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Review

Cross-border groundwater impacts and joint management interventions: An overview of case studies

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ABSTRACT

Transboundary aquifers (TBAs) are shared by different political entities, and their management often requires multilateral efforts. However, despite their strategic importance in sustaining ecosystems and human communities, the level of cooperation over TBAs remains generally low. Lack of awareness and political willingness are often cited for this. This paper further demonstrates the need for and relevance of TBA cooperation through an overview of real cases of cross-border groundwater impacts and joint management interventions across the world. The product of an extensive review of academic and grey literature, this study provides key insights into the types of cross-border groundwater impacts and joint management interventions, as well as the TBA settings where cases have been identified. This allows for important lessons on the scope of TBA cooperation to be drawn. Notably, the evidence-base suggests that in large TBAs, joint management interventions could often be prioritized over the border area. It also shows the need for proactive cooperation mechanisms to develop joint management interventions, not only to mitigate or remediate cross-border groundwater impacts, but also to prevent them.

1. Introduction

Transboundary aquifers (TBAs) are aquifers spanning over multiple political entities. The term is commonly used to indicate international aquifers shared by two or more countries, but in the broader sense, it also refers to domestic aquifers falling under different jurisdictions within the same country, such as federated states. Their governance implies bilateral or multilateral efforts (Puri, 2021). As pressures on water resources increase through population growth, increasing water demand, ecosystem degradation and climate change, the need to cooperate on shared water resources like TBAs is growing (UNESCO-IHP and UNECE, 2024).

However, the latest report of Sustainable Development Goal (SDG) Indicator 6.5.2 ("Proportion of transboundary basin area with an operational arrangement for water cooperation"), which tracks cooperation on shared water resources, indicates that 48 of the 111 countries where the indicator is available have less than 10 % of their TBA area covered by an operational arrangement (UNECE et al., 2024).[1] The indicator score is particularly low in the Americas and Asia. The report mentions that TBA cooperation is lagging behind that of transboundary river and lake basins. Scholars too have reported the slow progress in TBA governance (Puri and Villholth, 2018; Puri, 2021; Sindico, 2020; Rivera

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[1] Arrangements are considered operational in the case of i) existence of a joint body, ii) regular, formal communication between riparian countries (at least once a year), iii) joint or coordinated management plans or objectives, and iv) regular exchange of data and information (at least once a year).

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et al., 2023).

The need for TBA cooperation typically arises from the potential for cross-border impacts within these shared aquifers (Rivera et al., 2023; Eckstein and Eckstein, 2005), although other considerations play an important role, such as regional integration, peacebuilding, and security (UNECE, 2015; Adelphi and CAREC, 2017). While cross-border impacts – and even disputes – in surface water basins are well documented and easy to conceptualize, even for non-experts, awareness of cross-border impacts in TBAs remains hampered by the invisible nature of aquifers and a lack of groundwater data (Tapia-Villaseñor and Megdal, 2021; Puri and Villholth, 2018; Rivera et al., 2023; Eckstein and Eckstein, 2024). There are limited publications on the assessment and management of cross-border groundwater impacts (Maass-Morales et al., 2024), and the scientific literature on TBAs is mostly about the *potential* benefits of cooperation (UNESCO-IHP and UNEP, 2016; Altchenko et al., 2017; Fraser et al., 2020; Pétré et al., 2019; Narvaez-Montoya et al., 2022). This might not be sufficiently compelling for decision-makers to take action. They might be hesitant to invest resources on issues like cross-border groundwater impacts that are either undetected or that might only appear in the future (Giraut et al., 2010), and there is apparently a need to further demonstrate the relevance of TBA cooperation (Sindico and Martin-Nagle, 2019).

The aim of this study is to provide the first overview of real case examples of cross-border groundwater impacts and/or joint management interventions reported in the literature, to illustrate some of the practical needs and benefits of TBA cooperation. This overview is guided by the following research questions: i) What types of cross-border groundwater impacts have been reported worldwide, where do they occur, in which aquifer settings, at what scales? ii) What joint management interventions have been implemented in response to such impacts, and how effective have they been? To address these questions, the literature was systematically reviewed to identify all reported cases and their information was compiled and categorized into an inventory for consistent comparison and analysis.

2. Methodology

2.1. Identification of cases

Cases of cross-border groundwater impacts and/or joint management interventions were identified through a systematic literature review completed in July 2025. The conceptual boundaries of this review and the search strategy are outlined in the following subsections.

2.1.1. Conceptual boundaries

The definitions and the criteria adopted to distinguish the cases in the literature are presented below, together with the theoretical framework that underpins them. They are also synthetized in Fig. 1.

2.1.1.1. Cross-border groundwater impacts. Cross-border groundwater impacts can be defined as “any adverse effect on the quality and/or quantity of groundwater and/or connected surface water body, that develops in a TBA country due to human activity located in another” (Maass-Morales et al., 2024). For example, a decline of groundwater levels in one country due to pumping activities in the neighbouring country (Rivera et al., 2023). Maass-Morales et al. (2024) have developed a new conceptual framework for characterizing cross-border groundwater impacts (Fig. 2), in which they distinguish three stages in the development of cross-border groundwater impacts: the first is the human action that causes the impact, also known as the *triggering action*, such as Land Use/Land Cover (LULC) change affecting infiltration, groundwater abstraction or groundwater pollution. The second is the *initial groundwater impact* that occurs in the country or state where the triggering action takes place. The third is the *type of cross-border groundwater impact*, which affects transboundary flow: alter groundwater flow across the border, alter groundwater-surface water interactions across the border, abstraction-induced intrusion of low-quality water into the neighbouring country, and transport of groundwater pollutants across the border. These cross-border groundwater impacts can fall in the category of quantity impacts or quality impacts.

