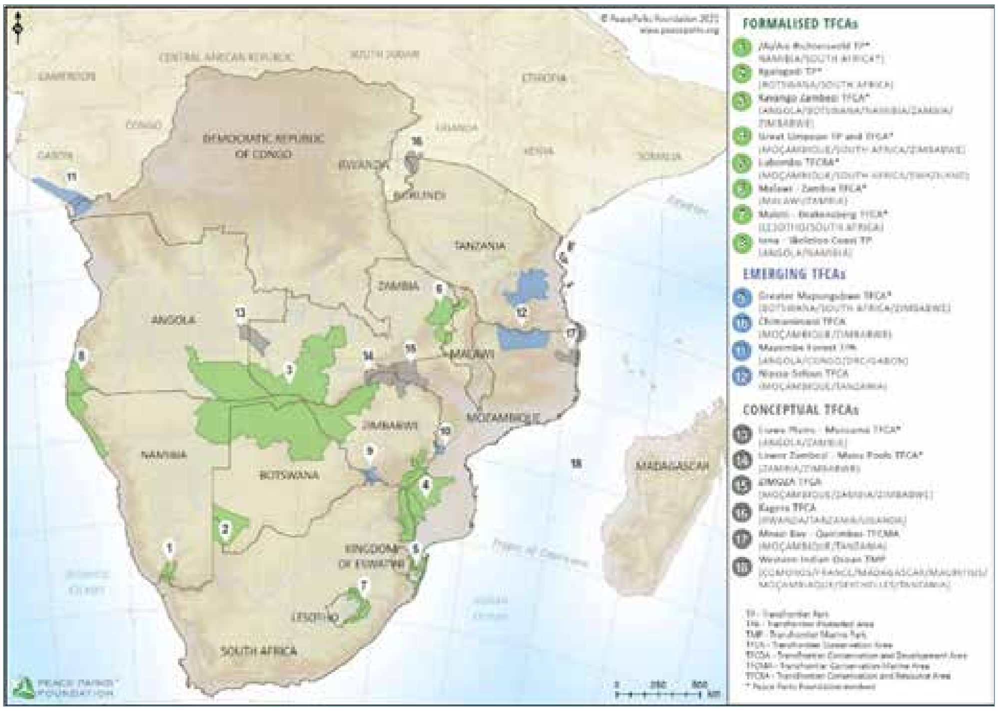
Introduction

TFCAs are defined in the SADC Protocol on Wildlife Conservation and Law Enforcement (SADC, 1999) as '*components of larger ecological regions that straddle the boundaries of two or more countries encompassing one or more protected areas as well as multiple resource use areas*'. They are acknowledged as '*vehicles for fostering regional cooperation and integration and enhancing socio-economic development in rural areas through the sustainable use of shared natural and cultural resources*' (SADC, 2012). The 18 TFCAs in SADC, located mostly in terrestrial environments, cover more than 1.000,000 km^2 or close to 10% of the land area[1] (Figure 1).

The KAZA TFCA is the largest terrestrial TFCA in the world, home to a population of around 3 million over an area of 520.000 km^2, and shared between five countries in the region, namely the Republics of Angola, Botswana, Namibia, Zambia and Zimbabwe (KAZA TFCA, 2014) (Figure 1).

Established in 2011, through a joint treaty, and supported by its Secretariat in Kasane, Botswana, it holds significant potential for enhancing multiple benefits based on a joint commitment and mission towards '*sustainably managing the Kavango Zambezi ecosystem, its heritage and cultural resources based on best conservation and tourism models for the socio-economic wellbeing of the communities and other stakeholders in and around the eco-region through harmonization of policies, strategies and practices*' (KAZA TFCA, 2014).

Figure 1.
Location of TFCAs in SADC



(© Peace Parks Foundation, 2012).

1 Peace Parks Foundation (2012).

The KAZA TFCA is a flagship transfrontier conservation area in Southern Africa because of the advanced cooperation mechanisms in place, with the Ministerial Committee at its apex and the KAZA TFCA Secretariat driving and coordinating the daily activities associated with the planning and development of the KAZA TFCA (KAZA TFCA, 2011). It also enjoys strong support from local and partner state entities, national governments, river basin organizations (OKACOM[1] and ZAMCOM[2]), non-governmental organizations (NGOs), as well as international cooperating partners (ICPs) with a common long-term vision of prosperity and sustainability for the region. The KAZA secretariat has a Memorandum of Understanding with OKACOM and is in the process of establishing one with ZAMCOM to strengthen collaboration on areas of mutual interest.

The TFCA concept is premised on two central tenets. The first is that of managing and protecting valuable natural habitats and landscapes and ensuring cohesion and connectivity across significant biomes. This enables movement and seasonal migration, especially of wildlife, to sustain their natural survival and breeding patterns. This, in practice, entails the purposeful creation and protection of wildlife corridors and dispersal areas between protected areas across the landscape, avoiding fragmentation of habitats and isolation of wildlife (SADC, 2012). The second is that of enhancing opportunities for income-generating activities for local communities to improve livelihoods and local economies. Fostering sustainable ecotourism, a key driver for TFCAs, aims to augment potential to generate employment in rural and marginalized areas, thereby contributing to poverty reduction (KAZA TFCA, 2014; SADC, 2012).

While the TFCA concept has proven successful in supporting regional integration and cooperation around nature and wildlife protection, with emphasis on harmonization of conservation policies and strategies (e.g., related to the reduction of trafficking in wildlife resources and poaching (SADC, 2012)), the TFCAs, like most regions in SADC, are coming under increasing pressure from global and economic change drivers like global warming and population growth. Recent trends of precipitation decrease and drying in the KAZA TFCA, combined with expansion of commercial irrigation, infrastructure development and other economic activities are rendering ecosystems and natural resources, and the people and wildlife depending on them, increasingly vulnerable (Villholth et al., 2022). On top of this, human population growth implies more stress on natural resources, from, for example, overfishing, water pollution, and overgrazing by livestock (Villholth et al., 2022).

Emphasizing the intrinsic interconnectedness between biodiversity-rich areas and areas of high water prevalence, the conclusions of two pivotal multistakeholder workshops held in Kasane in Botswana in January 2019 highlighted the following key aspects (KAZA TFCA, 2019a & b):

1. Water 'connectivity' is just as critical as landscape and habitat connectivity, and the natural integrity of major watercourse systems in the KAZA are under threat due to lack of explicit consideration, and hence coherent protection, of headwater areas of the TFCA.
2. Groundwater plays a key, but mostly unrecognized, role in maintaining healthy ecosystems in the KAZA.