The literature review targeted publications reporting past or present cross-border groundwater impacts (the 3rd stage in the Maass-Morales et al., 2024 framework). Publications reporting only *triggering actions* or *initial groundwater impacts* were not considered. Publications suggesting that cross-border groundwater impacts *might* occur in the future, have also not been considered, since the objective is to learn from real case studies. To qualify, the publication had to establish a causal relationship between a triggering action on one side of the border and a resulting change in groundwater quantity or quality on the other side. This causal relationship, grounded in a conceptual understanding of the system, should be supported by observed data and/or numerical modelling. For example, the drawdown of groundwater levels comparing pre and post groundwater development in the neighbouring state; or elevated nitrates concentrations linked to agricultural sources in the adjacent state. Therefore, publications reporting that a triggering action on one side of the border has reduced the quality or quantity of groundwater on the other side, without supporting data and/or a modelling assessment were not considered. The quality of such evidence was not evaluated, as doing so would have required reassessing data that lay out of the scope of this study. As an example, Fig. 3 shows the drawdown map in the Irtysh-Obsky Aquifer System presented by Podolny (2010), which supported the inclusion of that case in the inventory.

The significance of the cross-border groundwater impacts was not adopted as a criterion to distinguish the cases, because it is typically dependent on the context (e.g. water resources availability, ecosystems sensitivity, socioeconomic factors). Therefore, cross-border groundwater impacts of any spatial-temporal dimensions and intensity have been included.

In line with the Maass-Morales et al., 2024 framework, cross-border groundwater impacts resulting primarily from human activities on surface water (e.g. water abstraction from a river or construction of dams in the neighbouring country) have not been included. However interesting in terms of conjunctive water management, these cases usually fall in the remit of cooperation on transboundary river and lake basins, and it would not have been feasible to include them all (if we think of the effects of dams on groundwater resources in transboundary river basins, for example).

2.1.1.2. Joint management interventions. In addition to cross-border groundwater impacts, the literature review targeted publications reporting joint management interventions, which are defined here as measures coordinated by at least two countries or states, aimed at preventing, mitigating or remediating cross-border groundwater impacts. Although a wide range of groundwater management measures exist, only a few types of them are represented in the cases of joint management interventions that were identified in the literature review: groundwater use regulation, Managed Aquifer Recharge (MAR) – “the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit” (Dillon et al., 2009) –, Best Management Practices (BMP), protection zones, and water-saving investments. Other cooperation activities like data sharing, joint meetings or studies are essential to design such management interventions, where necessary; however, it falls beyond the scope of this study to include every case where such activities have not (yet) translated into joint management interventions. Such information can be drawn from the disaggregation of SDG indicator 6.5.2 data by Fraser et al. (2023). Joint management interventions that have not been adopted yet were discarded. Likewise, management interventions developed unilaterally (i.e. by one country or state) were not taken into consideration, as they do not necessarily

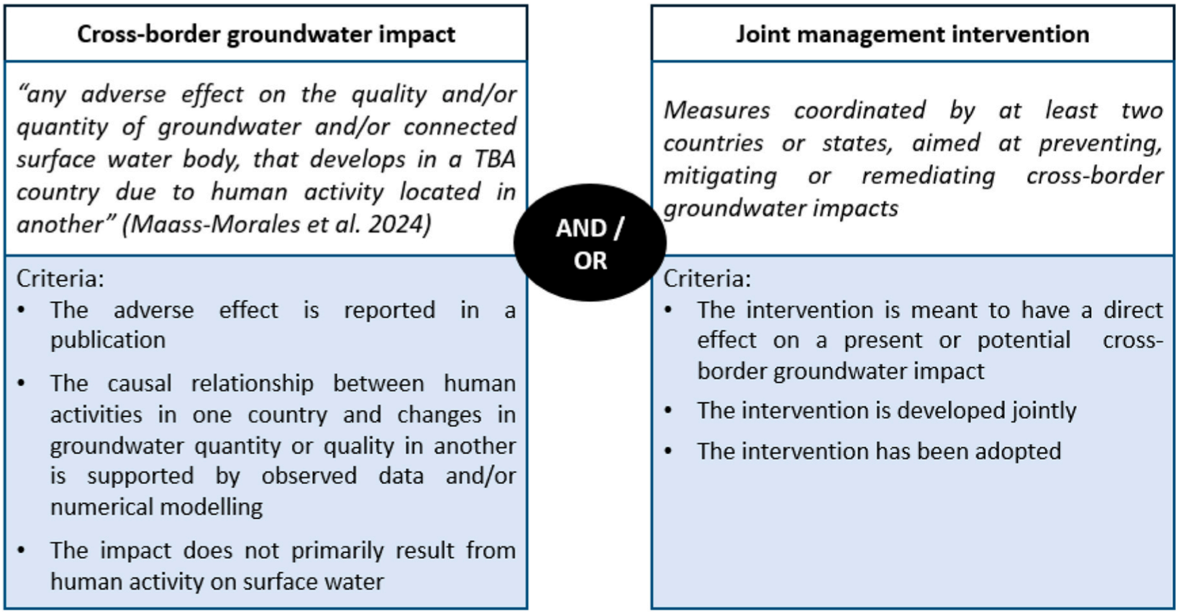

Fig. 1. Definition and criteria adopted to distinguish cases of cross-border groundwater impacts and/or joint management interventions in the literature.