1 OKACOM: Permanent Okavango River Basin Water Commission, established in 1994 (https://www.okacom.org/).
2 ZAMCOM: Zambezi Watercourse Commission, established in 2014 (https://zambezicommission.org/).

3. Groundwater holds a significant potential for supporting water security for local communities and wildlife populations under climate change, yet very little is known about these resources, and how best to develop them in the KAZA.
4. Climate change will likely exacerbate current water challenges, especially from droughts, thereby accentuating current issues of poor water security and intermittent food insecurity (Scovronick et al., 2007). Such trends will also limit livelihood options among local poor communities and aggravate conflicts between humans and wildlife for the same natural resources, including water and crops.
5. 'Smart' transboundary frameworks are required that conjunctively address climate change challenges and the need for more integrated approaches to water and ecosystem management in the KAZA TFCA.

Importantly, acknowledging that the KAZA TFCA exemplifies more generic issues across TFCAs in SADC, the options and mechanisms for sharing lessons and upscaling findings and legal, policy, and institutional recommendations from this work across the region should be sought.

Regional and transboundary water management in SADC is very well-established and institutionalized, principally through shared watercourse institutions or river basin organizations (RBOs), based on the Revised Protocol on Shared Watercourses in SADC from 2000 (SADC, 2010). The RBOs are mandated with the task of facilitating, guiding and coordinating sustainable management of the primary international river basins in the region, providing a first-line approach to the management of shared water resources. This includes aquifers, to the degree that they are encompassed within the river basin areas (UNESCO and IWMI, 2021). In addition, the SADC Groundwater Management Institute (SADC-GMI), as a well-established regional entity, promotes sustainable conjunctive surface and groundwater management. Hence, it is imperative to ensure coordination and harmonization between approaches, priorities, and institutions across TFCAs and RBOs in order to attain sustainable development.

Based on this background, this paper expands on the issues discussed above with the aim to support and devise sustainable groundwater and aquifer development, use, protection and management for the benefit of nature and socioeconomic development in the KAZA TFCA. The specific objectives of the paper are: i) to demonstrate and profile the intrinsic value of groundwater for ecosystems and ecosystem services, especially through the interlinkages between groundwater and surface water and its importance for habitat distribution and connectivity; ii) to highlight the strategic value of groundwater/TBAs for developing resilient water supplies for local communities and wildlife in the KAZA TFCA and the need to do this in a technically and evidence-based sound way; iii) to explore and propose possible integrated 'smart' approaches and frameworks for joint governance structures for TBAs and TFCAs using the KAZA TFCA as a case study with a view to enhance climate resilience of ecosystems and livelihoods. This analysis is anchored in the project, KAZA-GROW[1], which was sparked by demand from a wide group of local, regional and international stakeholders (KAZA TFCA, 2019a & b) and spearheaded by the KAZA TFCA Secretariat[2] together with central partners.

1 *Sustainable Groundwater Development and Management for Humans, Wildlife, and Economic Growth in the Kavango Zambezi Transfrontier Conservation Area* project (KAZA-GROW) is a flagship project led by the International Water Management Institute (IWMI) in partnership with the KAZA TFCA Secretariat and Peace Parks Foundation and funded by the United States Agency for International Development (USAID) under the Resilient Waters Program and the CGIAR (Consultative Group on International Agricultural Research) Research Program on Water, Land and Ecosystems (WLE) (https://kaza-grow.iwmi.org/).

2 KAZA TFCA Secretariat, https://www.kavangozambezi.org/en/

Methodology

The project set out to establish a baseline of information around the KAZA TFCA, through a Transboundary Diagnostic Analysis. The TDA was the first of its kind in the area, drawing existing information together on the biophysical and environmental (with focus on water resources, groundwater and transboundary aquifers), socioeconomic, and legal/policy / institutional aspects of the TFCA (Villholth et al., 2022).[1]

As a pilot project and responding to priorities of the partners, the TDA focused on the Kwando system, which was defined as the combined areas of the Kwando River Basin and the Kwando River Wildlife Dispersal Area, an area of approximately 190,000 km^2 in the northwestern part of the KAZA TFCA. The Kwando system is a critical freshwater habitat providing immense opportunities in terms of ecosystem-based adaptation as well as various associated ecosystem goods and services linked to its character as a free-flowing and perennial river system, hydrologically connected to the Angolan highlands and the downstream permanent Linyanti Swamps. At the same time, it covers large wildlife migration areas that are closely linked to seasonal water availability. As such, it provides a representative transboundary sub-system that connects both critical water and ecosystems as well as underlying groundwater and aquifer systems providing a workable case for how to potentially define governance structures that can be out-scaled to the larger KAZA and possibly the SADC scale.

Secondly, the project applied a water scarcity vulnerability mapping and groundwater potential assessment of the Kwando system, as a rapid appraisal of the congruence between water demand and availability from a human water security perspective (Magombeyi and Villholth, 2021). Finally, building on the TDA and the mapping exercise, the project embarked on a process to develop a Transfrontier Groundwater Management Framework (TGMF) for the KAZA TFCA, which would identify and fill gaps in existing groundwater management and institutional frameworks that apply to groundwater in transfrontier and inter-basin contexts (Villholth and Altchenko, 2014).The work evolved around two major axes of analyzing existing settings for institutional frameworks, knowledge management, stakeholder context, and financing, i.e. 1) at different levels/scales, from local to national to regional (Figure 2); and 2) for groundwater management and for natural resources conservation.

These efforts were carried out in consultation and engagement with established stakeholder forums in the Kwando area, in particular the Kwando Joint Action Group (KJAG), which is a transboundary dialogue platform that fosters cooperation and knowledge sharing between government ministries of water, agriculture, energy, environment, and tourism as pertains to the Kwando system. It is organized by National Administrative Steering Committees from these ministries. The sole mandate to convene the KJAG is held by ZAMCOM (O.C. Mwanza, pers. comm.).

1 OKACOM did a comprehensive TDA of the CORB, which was adopted by the three Partner States in 2011 (https://www.okacom.org/cubango-okavango-river-basin-transboundary-diagnostics-analysis).

Results, Findings, and Recommendations

Based on the TDA (Villholth et al. 2022) and the water scarcity vulnerability assessment (Magombeyi and Villholth, 2021), both with specific focus on the Kwando system and associated groundwater conditions and challenges, the following key messages were derived, which in cases by inference apply to the KAZA TFCA as well:

1. Since TFCA delineations are focused on critical landscapes and ecological systems – not necessarily aligned with rivers basins - their remit related to river basin and aquifer system management is less prominent and less well-founded (e.g., the upper part of the Kwando River is not part of the KAZA TFCA). However, with water resources coming under increasing stress, this indicates the clear need for, and the potential synergy between, stronger TFCA, RBO, TBA, and Partner State cooperation. The free flowing mostly pristine character of the Kwando River makes it a key candidate for international cooperation, in order to sustain its critical ecosystem services, biodiversity and habitats and livelihood activities across upstream and downstream areas and linked to seasonal high and low flows, floods and droughts. Pre-existing stakeholder platforms such as the KJAG provide an excellent vehicle to build these synergies across Partner States.
2. The groundwater resources and subsurface hydrogeological and surface morphological setting and dynamics, along with the climate, of the KAZA TFCA are, to a large extent, controlling the natural environment (e.g. with respect to the soil systems, topography, catchment responses and characteristics of ecosystems).
3. The Kwando River Basin is very groundwater/subsurface-driven, supporting perennial and relatively steady river flows downstream. Compared to the Okavango River system, which is driven by seasonal pulses dominated by surface water runoff, the Kwando River is less seasonal given the maintained level of baseflow throughout the year, which makes it less prone to larger floods and droughts and, hence, more climate resilient.
4. It is important to protect catchment areas that are upstream of, and contribute flow to, critical ecological sites, aquatic ecosystems and potential groundwater-dependent ecosystems (GDEs). This is the case for both the Okavango and Kwando Rivers, which have significant inland deltas or wetlands downstream. Since the headwaters or water source areas are located outside the KAZA TFCA, in the Angolan highlands, it is important that these areas are protected as part of ongoing priority setting. This includes recognizing and protecting key groundwater recharge areas and pertinent upstream-downstream linkages.
5. To keep the Kwando River Basin and associated conservation and wildlife dispersal areas healthy and climate-resilient, better groundwater management and understanding is required along with better assessment of human and climate change impacts over the medium term.
6. The KAZA TFCA overlaps with five identified TBAs, while only two of them are presently associated with an appreciable level of knowledge. These are the Eastern Kalahari Karoo Basin Aquifer System (shared between Botswana and Zimbabwe) (Beekman et al., 2022), and the Nata Karoo Sub-Basin Aquifer System. The latter is located partly within the Kwando system and possibly shared between the five Partner States and straddling the Cubango-Okavango River Basin (CORB) and the Zambezi River Basin (Villholth et al., 2022). It is important to indicate the interlinkages

between TBAs and the river basins based on Article 1 of the SADC Revised Protocol on Shared Watercourses[1] in the definition of a Watercourse[2]. Some TBAs straddle two or more river basins and in essence link them. It cannot be ruled out that other TBAs exist in the KAZA TFCA (e.g., that the Nata Karoo consists of several distinct TBAs). It is also possible that a larger more regional aquifer system that ties upland headwaters and recharge areas in Angola to downstream discharge areas is present.

7. Water resources will come under increasing pressure in lowland, more arid and populous areas of the Kwando system. This is due to climate change and human development combined with groundwater challenges of inherent salinity and other water quality issues of geogenic and anthropogenic nature (Villholth et al., 2022). The Nata Karoo and other TBAs, as well as local fresh shallow groundwater resources in the region, will be increasingly important for water supply for growing populations. For rural communities, fresh shallow groundwater in proximity to rivers that mostly feed groundwater will be key to support local rural communities, while larger deeper, potentially transboundary, aquifers will increasingly be the target for growing urban population centers. In rural areas, purposefully protecting water sources and human access to these from human-wildlife conflicts is critical (Villholth et al., 2022).
8. Due to increasing drought pressure, groundwater is beginning to serve wildlife through the implementation of artificial waterpoints (AWPs) in protected areas in the KAZA TFCA. The strategies and methodologies for implementing AWPs need very careful consideration, as the interventions can have unintended side effects on the ecosystems (e.g., in terms of changing or reducing natural migration patterns and concentrating wildlife around the AWPs resulting in pressure on natural vegetation from herbivores and changing dynamics of predator behavior)[3].

The Transfrontier Groundwater Management Framework

Protected areas in the KAZA TFCA, including national parks, forest reserves, conservancies, sanctuaries, and wildlife and game management areas, cover 71% of the TFCA and encompass a wide diversity of ecosystems. The Ramsar Convention of 1971[4] and the UNESCO World Heritage Convention of 1972[5] have designated five of these as key ecosystems and areas of high cultural value, of which two emblematic ones enjoy both statuses — the Okavango Delta System and the Victoria Falls National Park. The mission of the Ramsar Convention on wetlands is '*the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world*'. As of March 2022, 172 nations globally have joined the Convention, and hence it provides a strong and unique foundation for the protection of wetlands globally.

1 SADC Revised Protocol on Shared Watercourses, https://www.sadc.int/files/3413/6698/6218/Revised_Protocol_on_Shared_Watercourses_-_2000_-_English.pd
2 "Watercourse system" means the inter-related hydrologic components of a drainage basin such as streams, rivers, lakes, canals and underground water which constitute a unitary whole by virtue of their physical relationship.
3 Ecological Aspects of Artificial Water Provision in African Ecosystems, https://www.rainharvest.co.za/2011/04/ecological-aspects-of-artificial-water-provision-in-african-ecosystems/.
4 The Ramsar Convention of 1971, https://www.ramsar.org/
5 UNESCO World Heritage Convention of 1972, https://whc.unesco.org/en/convention/#:~:text=The%20Convention%20concerning%20the%20Protection%20of%20World%20Cultural%20and%20Natural,the%20Cultural%20and%20Natural%20Heritage

Ramsar acknowledges groundwater as a key resource supporting, or supported by, wetlands (Ramsar, 2005), and provides guidelines on the management of groundwater in the context of wetlands (Ramsar, 2010). Similarly, the two global treaties of the UN Convention on the Law of the Non-Navigational Uses of International Watercourses (UN Watercourses Convention[1]) and the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention[2]) as well as the UN ILC Draft Articles on the Law of Transboundary Aquifers[3] provide keystone principles and provisions for the protection and sustainable use of transboundary waters and their resources. Nonetheless, it is widely acknowledged that the dedicated application and adoption of these tools are relatively limited when it comes to internationally shared groundwater resources and aquifers, and GDEs (Gleeson et al., 2022; Eckstein and Sindico, 2014).