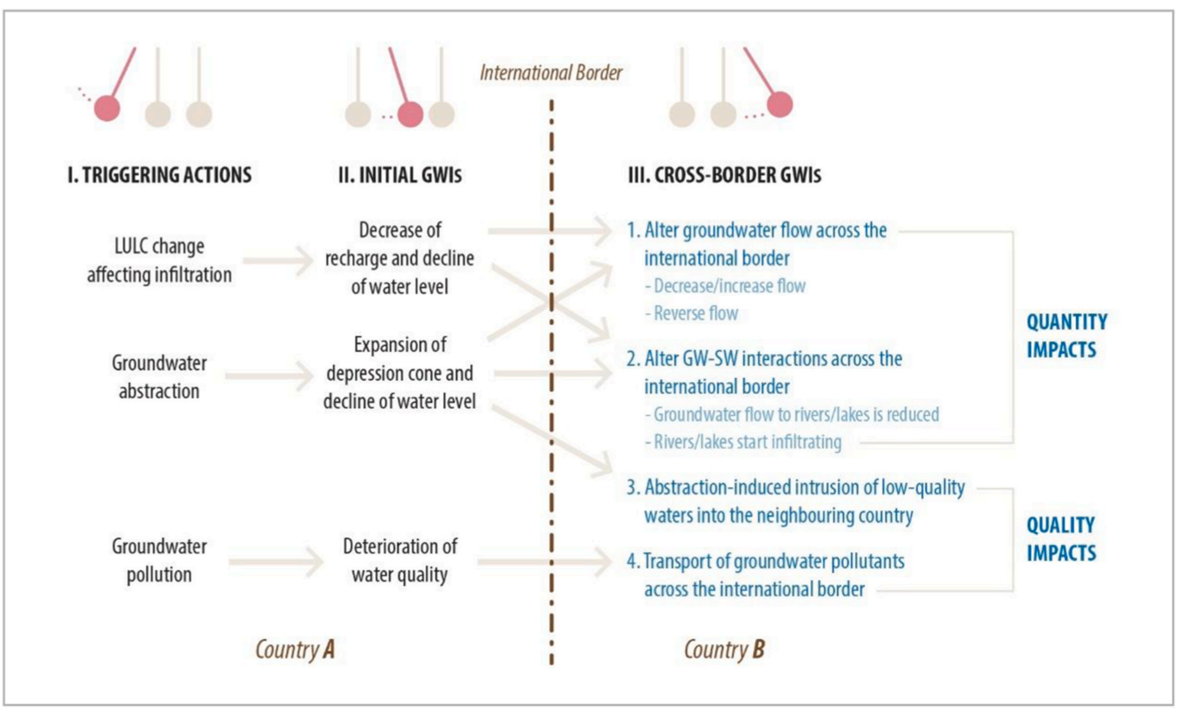

Fig. 2. Conceptual framework of cross-border groundwater impacts introduced by Maass-Morales et al. (2024).

relate to cross-border groundwater impacts.

2.1.2. Search strategy

The literature review of cases of cross-border groundwater impacts and/or joint management interventions was carried out primarily in English. Relevant publications in Dutch, French, German, Russian and Spanish, cited in English publications or known by the authors, were also reviewed, sometimes with the help of automatic translation tools. Publications from all years were considered, as both contemporary and historical cases are relevant for providing a first overview of the topic, even when the present status of cases reported in older publications is unknow.

Scientific publications were first searched in scholarly databases (i.e. Web of Science and Google Scholar) for each of the 468 international TBAs identified by IGRAC (2021). As only a limited number of cases reported in academic publications were found, the literature review was extended to include grey literature such as reports, legal and policy documents, theses, conference proceedings, books chapters, and blog articles. The search was done using the names of the TBAs and keywords related to cross-border groundwater impacts and joint management interventions. Since these terms are rarely used explicitly in the literature, different combinations of keywords from the following categories were applied:

Fig. 3. Extent of the transboundary cone of depression in the Irtysh-Obsky Aquifer System (Podolny, 2010).

- Category 1: “cross-border”, “transboundary”, “cross-boundary”, “shared”, “joint”
- Category 2: “impact”, “depletion”, “decline”, “over abstraction” “contamination”, “pollution”, “seawater intrusion”, “flow reversal”, “salinization”, “conflict”, “issue”
- Category 3: “protection”, “management”, “zone”, “area”, “MAR”

The literature review was updated during the recent update of the map (IGRAC and UNESCO-IHP, 2025), in which the authors were involved. Next to the publications of cases in international TBAs, literature of three cases reported in domestic TBAs were known to the authors. As domestic TBAs are often not referred to as “TBAs”, it was difficult to identify more of such cases during the literature review.

2.2. *Characterization of cases*

The identified cases of cross-border groundwater impacts and/or joint management interventions were compiled in an inventory in which each case was characterized. The inventory was structured into three tables, one for the cross-border groundwater impacts, another for the joint management interventions, and a third one for the TBA setting in which these cases occur.

Cases of cross-border groundwater impacts were characterized based on the three development stages presented in the framework of Maass-Morales et al. (2024): *triggering action, initial groundwater impact, type and category of cross-border groundwater impact*. Where possible, an indication of the spatial scale of the cross-border groundwater impact is provided, expressed as the distance between the cause of the cross-border groundwater impact and the border.