Conversely, acknowledging that groundwater is and will be a critical resource for resilience and water security under future scenarios for both ecosystems and human development in the KAZA TFCA, understanding and managing the interdependencies between ecosystems, groundwater and human systems will become increasingly important. A transboundary ecosystem approach combined with integrated water resources management that specifically addresses groundwater is required. To address this, the proposed Transfrontier Groundwater Management Framework (TGMF) is currently under development with the following required components:

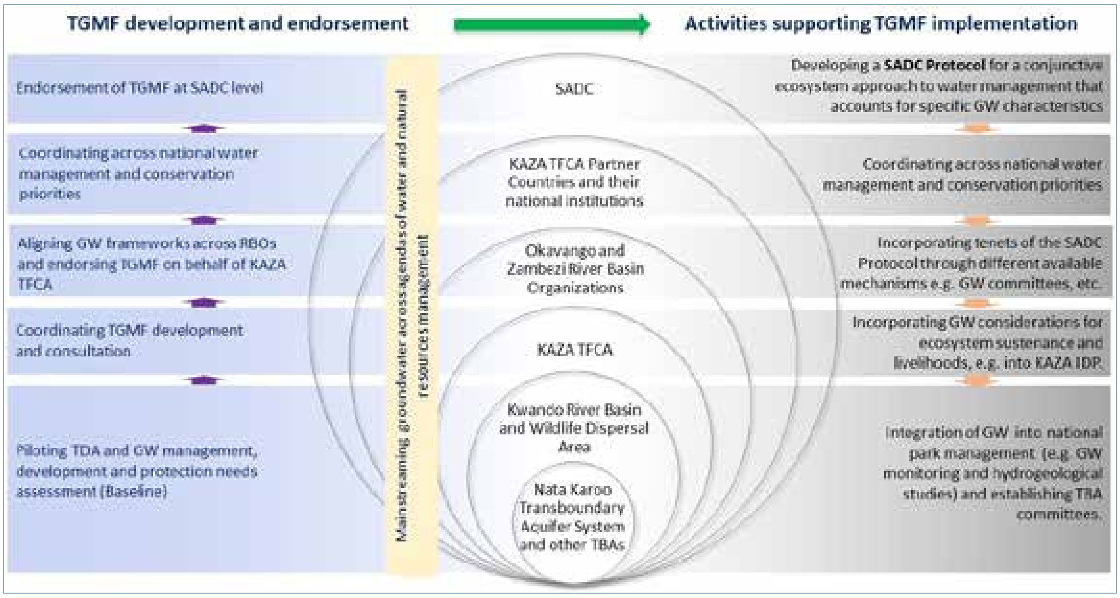
1. Participation across an existing transdisciplinary and multi-level institutional foundation with mandates in relevant fields, most notably RBOs, KAZA TFCA, KJAG, NGOs, and community-based organizations.
2. Identification of key complementary existing management frameworks that need to be integrated into the TGMF for the KAZA TFCA
3. Identification of key roles and needed coordination mechanisms among the existing institutional frameworks.
4. Refinement of mapping and assessment of TBAs in the KAZA TFCA and the role of groundwater systems in sustaining ecosystems, including for environmental flows, with resultant requirements for groundwater management and protection.
5. Identification of key priorities and staged interventions to sustainably develop groundwater for wildlife support and human sustenance for health and livelihoods under current drivers of global change.
6. Endorsement of the TGMF at KAZA level, outscaling the framework and approach to other TFCAs, and ultimately endorsement at SADC level (Figure 2, left side).
7. Using the TGMF to leverage further support to establish and implement sustainable TBA governance in SADC more broadly (Figure 2, right side).

The main aims of the framework are: A) Integration of conservation and water management imperatives, particularly as they relate to sustainable development, use, protection, and management of groundwater in dedicated transfrontier conservation areas. B) Transboundary and inter-basin assessment and management of groundwater resources, in particular regarding: 1) Identified transboundary aquifers that straddle more than one international river basin; 2) Protection of upstream recharge areas of important regional/transboundary aquifer systems, which could be

1 UN Watercourses Convention, https://www.unwatercoursesconvention.org/
2 UNECE Water Convention, https://unece.org/environment-policy/water
3 UN ILC Draft Articles on the Law of Transboundary Aquifers, https://legal.un.org/ilc/texts/instruments/english/commentaries/8_5_2008.pdf

achieved through designation of new (possibly transboundary) Ramsar sites located in such areas; 3) Identifying GDEs and understanding their dependence on groundwater and associated management requirements; and 4)

Figure 2.
Development and implementation of the Transfrontier Groundwater Management Framework, indicating significant roles at various levels and layers of governance in SADC



(©Own Elaboration)

Better land use management and chemical and waste handling to avoid pollution. C) Strengthening of capacity development and communities-of-practice around groundwater management in TFCAs located within SADC at multiple governance levels (Figure 2).. D) Agile addressing of water scarcity and insecurity for human and wildlife populations in TFCAs, based on best evidence and technologies, while avoiding human-wildlife conflicts. This includes water supply for small-scale productive uses and livelihood enhancement. E) Enhancing participatory groundwater management at local to national levels, adhering to the subsidiary principle, and integrating such approaches into broader established Community Based Natural Resources Management (CBNRM) frameworks in TFCAs (Villholth et al., 2022).

Conclusions

Groundwater resources and many transboundary aquifers in SADC underpin transfrontier conservation areas, supporting ecosystem health while also becoming increasingly important for water supply that address climate variability and more frequent droughts. The paper argues that proactively managing groundwater located in and TBAs intersecting TFCAs in SADC may provide a vehicle for synergy between the imperatives of protection of ecosystems and broader landscapes on the one hand, and the sustainable development, use, and protection of water resources on the other hand, which in turn may enhance climate resilience and water security in these areas. The synergy is predicated on a deliberate 'water systems' (typically a river basin, aquifer, or combined) approach integrated within a landscape network approach, ensuring connectivity in both a hydraulic, ecosystem, and wildlife migration sense. In practice, for the KAZA TFCA, this entails bringing the KAZA Secretariat and the two river basin organizations, OKACOM and ZAMCOM, closer together to jointly address and co-manage the natural resource base. This is a novel and, so far, relatively untested approach in SADC, but starting to yield concrete outcomes in the KAZA TFCA through agreed joint activities, as seen for example around the Transboundary Diagnostic Analysis and the incipient Transfrontier Groundwater Management Framework. The fact that the two RBOs, KAZA TFZA and SADC closely collaborate, and all have focus on shared groundwater, is a clear testimony to a solid foundation and goodwill for further progress in the field.

Besides establishing a framework around joint assessment of shared TBAs and regional aquifers across national borders and river basins, the TGMF proposes avenues to identify best opportunities for groundwater development to sustainably address unmet needs among human and wildlife communities under increasing climate pressure and other drivers of water scarcity. These interventions are crafted mindful of the challenges resulting from conflicts over the resources and the need for water-based but climate-smart livelihoods for poverty alleviation among local communities. Embedding participatory groundwater management in existing governance structures, such as Community Based Natural Resources Management frameworks, provides yet another mechanism of integrating conservation and groundwater governance within existing complementary mechanisms. The TGMF will be further elaborated and vetted through consultation and collaboration with local to national and regional stakeholders in the KAZA TFCA as well as SADC to enhance regional integration, stability, and prosperity across the region.