Cases of joint management interventions were characterized in terms of type, whether it was restricted to a specific area, the institutional level of the parties engaged in joint management interventions, and the type of arrangement under which joint management interventions are made. An indication of the spatial scale of the joint management interventions is provided, expressed as the distance between the intervention and the border, or the area covered by joint management interventions.

For each case of cross-border groundwater impact and/or joint management interventions, the TBA was characterized by identifying the aquifer states, size, main lithology, main aquifer type, climate zone and main use(s) of groundwater. The types of aquifers were categorized as unconfined or confined and, where possible, further indication was provided following the conceptual models introduced by Eckstein and Eckstein (2005). Climate zones were extracted from the Köppen-Geiger map for the period 1991–2020 (Beck et al., 2023).

3. Overview of cases

Ten cases of cross-border groundwater impacts and ten cases of joint management interventions were found in the literature, in a total of 18 TBAs, including two TBAs where both cross-border groundwater impacts and joint management interventions were identified (Fig. 1). In the following sections, an overview of the cross-border groundwater impacts, joint management interventions, and related TBAs is given. A short description of each case is provided in Appendix A.

3.1. *Cross-border groundwater impacts*

Ten cases of cross-border groundwater impacts were found, which are summarized in Table 1. Eight cases fall in the category of groundwater quantity impacts, with declines in groundwater levels and an alteration of groundwater flow across the border resulting from groundwater abstraction. In some of these cases, a reversal of the groundwater flow direction was reported, as in cases n°3 and 16. In the coastal Concordia-Escritos/Caplina Aquifer (case n°5), groundwater abstraction not only led to a decrease of groundwater flow across the border, but also to seawater intrusion. In the Allende-Piedras Negras Aquifer (case n°2), groundwater abstraction affected the river baseflow of the Rio Grande. This is the only case that was found where the main impact is a modification of groundwater/surface water interactions. Next to these quantity impact cases, there are two cases of quality impacts resulting from the transport of groundwater pollutants across the border. However, groundwater quality is sometimes a secondary concern in cases of groundwater depletion, for example in case n°16, where groundwater depletion also led to groundwater salinization.

The spatial scale of cross-border groundwater impacts could be quantified in all but two cases. They are mostly limited to the area adjacent to the border: except for case n°9, where the distance between the triggering action and the border is more than 25 km. Many cases of cross-border groundwater impacts were based on numerical modelling studies (e.g. cases n°2, 3, 5, 9, 12 and 16).

3.2. *Joint management interventions*

Ten cases of joint management interventions were found, including in two TBAs where cross-border groundwater impacts were also identified (cases n°1 and 3). All but one of these joint management interventions primarily address groundwater quantity issues. They consist of pumping restrictions or bans, MAR and water-saving investments. It is worth noting that the control of new wells sometimes has a secondary objective to prevent groundwater salinization, which can result from groundwater depletion (e.g. case n°16), or contamination from the surface or across aquifers, since boreholes can act as vertical pathways for contaminants (e.g. case n°14). In case n°3, management interventions not only address the cross-border groundwater depletion issue but also aim to prevent groundwater contamination through a combination of limiting of abstraction and polluting activities.

There is only one case where groundwater quality is the main issue being addressed, the Abbotsford-Sumas Aquifer (n°1), where Best Management Practices (BMP) were disseminated to reduce nitrate pollution from the agricultural sector. In the Una Aquifer (case n°15), a Sanitary Protection Zone has been designed to protect the two springs supplying the city of Bihać from pollution (Holinger et al., 2020). However, no evidence could be found indicating that this protection zone has been adopted by the authorities, and therefore it has not been

Table 1
Inventory of cross-border groundwater impacts reported in the literature.

n°	TBA Name	Triggering action	Initial groundwater impact	Type of cross-border groundwater impact	Category	Spatial scale	References	Type(s) of references
1	Abbotsford-Sumas Aq.	Groundwater pollution	Degradation of water quality	Transport of groundwater pollutants across the border	Quality impacts	Unknown	Mitchell et al., 2003	Scientific article
2	Allende-Piedras Negras Aq.	Groundwater abstraction	Decline of water level	Alter GW-SW interaction across the border	Quantity impacts	<15 km	Rodriguez et al., 2020	Scientific article
3	Al Saq/Al Disi Aq.	Groundwater abstraction	Decline of water level	Decrease or reverse groundwater flow across the border	Quantity impacts	Unknown	UN-ESCWA and BGR, 2013	Report
5	Concordia-Escritos/Caplina Aq.	Groundwater abstraction	Decline of water level	Decrease or reverse groundwater flow across the border; Abstraction-induced intrusion of low- quality water into the neighbouring country	Quantity & quality impacts	<25 km	Narvaez-Montoya et al., 2022	Scientific article
6	Estevan Valley Aq. System	Groundwater abstraction	Decline of water level	Decrease or reverse groundwater flow across the border	Quantity impacts	23 km	Rivera (ed.), 2014	Book
9	Irtysh-Obsky Aq. System	Groundwater abstraction	Decline of water level	Decrease or reverse groundwater flow across the border	Quantity impacts	<50 km	Podolny, 2010; Podolny, 2024	Conference article, conference presentation
11	Memphis Aq.	Groundwater abstraction	Decline of water level	Decrease or reverse groundwater flow across the border	Quantity impacts	<20 km	Waldron and Larsen, 2015; Eckstein, 2021b	Scientific article, blog article
12	Mimbres/Las Palmas Aq.	Groundwater abstraction	Decline of water level	Decrease or reverse groundwater flow across the border	Quantity impacts	<10 km	Hawley et al., 2000	Report
15	Una Aq.	Groundwater pollution	Degradation of water quality	Transport of groundwater pollutants across the border	Quality impacts	<15 km	Holinger et al., 2020	Report
16	Valle de Juarez Bolson/Hueco-Tularosa Bolson	Groundwater abstraction	Decline of water level Degradation of water quality	Decrease or reverse groundwater flow across the border; Alter GW-SW interactions across the international border	Quantity impacts	At the border	Sheng and Devere, 2005; Texas Water Development Board and New Mexico Water Resources Research Institute, 1997	Scientific article, report

considered as a case of joint management intervention.