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TOPIC 4/Paper 26

Collective Aquifer Governance Through Unitization

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Abstract

Groundwater governance is reaching a paradigm shift. The issues with groundwater extend not only to water quantity and access, but also to the indirect harms of groundwater development like degrading water quality, subsidence, transboundary political conflicts, and saltwater intrusion. At the same time, debates continue over the adoption of groundwater marketing and banking policies to improve resource utilization. Few policy tools appear to incorporate each of these components into a single approach to aquifer governance. The paradigm shift is the transition from groundwater management to aquifer governance, accomplished by focusing less on the contents of an aquifer but instead on the container itself.

A similar transition occurred in another subterranean substance in the early 1900s: oil and gas. The current struggle to identify policy tools closely aligns with the debates in the early years of oil and gas development. Regulation proved ineffective in encouraging sustainable, controlled development of oil and gas resources. The result was large amounts of waste, environmental damages, and conflicts. To address these issues, developers negotiated the first cooperative agreements to maximize the benefits for all. Unitization agreements enabled collective, voluntary, and effective resource management for numerous stakeholders across international and domestic political boundaries. The principles of unitization agreements serve as the model for a new approach to aquifer governance.

Unitization agreements follow a general set of principles that could be used to create aquifer unitization agreements. These agreements are essentially voluntary contracts that centralize resource use decision-making to a central committee of stakeholders yet distribute resource benefits to all participants in the agreement. Aquifer resource use is negotiated and based on scientific principles, negotiated goals, and local conditions. Multiple resources can be managed under a single agreement, including groundwater, geothermal heat, water quality, pressure, surface water interactions, subsidence, and biological factors. Each of these resources may form the basis for shares or interests owned by the participants to the agreement and redetermined as needed to ensure scientific accuracy. Just as in the oil and gas context, these agreements can span international borders and include offshore groundwater resources. As resource shares or interests are at the core of unitization agreements, markets could form around these agreements and directly incorporate negative externalities.

Keywords: unitization, collective, agreements

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Introduction and Background

Unitization agreements developed as a matter of necessity in the late 1800s in the state of Texas in the United States. Very soon thereafter, a profession of "lawgineers" emerged, that drafted a particularly effective cooperative agreement system to reign in the explosion of wellfield overdevelopment. (Hardwicke, 1948). A new kind of lawgineer may lead the way in applying these novel agreements to aquifers.

At its most basic, a unitization agreement is simply a contract between multiple owners and users of a commonly accessed resource. These agreements are voluntary and privately organized. Each agreement is tailored to the individual conditions of the oil and gas reservoir and the parties' interests.

Some countries have imposed basin-wide management systems to reduce groundwater extraction. Basin-based regulation attempts reduce groundwater use to a "safe yield" by limiting the use of groundwater. These kinds of restrictions are often unpopular, economically damaging, and socially problematic.

What these basin-wide approaches can never address is the complexity of each aquifer, the unique benefits and challenges each aquifer possesses, and how aquifers are much more than groundwater.

Unitization is an example of a customizable, collaborative, voluntary approach to governing complex subterranean resources. Unitization principles shift the narrative from crisis and conflict to goal-driven, cooperative, and planned resource development.

Origins of Unitization in the Wild West

The origin of unitization is reminiscent of the modern concerns with aquifers worldwide. In the late 1800s, the oil and gas industry were booming and becoming an ever more critical resource. The frenzy to develop Texas's oil and gas reservoirs came with large amounts of waste, environmental damage, and lost profits. In the United States, oil and gas are considered private property rather than a resource owned by the sovereign or the public. The primary law related to oil and gas production is the rule of capture. Under this rule, the person that extracts the oil and gas becomes the owner, even to the detriment of neighbors. In theory, the rule of capture encouraged maximum development and market competition. In practice, it created over development, waste, conflict, and environmental harm.

The rule of capture resulted in thousands of wells being drilled in close proximity, with each developer attempting to pump as much oil out of the ground as quickly as possible before their neighbors. The scramble to out-pump neighbors had some negative consequences, including depressurizing the formation, "stealing" oil from neighboring properties, and the solidification of some components of the oil (sealing the well). Over-pumping can cause pockets of oil to become inaccessible in the reservoir, benefitting nobody. (Weaver, 1989). States dealing with oil and gas controversies introduced new laws and protections for neighboring landowners. However, these new laws could not overcome the fundamental flaws with the competition between pumpers.

Instead of relying only on potential legal reforms, oil and gas pumpers developed unitization agreements themselves to allow greater collective production without financial harm to small landowners that forgo drilling their own wells. Collective resource governance agreements, also referred to as unitization agreements, overcame individual self-interest, realigning individual benefits with benefits to the whole community. These same principles might be brought to bear in the modern efforts to address the problems facing use of aquifers.

Unitization Today: Secondary Recovery

Unitization enables a key oil and gas reservoir management system: secondary recovery. Primary recovery of oil is the stage when the pressure of the reservoir is high enough to drive oil to the well without the addition of external pressure. Only about 10 percent of all the oil can be recovered in the primary stage, leaving much of the oil remaining in the reservoir. (Weaver, 1986).

Secondary recovery involves the injection of water or gas to force oil towards the well. Secondary recovery requires coordination of the entire wellfield, since certain wells will be used to push oil while others extract the oil. For example, one side of a wellfield may be injecting water and pushing oil to the other side, where it is removed. Secondary recovery allows a much larger percentage of the oil to be removed but requires the coordinated use of injection and recovery wells across the entire reservoir. (Weaver, 1986).

Under the rule of capture, this kind of coordination would not be possible without unitization agreements. Under this rule, each pumper would be unable to recover large percentages of the oil within the reservoir. Further, the large benefits of secondary recovery could not be realized, since it forces oil away from some wells while benefiting others. Without unitization, there would be no incentive to undertake secondary operations, because it would be effectively giving oil to neighboring well owners. Unitization enables the participants to utilize the optimum number of wells in the optimum locations, to produce at the optimum, efficient rate, while also equitably distributing the benefits to all participants.

Aquifers Today

In many ways, the current situation with aquifer depletions, use of groundwater to generate marginal economic value, and waste is reminiscent of the heyday of the Texas oil boom. Aquifers in many places around the world are being depleted at a rapid pace without controlled long term planning. Conflicts are becoming more frequent between neighboring communities, local jurisdictions, and national governments. Protective laws are being introduced to protect access to the resource, but the damaging effects of groundwater extraction are still growing. Further, these laws tend to apply broadly and are not customized to the unique natural and social conditions of each aquifer.

For aquifers, the coordinated study and installation of wells, optimum pumping rates, and control of subsurface flow could dramatically improve the sustainability of the world's aquifers. Aquifer unitization could allow projects such as water pressure head management, pollutant control, equitable sharing of water, or provide a method of compensating local communities which are exporting water to another area.

Unitization for aquifers has the potential to bridge the same kinds of gaps that policymakers could not resolve for oil and gas production. These laws serve mainly to prohibit certain actions that cause harm to a community but cannot promote private enterprise and public entrepreneurship. (Doherty, 1924; Ostrom, 1990). Instead, unitization could enable communities to gain unrealized benefits based on the unique circumstances of their aquifer.

Collective Resource Governance and Unitization Principles

There are several principles that many unitization agreements have in common. Every unitization agreement reflects the negotiation of the parties who customize it to the specific conditions of the oil reservoir, and parties involved. These common features appear in most unitization agreements, forming a governance model that may transfer to aquifers. Further, these same principles are used for the development of transboundary and offshore oil and gas reservoirs.

Centralized Governance. Unitization agreements place much of the planning, management, and operations with the "unit operator." (Weaver, 1989). The unit operator is the primary authority for the daily decision making in the unit, gathers data, and completes the "unit plan" for the unit that is later approved by the individual parties to the agreement.

- Reservoir-Scale Planning. The "unit plan" encompasses the entire reservoir, seeking to maximize the production from the entire reservoir rather than individual wells. Through this planning mechanism, all wells accessing the reservoir are coordinated and operated to produce the maximum benefits for the entire unit.
- Respect for Individual Rights. Participation in a unitization agreement is often voluntary, which means that individual rights to withdraw oil and gas must be either protected or compensated to encourage participation. Unitization agreements benefit individual landowners by giving each landowner "equity shares" or "working interests" in their land's contribution to the common reservoir. As the unit operator produces oil and gas, the unit operator compensates each party holding shares. Using shares, the greater long-term benefit of participation in the unit overcomes individual incentive to overproduce at their own well. Multiple classes of shares are used to reflect the diverse number of resources present in the reservoir (oil, gas, water, pressure, etc.).
- Unit Boundary. The unit boundary defines the three-dimensional extent of the unit's operations. Typically, this includes the entire reservoir, or multiple overlying reservoirs, based on the predicted extent of the oil and gas stored in the formation.
- (Re)determination. As the unit operator gathers data and refines the models of the reservoir, the original allocation of shares and determination of the unit boundary may become incorrect. Redetermination redistributes the shares to individual parties based on the best prediction of the original volume of oil, gas, or other transresources.
- Inclusion of Transresources. Because the reservoir is not a single resource, the unitization agreement includes all relevant resources present in the reservoir. For example, the unit plan may include extraction of oil on one side of the reservoir and injection of water on the other to extract oil more efficiently from producing wells. A unitization agreement directly or indirectly incorporates each component of the reservoir in shares, unit plan, or unit boundary.

International and Transboundary Unitization

Because unitization agreements are based on private contracts, they can be adapted to span international borders and facilitate cooperative development. The equity interests created within the unitization agreement reflect the legal access to the oil and gas resources within a reservoir, without regard to whether that access is authorized by license, private ownership interest, or concession. (Easo, 2014).

Depending on the region, groundwater on one side of a national boundary may be privately owned, while on the other side water is considered a publicly owned resource. Other resources, like geothermal heat or minerals, may have more complex ownership or regulation across a common border or even within the same jurisdiction. Further, the conditions of an aquifer may change over time, making perpetual renegotiation of interests a necessity. These issues indicate that perpetual and unchanging policy tools, like international treaties, may form sources of additional conflict as aquifer conditions change over time.

In transboundary international unitization, the national boundary (onshore or offshore) determines the relative allocation of resources between the nations, not a certain volume of production. The physical volumes of hydrocarbons are estimated for the entire reservoir and equity interests are allocated by the estimated volume present below the surface. Different classes of equity interests are provided for different resources, like oil, gas, brackish water, or pressure. As more information is gathered and reservoir conditions change, the equity interests are redetermined without renegotiating the national boundary or the basis of the equity interests.

This approach contrasts with the approach for international surface water treaties, which generally allocate specific volumes of flow or production. If a similar approach were used for a transboundary aquifer, equity interests would be allocated not by a specific pumping rate, but instead a total volume of pore spaces, groundwater, geothermal heat, pressure, or brackish water present within the aquifer. These allocations would change over time as the aquifer conditions evolve, rather than remain a stationary volumetric amount that may or may not be sustainable in the future.

Frequently, international transboundary unitization agreements have a handful of participants, which are the companies that possess a license, lease, or concession within the reservoir. (Weaver, 2005). In the United States, unitization agreements may have many participants due to the diverse private ownership of the surface.

For a transboundary aquifer, unitization could include a combination of different actors from both sides of the national boundary depending on the applicable laws and rights to the aquifer's resources. Equity interests would be allocated to those parties that have a right to use the aquifer's groundwater, pore spaces storage capacity, geothermal heat, or environmental benefits, without regard to the source of those rights.

Legal and Economic Theory: Why Does Unitization Work?

Unitization fundamentally changes the incentives and interests of the participating parties by changing the theoretical form of property among the participants. Under the rule of capture, each well owner competes to gather oil and gas before the other well owners draw the resources away from their land. After unitization of the reservoir, the agreement splits each party's right to pump under the rule of capture into two components: (1) a right to control (pump) and (2) a right to the benefits of the well. Barbanell (2001) terms these the "liberty" and "claim" rights respectively. Parties to the agreement grant the right to management of their wells to the unit operator but retain the right to income from wells.

The splitting of rights into management and income components represents the conversion of rule of capture property interests into community property, or, more specifically, a collective property system. Common property systems grant a specific group of individuals use of a resource managed by the whole group. Collective property systems are similar, but instead of granting an undefined amount of access, they grant each individual a specific amount of the resource managed by the group. (Peredo et al., 2017). These forms of property contrast with circumstances of no property and open access, often confused with common property and conflated with the theory of the "tragedy of the commons" by economists. (Barbanell, 2001). This theory suggests that parties with unlimited access to a resource will compete and overconsume a common resource. (Ostrom, 1990). By designating the benefits to a limited group of individuals and allotting a portion of the common resource to each party, the theory of tragedy of the commons is mitigated by contract.