In more than half of the cases, joint management interventions were restricted to a specific area adjacent to the border, such as the "Protection Area" and the "Management Area" in the Al Saq/Al Disi Aquifer (case n°3), or the "Designated Area" in the Tertiary Limestone Aquifer and Tertiary Confined Sand Aquifer (case n1°4). These cases are mapped in Fig. 5, with the exception of the Western Aquifer.

Joint management interventions occur under different sorts of arrangements. There are three cases of joint management interventions falling under international, aquifer-specific arrangements or agreements. Four cases fall under domestic, aquifer-specific arrangements or agreements, including two cases in international TBAs: the Calcaires Carbonifères du Tournaisis/Kolenkalk Aquifer (case n°4), because the joint management interventions were implemented on the Belgian side only, under the eponymous agreement of 1997 between the administrative regions of Flanders and Wallonia, and the Pretashkent Aquifer (case n°13), because the joint management interventions took place at a time when the two countries, Kazakhstan and Uzbekistan, were still part of the Union of Soviet Socialist Republics (USSR). Two cases fall under international river basin agreements, and one case falls under an international, non-water specific agreement.

Evidence of the effectiveness of joint management interventions could not always be found in the literature. In the Genevois Aquifer (case n°7) and the Lower-Bavarian – Upper-Austrian Molasse Basin (case n°10), for example, limiting abstraction and MAR allowed for groundwater levels to stabilize or recover. In the Abbotsford-Sumas Aquifer (case n°1), on the contrary, the dissemination of BMP was not followed by a significant reduction of nitrate contamination.

3.3. *TBA settings*

The main characteristics of the TBAs where cross-border groundwater impacts and joint management interventions were reported are presented in Table 3. There are 15 international TBAs and three domestic TBAs, many of which are located in North America. Other cases were identified in TBAs in South America, Europe, the Middle East, Central Asia and Oceania. The size of TBAs is highly variable, ranging from a few tens of square kilometers to more than one million square kilometers. Cases are found in a similar proportion of confined and unconfined aquifers. In terms of lithology, more cases have been identified in unconsolidated or partially consolidated sand and gravel aquifers than in carbonate-rock or sandstone aquifers. Many TBAs are located in arid, temperate and (to a lesser extent) continental climate zones. Drinking water supply has been identified as the main use of groundwater - or one of the main uses - in a majority of TBAs, and irrigation in just under half of them. Other groundwater uses, such as tourism, livestock, the mining industry, the production of geothermal energy, and the bottling industry, have also been reported.

4. Discussion

4.1. *Challenges in identifying cross-border groundwater impacts*

The inventory of cross-border groundwater impacts and joint management interventions led to the identification of a limited number of cases of cross-border groundwater impacts: 10 in total, including one in a domestic TBA. This number is small with respect to the 426

Table 2
Inventory of joint management interventions reported in the literature.

n°	TBA Name	Type of joint management intervention	Management zone	Spatial scale	Institutional level	Arrangement	References	Type(s) of references
1	Abbotsford-Sumas Aq.	Best Management Practices (BMP)	No	200 km^2	Nat & subnat.	International aquifer-specific arrangement	Messa, 2014; Zebarth et al., 2015	Thesis, scientific article
3	Al Saq/Al Disi Aq.	Pumping regulation & protection zone	Yes	<10 km 10–26 km	Nat.	International aquifer-specific arrangement	Eckstein, 2015; Government of the Hashemite Kingdom of Jordan and Government of the Kingdom of Saudi Arabia, 2015	Legal and policy document, Blog article
4	Calcaires Carbonifères du Tournaisis/ Kolenkalk Aq.	Pumping restriction or ban	Yes	<15 km	Subnat.	Domestic aquifer-specific arrangement	Flemish Region and Walloon Region, 1997	Legal and policy document
7	Genevois Aq.	Pumping restriction or ban/MAR	No	31 km^2	Subnat.	International aquifer-specific arrangement	de los Cobos, 2018; State Council of the Republic and Canton of Geneva and Prefect of Haute-Savoie, 1977	Scientific article, Legal and policy document
8	Great Artesian Basin	Water-saving investments[a]	No	1,700,000 km^2	Subnat.	Domestic aquifer-specific arrangement	Habermehl, 2018	Book chapter
10	Lower-Bavarian - Upper-Austrian Molasse Basin	Pumping restriction or ban/MAR	Yes	<20 km 5900 km^2	Subnat.	International river basin agreement	Expert group "Thermal water", 2012	Report
13	Pretashkent Aq.	Pumping restriction or ban	No	15,920 km^2	Nat.	Domestic aquifer-specific arrangement	UNESCO-IHP, 2016; UNECE, 2024	Report
14	Tertiary Limestone Aq. and Tertiary Confined Sand Aq.	Pumping restriction or ban	Yes	<20 km	Subnat.	Domestic aquifer-specific arrangement	DEWNR and DELWP, 2014; State of South Australia and State of Victoria, 1985	Legal and policy document, factsheet
17	Valle de Mexicali-San Luis Rio Colorado Aq./Yuma-Imperial Valley	Pumping restriction or ban	Yes	<8 km	Nat.	International river basin agreement	Bradley and DeCook, 1978; IBWC, 1973	Legal and policy document, scientific article
18	Western Aq.	Pumping restriction or ban[b]	Yes	1678 km^2	Nat.	International non water-specific agreement	United Nations, 1980; UN-ESCWA and BGR, 2013	Report