Oil and gas unitization shares take a variety of forms, discussed in Wiley and Jarvis (2021) and in Wiley (2018). Each of these convert the right to extract into an *in situ* right of the resource within the reservoir. The variety of approaches used in the oil and gas industry could be used as allegories to develop a similar share system for aquifers. Further, these aquifer shares or equity interests could form the basis of science-based groundwater markets, discussed more fully in Wiley and Jarvis (2021) and Wiley (2018).

For aquifers, unitization agreements would task the unit operator with the management of the entire aquifer, including distributions of groundwater and aquifer storage and recovery ("ASR") activities, and with planning projects and water use to maximize the benefit of the aquifer for the entire unit. Because unitization is akin to a collective property system, the benefit or income provided by groundwater rights remain with the parties to the agreement. Use of those water rights, however, vests with the group. Using this system, the unit operator may develop new ASR systems, place new wells in geologically preferable locations, abandon harmful or poor-quality wells, or develop pipelines to provide water to those parties whose wells are determined to be unfavorable. The key feature of unitization is that individuals do not bear the costs or receive benefits of redesigning the entire aquifer infrastructure as individuals, but as members of the contracting unit.

The Challenges to Unitization: Cooperation, Monopolies, and Perception

Applying unitization principles to aquifers presents a collection of challenges. Like any new concept, especially one attempting to address a "wicked problem," aquifer unitization will likely face a series of challenges if pursued. (Jarvis, 2014). Like oil and gas unitization that took several decades to settle on a definite structure, aquifer unitization would take many forms and face unprecedented challenges as the legal tool matures.

Internal Resistance

One of the first issues faced by advocates for the unitized development of oil and gas reservoirs was internal resistance within the proposed unit. Because early unitization agreements were voluntary, reluctant parties could refuse to join the unit and create a "free rider" problem. (Weaver, 1986). For this reason, some commentators claim that voluntary unitization agreements may be "too utopian" to actually be a viable option. (Clyde, 2011). Today, all oil-producing states, excluding Texas, have compulsory unitization statutes. (Weaver, 2005). These statutes force reluctant parties into the unitization agreement when a certain threshold of participation is met. Without a compulsory unitization statute specifically for aquifers, reluctant parties may undermine the potential effectiveness of a unit. Most problematically, the reluctant parties would likely be the same parties with plentiful and secure groundwater rights that would be the most beneficial to a unitized aquifer. A counteracting incentive could be the threat of the imposition of government regulation, like those discussed by Clyde (2011). The threat of government regulation of the entire aquifer may encourage reluctant parties to the negotiation table that would otherwise have no interest in participating.

At the same time, examples in the groundwater context show fears of free-riders may be overblown. Several examples of cooperative groundwater organizations and agreements are discussed in Wiley and Jarvis (2021) and Wiley (2018). Efforts to address groundwater depletion using methods similar to unitization in Utah's Escalante Valley appear to rebut the perceived difficulty of cooperatively managing an entire aquifer. (Jarvis, 2011). The Escalante Valley Water Users Association ("EVWUA") negotiated a voluntary agreement that would gradually reduce overall groundwater pumping in the valley over 40 years to the state mandated "safe yield" level, with senior appropriators providing water supplies to junior water users facing curtailment under threatened government regulations. (Keiter, et al., 2011). The agreement pooled the basin's groundwater rights, sharing curtailments of any individual groundwater use on a pro-rata basis by all participating parties. The Utah Division of Water Rights adopted the Beryl-Enterprise Groundwater Management Plan, developed with the EVWUA in December 2012. The experience in the Escalante Valley shows that voluntary agreements, even those where some users forego their senior priority position, are possible in some circumstances.

Threat of Aquifer Monopolies

The largest perceived threat to unitization in the oil and gas industry was anti-trust laws. Some of the attention to the monopoly issue may be due to the politics of the period in which unitization agreements developed. (Hardwicke, 1948). However, later-adopted statutes explicitly authorizing unitization agreements alleviate the threat of antitrust litigation against parties to a unitization agreement for oil and gas operations. Aquifers, on the other hand, do not have the same explicit statutory authorization to unitize. Just as seen in the oil and gas industry's experience, the threat of antitrust litigation may be more academic conjecture than reality.

Lack of Public Interest and Environmental Review

The final challenge that unitization agreements face is the perceived differences in purposes between oil reservoirs and aquifers. The purposes of unitization agreements in the oil and gas context are to (1) prevent physical waste of the resource by leaving oil within the reservoir; (2) prevent economic waste by drilling and operating excessive numbers of wells; and (3) protect parties' rights in the common reservoir and fairly distribute benefits. (Weaver, 2006).

These purposes are compatible with the goals for an aquifer to (1) efficiently and conjunctively manage groundwater and aquifer storage resources; (2) reduce costs for the basin and sustainably develop the aquifer (like implementation of ASR projects); and (3) protect individuals from bearing the costs of development and water curtailments alone. The two resources share the same goals of collective, efficient, and science-based resource management. Unitization incorporates the public interest in conserving and beneficially using an aquifer into the purposes of the agreement.

Further, as environmental features and interest groups gain rights to protect resources, these features and groups could be assigned equity interests in the aquifer unitization agreement - as direct participants. In this manner, environmental interests associated with aquifers could be directly reflected in the control and management of such an aquifer unit.

Many of the hurdles facing aquifer unitization are the same ones that faced oil and gas unitization in the past. The perception that aquifer unitization agreements will be ineffective, generate monopolies, and lead to further depletions of groundwater resources may be valid. However, "[u]nitization certainly did work in the oil and gas context. While it was fought by some, it has proven to be the savior of all." (Clyde, 2011).

The Next Step: Why Unitization Principles Could Advance Groundwater Governance

While the timeline in the oil and gas industry from its first conflicts to the acceptance of unitization to achieve coordinated, comprehensive governance spanned approximately 50 years, groundwater's timeline is still unfolding. The final catalyst for the adoption of unitization in the oil and gas industry was rampant overproduction, low oil profits for individual well owners, the national focus on preventing resource waste during the Second World War, and the possible untapped benefits of secondary recovery using injection wells. (Hardwicke, 1948). Similar circumstances to those seen in the oil and gas industry are developing for aquifers today. Ever increasing pumping costs to reach deeper water tables, the potential reuse of aquifers as storage reservoirs using ASR technology, and the water availability challenges associated with climate change require the development of new groundwater governance systems.