[a] Consisting in the rehabilitation of boreholes and the installation of water-saving infrastructure.
[b] Groundwater abstraction is regulated in the West Bank by the Joint Water Committee (JWC), inherited from the Oslo-II interim agreement of 1995, in a context of military occupation of the State of Palestine by Israel. Through the JWC, Israel uses its veto right to oppose the development and the maintenance of water infrastructure in Palestine. In practice, this case hardly qualifies as an example of cooperation. It nonetheless illustrates the relevance of cross-border groundwater impacts in the aquifer.

international TBAs that have been reported to date (IGRAC and UNESCO-IHP, 2025). However, several limitations suggest that cross-border groundwater impacts are more common than recorded in this inventory. First, there is limited literature on this topic in academic journals and other publications. Many references come from the grey literature. Unlike academic literature, grey literature does not lend itself to a comprehensive and systematic review: there are no centralized databases of grey literature, and it comes in various languages. A similar issue was reported during the revision of the map Transboundary Aquifers of the World (IGRAC and UNESCO-IHP, 2025). That half of the cases have been found in English-speaking countries probably reflects that the literature review was mostly carried out in English. The grey literature likely holds more information on cross-border groundwater impacts, which was not readily available to the authors.

Secondly, the literature review showed how challenging it is to positively identify cross-border groundwater impacts. In many reviewed publications, the availability of monitoring data and other scientific evidence was insufficient to demonstrate a causal relationship between human activities on one side of the border and groundwater impacts on the other, for example in the Valle de Mexicali-San Luis Rio Colorado Aquifer/Yuma-Imperial Valley (Bradley and DeCook, 1978; Eckstein and Eckstein, 2024), in the Guarani Aquifer (Banega et al., 2019) or in the Conejos-Medanos/Mesilla Bolson (Robertson et al., 2022). Identifying causal relationships might require advanced investigations and numerical modelling studies, particularly so in TBAs with groundwater - surface water interactions. In fact, several cases are based on numerical modelling studies. Since groundwater data availability and research are usually higher in high-income countries, it may not be a coincidence that almost 90 % of the cases have been identified in TBAs shared by high-income countries.[2] Cross-border groundwater impacts remain likely undetected in countries where data availability is low. Even in data-rich contexts, identifying cross-border groundwater impacts might be very complicated, for instance in TBAs where similar human activities and groundwater impacts are observed in both aquifer states, making it virtually impossible to disentangle causal relationships between triggering actions and impacts across the border. Several TBAs along the Mexico-USA border are in that situation, for example (Sanchez et al., 2024).

Moreover, some types of cross-border groundwater impacts will be more complicated to identify than others. For instance, quantity impacts related to drinking water supply, irrigation, and industry will usually manifest themselves as cones of depression below wellfields (Zawadzki et al., 2016), which makes them more easily identifiable than the more diffuse impacts caused by agricultural LULC (Foster and Candela, 2008). In fact, 70 % of the cases of cross-border groundwater impacts were found in TBAs where drinking water supply is the main use of groundwater (or one of the main uses), although drinking water supply is

[2] According to World Bank classification, 2024 (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups).

Table 3
Inventory of TBA settings for cases of cross-border groundwater impacts and joint management interventions reported in the literature.

n°	TBA Name	States	Aquifer size*	Main aquifer type	Main lithology	Climate zone	Main aquifer use	Primary references
1	Abbotsford-Sumas Aq.	Canada, United States of America	200 km^2	Unconfined	Sand and gravel	Temperate	Irrigation/ Drinking water supply	Zebarth et al., 2015
2	Allende-Piedras Negras Aq.	Mexico, United States of America	7024 km^2	Unconfined, linked to a contiguous transboundary river	Sand and gravel	Arid	Irrigation	Rodriguez et al., 2020
3	Al Saq/Al Disi Aq.	Jordan, Saudi Arabia	308,000 km^2	Unconfined & confined	Sandstone	Arid	Irrigation/ Drinking water supply	UN-ESCWA and BGR, 2013
4	Calcaires Carbonifères du Tournaisis/ Kolenkalk Aq.	Belgium (Flanders, Wallonia), France	1420 km^2	Unconfined & confined	Carbonate-rock (karst)	Temperate	Drinking water supply	Vandelois et al., 2025
5	Concordia-Escritos/ Caplina Aq.	Chile, Peru	*1199 km2*	Unconfined, linked to a domestic river	Sand and gravel	Arid	Irrigation	Narvaez-Montoya et al., 2022
6	Estevan Valley Aq. System	Canada, United States of America	*9218* km^2	Confined	Sand and gravel	Continental	Drinking water supply	Rivera (ed.) 2014
7	Genevois Aq.	France, Switzerland	31 km^2	Confined	Sand and gravel	Temperate	Drinking water supply	de los Cobos, 2018
8	Great Artesian Basin	Australia (New South Wales, Northern Territory, Queensland, South Australia)	1,700,000 km^2	Confined	Sandstone	Arid	Livestock/ Drinking water supply/Mines	Habermehl, 2018
9	Irtysh-Obsky Aq. System	Kazakhstan, Russia	>400,000 km^2	Unconfined & confined	Sand and gravel	Arid/ Continental	Drinking water supply	Podolny, 2010; Podolny, 2024
10	Lower-Bavarian - Upper-Austrian Molasse Basin	Austria, Germany	5900 km^2	Confined	Carbonate-rock (karst)	Continental/ Temperate	Geothermal energy/Tourism	Expert group "Thermal water", 2012
11	Memphis Aq.	United States of America (Mississippi, Tennessee)	*158,000* km^2	Confined	Sand and gravel	Temperate	Drinking water supply	Eckstein, 2021b; Waldron and Larsen, 2015
12	Mimbres/Las Palmas Aq.	Mexico, United States of America	13,300 km^2	Unconfined	Sand and gravel	Arid	Irrigation	Hawley et al., 2000
13	Pretashkent Aq.	Kazakhstan, Uzbekistan	15,920 km^2	Confined	Sandstone	Arid/ Temperate/ Continental	Drinking water supply/ Tourism/Bottled water	UNESCO-IHP, 2016
14	Tertiary Limestone Aq. and Tertiary Confined Sand Aq.	Australia (South Australia, Victoria)	*51,750* km^2	Unconfined & confined	Carbonate-rock & Sand and gravel	Arid/ Temperate	Irrigation/ Drinking water supply	DEWNR and DELWP, 2014
15	Una Aq.	Bosnia & Herzegovina, Croatia	1773 km^2	Unconfined	Carbonate-rock (karst)	Continental/ Temperate	Drinking water supply	Stevanović and Marinović, 2020
16	Valle de Juarez Bolson/Hueco-Tularosa Bolson	Mexico, United States of America	*7766* km^2	Unconfined, linked to a contiguous transboundary river	Sand and gravel	Arid	Drinking water supply	Sheng and Devere, 2005
17	Valle de Mexicali-San Luis Rio Colorado Aq./ Yuma-Imperial Valley	Mexico, United States of America	*28,000* km^2	Unconfined	Sand and gravel	Arid	Drinking water supply	Bradley and DeCook, 1978
18	Western Aq.	Israel, State of Palestine	9000–14,167 km^2	Confined, with a recharge zone in one riparian jurisdiction	Carbonate-rock (karst)	Temperate	Irrigation/ Drinking water supply	UN-ESCWA and BGR, 2013

* Areas in italic were calculated by the authors.

estimated to account for some 21 % of total groundwater use globally (Margat and van der Gun, 2013). Less cross-border groundwater impacts were found in TBAs used for irrigation, and no case was found that is caused by LULC change affecting infiltration.

4.2. TBAs as strategic water resources

Another explanation for the higher number of cases in TBAs used for drinking water supply is that such aquifers are often considered as strategic resources, where groundwater monitoring and protection will be prioritized. This increases the likelihood of identifying cross-border groundwater impacts and the probability of adopting joint management interventions. In general, most of the cases found in this inventory occur in TBAs that can be considered strategic. Apart from drinking water supply, TBAs can be strategic for various economic sectors, such as the agriculture, tourism, etc. For example, the Lower-Bavarian - Upper-Austrian Molasse Basin (case n°10) is essential for the tourism industry and the production of geothermal energy. More than half of the cases were found in arid or semi-arid regions, where TBAs can be the main (sometimes only) source of freshwater. The strategic importance of cross-border groundwater impacts is well illustrated by the Mississippi v. Tennessee et al. lawsuit over the Memphis Aquifer (case n°11), where the state of Mississippi sought 615 million USD in damages for depleting the aquifer by the City of Memphis (the Supreme Court eventually rejected Mississippi's claim) (Eckstein, 2021b). The Western Aquifer (case n°18) is yet another illustration of the relevance of cross-border groundwater impacts in strategic TBAs.

4.3. Expanding the evidence-base

Despite the limited number of cases found, this study represents a significant improvement in comparison to earlier studies. Maass-Morales et al. (2024), for instance, mentioned only two cases of cross-border groundwater impacts (cases n°1 and 9) and one case of an adopted transboundary groundwater management zone (case n°2), while this study has five of them. In their analysis of the legal implications of cross-border groundwater impacts, Eckstein and Eckstein (2024) also mentioned a limited number of real-case examples of such cross-border groundwater impacts: case n°2, again, and case n°17. The inventory is also useful as it sheds light on several cases from the grey literature, such as the Irtysh-Obsky Aquifer System (case n°9), the Lower-Bavarian - Upper-Austrian Molasse Basin (case n°10) or the Tertiary Limestone Aquifer and Tertiary Confined Sand Aquifer (case n°14). It therefore contributes to expanding the evidence-base of TBA experiences and practices, which is limited (Eckstein, 2021a). In general, this study mobilizes several cases in TBAs that have not received as much attention as the few TBAs covered by international, aquifer-specific arrangements, on which the literature on TBA cooperation often revolves (Sindico, 2020; Tapia-Villaseñor and Megdal, 2021; Velis et al., 2022). As other authors have highlighted (Lipponen and Chilton, 2018), lessons on TBA cooperation can be learnt from joint management interventions implemented in TBAs not covered by such aquifer-specific arrangements, for instance under domestic agreements or international river basin agreements. This study provides several of such cases (Table 2).