Today, efforts to address groundwater issues remain focused on reining in use on a basin-wide level and limiting the effects of groundwater use to hydraulically connected streams though conjunctive management. These efforts are similar to the limited regulatory efforts to prevent overproduction and protect correlative rights developed before the advent of the unitization age in the oil and gas industry. Just as secondary recovery efforts required more cooperation than these laws provided, the emerging use of ASR may necessitate that groundwater injections and withdrawals are coordinated by many overlying groundwater users. The policies surrounding ASR are still in development or experimental stages in many states. Basin-wide planning, cooperation, and coordination could greatly expand the potential benefits of ASR technology.

Unitization may serve as a valuable model to advance aquifer governance. While never attempted in its complete form, pressures to solve the groundwater crisis and the potential benefits provided by collective aquifer governance may serve as the catalyst for unitization. However, until a group of groundwater users attempt to negotiate one of these agreements, aquifer unitization will remain untested.

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Conclusions

by Stefano Burchi

The legal foundation of cooperation regarding transboundary aquifers is nowadays identified with the United Nations "Draft Articles on the Law of Transboundary Aquifers", that are universally acclaimed as the most comprehensive and authoritative reference for States on the path to strengthening cooperation in regard to transboundary aquifers. Except for a few "core" norms of customary origin however, the Draft Articles posit a bundle of rules that are not the source of legally binding obligations for States. Yet the normative value of the Draft Articles is enhanced and amplified in synergy with other branches of international law, and in particular human rights law. The obvious reference is to the human right to water for the satisfaction of basic human needs, including subsistence livelihoods, and to sanitation, that is crystallized in the pronouncements of authoritative international bodies, and is nowadays regarded as the source of legally binding obligations on States. To the extent that groundwater in general, and groundwater in transboundary aquifers in particular, is instrumental to meeting the legal obligations deriving from international human rights law, and as this particular role of transboundary groundwater is echoed in the UN Draft Articles, the synergy between the two domains of international law is destined to power transboundary aquifers cooperation, and to strengthen it.

As many a transboundary aquifer is often hydraulically linked to surface water systems, notably rivers and the relevant basins, existing transboundary river and/or river basin multi-State organizations are an attractive option for "homing" institutionalized cooperation regarding such aquifers. Already examples of this option being successfully pursued are on record, and on the rise. The synergic impact of this approach across diverse but interconnected freshwater systems, surface and underground, is bound to reverberate on the effectiveness of transboundary aquifer cooperation, and to strengthen it. In similar vein, regional intergovernmental organizations that do not center on transboundary freshwater systems, and that operate at a different spatial scale - such as transfrontier nature conservation areas - may offer opportunities for "homing" transboundary aquifer cooperation that are worth exploring. Synergy between the transboundary aquifer spatial scale and the transfrontier nature conservation scale seems thus to hold promise for strengthened transboundary aquifer cooperation. Moreover, ground-level cooperation happens through the active engagement of governmental and non-governmental personnel and stakeholders in general on both sides of an international border. Synergy between and among individuals and institutions acting on the different sides of such border and working towards a common purpose is therefore of the essence if inter-State arrangements and agreements providing for transboundary aquifer cooperation are to make a dent, and cooperation strengthened as a result.

A final important factor at work towards strengthened transboundary aquifer cooperation is the communication between and across the different disciplines and professionals involved on either and both sides of an international boundary, in particular the scientists who investigate the physical characteristics and properties of a transboundary aquifer, and the policy- and decision-makers who translate the scientific findings and recommendations into governance and management propositions and relevant cross-border cooperation modalities. Synergy between the two groups is at the heart of cooperation eventually, and effective translation of scientific findings into policy-relevant material and recommendations that can be internalized and acted upon by decision-makers, is at the heart of strengthened cooperation.

TOPIC 5

Education, capacity development and raising awareness

Conclusions

by Kevin Peterson

Addressing governance of transboundary aquifers (TBA) requires developing education, improving capacity development and raising awareness of transboundary water cooperation. The educational initiatives throughout the last decade have provided critical information about the TBA to the Member States and their management. The capacity developed has resulted in a cohort of practitioners and academicians able to respond to physical assessments, establish cooperation and collaboration mechanisms, and institutionalise shared management of the TBA. Awareness among the River Basin Organisations (RBO) has resulted in cooperative mechanisms to include groundwater and constructive dialogues among scientists and decision-makers for TBA shared management.

The primary issue confronting implementing policies and programmes in the groundwater sector is having skilled, capable persons and competent persons to oversee the implementation processes needed for TBA management. The higher education system has a significant responsibility to develop the capacities needed to define and implement policies, uncover innovations and generate the cadre of leaders needed to change societies and economies.

During the ISARM conference, this topic highlighted the need to continue supporting programmes that advance knowledge and knowledge sharing around transboundary aquifers. Not many abstracts were received at the conference directed to the specific topic. This may be due to education, capacity development and raising awareness being very much a cross-cutting issue – cutting across many of the other topics of the conference.

Some of the issues highlighted include:

- Knowledge and capacities need continual development in TBA, involving stakeholders and capacity development where riparian countries cooperate. Groundwater-related knowledge, capacity development and data availability are crucial for ensuring water access for all in TBA.

- Investment is also needed for capacity development to strengthen and sustain institutions dealing with TBA shared management. This is necessary to support informed decision-making and cooperation. As stated by one of the keynote speakers "The value of water as a catalyst for development needs to be better understood, utilising a holistic approach that capitalises on existing experiences, mobilises partners, and allows stakeholders to contribute meaningfully".

Researchers gave examples of sub-regional cooperation on isotope basin assessments in Europe, Central Asia and Sahel Africa. Higher education programmes in MSc and GIS have started. Resource Centers have been established to provide public and private sector services. As one of the presenters noted, we need data on the ground for implementing policy, and to obtain data on the ground, we need capacity.

The conference has shown that education, capacity development, and awareness-raising are mechanisms for cooperation, and there are examples of long-standing support for capacity development. Future attention must focus on the structural challenges at the institutional level for TBA shared management within countries and the regional institutions. Local stakeholders are frequently neglected in TBA assessments which require renewed focus.

Annex

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(*) With the sad and sudden passing of Dr Ralf Klingbeil in 2021, UNESCO-IHP is reminded of Ralf's personal and professional committement to groundwater studies and to the ISARM2021 programme.

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The world is facing challenges related to population growth, surface water scarcity, and more importantly, to the increasing dependency on shared groundwater resources.

This book, which is a compilation of studies, representing the status of transboundary aquifers knowledge around the world, offers an attempt to depict a variety of assessments of transboundary aquifers in different regions of the world as well as some insights on policy development.

This book is a contribution to the UN-Water Summit on Groundwater, the culminating event of the 2022 UN-Water campaign "Groundwater: making the invisible visible".

This book is a contribution to the UNESCO IHP studies on Groundwater Resources and Aquifer Systems

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