4.4. Conditioning factors of cross-border groundwater impacts

The limited number of cases presented in this inventory does not allow for a quantitative analysis, but some observations can be made. First, groundwater abstraction caused in several cases not only the decrease but the reversal of groundwater flow across the border. This shows, in line with other studies (OAS, 2009), that the need and the scope for TBA cooperation cannot be assessed simply on the basis of pre-development groundwater flow patterns, and the distinction between upstream and downstream states is not as relevant as in river basins. Second, cases of cross-border groundwater impacts and joint management interventions concerning groundwater quantity are found in TBAs where the recharge rate is low, in deep and confined aquifers or under arid climates. These aquifers are indeed more vulnerable to over-abstraction (Margat and van der Gun, 2013). Likewise, cases of cross-border groundwater impacts and joint management interventions concerning groundwater quality were identified in TBAs that are vulnerable to groundwater pollution (Margat and van der Gun, 2013), like the Abbotsford-Sumas Aquifer (case n°1), which is characterized by a shallow water table, high recharge and high groundwater velocity, and the Una Aquifer (case n°15), which is highly karstic. This finding illustrates the intrinsic vulnerability of TBAs to cross-border groundwater impacts – or conditioning factors, as outlined by Maass-Morales et al. (2024). The relevance of conditioning factors and triggering factors in the development of cross-border groundwater impacts further supports multi-criteria assessments and other prioritization methods to invest efforts in transboundary cooperation where it is most valuable (Tapia-Villaseñor et al., 2025; Davies et al., 2013; Fraser et al., 2020).

4.5. Transboundary groundwater management zones

In this study, cross-border groundwater impacts and joint management interventions mostly occur near the border (within 25 km from the border, or less than 2.000 km^2). Long-ranging cross-border groundwater impacts are less common. For instance, numerical modelling of the Nubian Sandstone Aquifer System, covering more than 2.6 million km^2, showed that transboundary drawdown would likely be minimal and limited to the border area (Voss and Soliman, 2014). In the Guarani Aquifer System (±1.2 million km^2), emerging groundwater issues that might require cross-border cooperation are restricted to the border area (Sugg et al., 2015), over "no more than a few dozen kilometers depending upon local specific hydrodynamic conditions" (OAS, 2009). If any, long-ranging cross-border groundwater impacts would take more time to manifest and probably be challenging to identify.

These findings support previous calls to prioritize TBA cooperation efforts over transboundary groundwater management zones, where cross-border groundwater impacts are most likely to occur (Fraser et al., 2020; Kettelhut et al., 2010; Kukuric et al., 2011; Rivera, 2021; Rivera et al., 2023; Rivera and Candela, 2018; Maass-Morales et al., 2024; Sanchez et al., 2024; Velis et al., 2022). This is seen as a cost-effective pathway to translate transboundary cooperation mechanisms into joint management interventions. In the Bellaggio Draft Treaty, prioritization was a key element ("Article VII - Transboundary Groundwater Conservation Areas") intended to spare sovereign sensitivities (Hayton and Utton, 1989). Prioritization would be particularly relevant in large TBAs: indeed, about 25 % of the TBAs identified by IGRAC and UNESCO-IHP (2025) are larger than 20.000 km^2, roughly the size of a country like Slovenia.

The inventory contains five case examples of transboundary groundwater management zones (Fig. 4). In four of them, the transboundary groundwater management zone was delineated until a certain distance from the border. In the fifth case (Calcaires Carbonifères du Tournaisis/Kolenkalk Aquifer, case n°4), the control of groundwater abstraction did not apply over a whole border area but instead targeted a set of wellfields. In two instances (cases n°3 and 10), two levels of transboundary groundwater management zones have been established next to each other, with more stringent joint management interventions applied in the zone adjacent to the border. In case n°14, the transboundary groundwater management zone was divided into 22 sub-zones (11 on each side of the border), perpendicularly to the border, which allows for the adoption of context-specific joint management interventions. These cases show how transboundary groundwater management zones can be put into practice and suggest that there is a value in multi-level approaches.

Other cases of joint management interventions applied over the entire area of the TBA. These are mostly small TBAs, however the study contains two cases of joint management interventions that were implemented over the entire area of large TBAs (cases n°8 and 13). These two cases are found in deep artesian aquifers, the Pretashkent Aquifer and the Great Artesian Basin, where hydraulic diffusivity is typically high (water pressure declines propagate fast). In such aquifers, transboundary groundwater management areas might not be appropriate. It calls back to the need for a sound assessment of hazards and conditioning factors in TBAs to design appropriate joint management interventions.

4.6. Institutional mechanisms

The spatial scale of cross-border groundwater impacts and joint management interventions suggest handling these issues locally. Most of the joint management interventions have been adopted or are being adopted by institutions at the local or subnational level (municipalities, water utilities, regional governments), not by the central states. Decentralized, local-scale management of TBA cooperation has been seen as a key factor of the success of the Genevois Aquifer agreement (de los Cobos, 2018), and several authors have recommended addressing TBA cooperation at the local level (Eckstein, 2013; Fraser et al., 2020; Sanchez and Eckstein, 2020; Walter, 2010) and with polycentric governance models (Mukuyu et al., 2024, Wuijts et al., 2022), in line with the principle of subsidiarity. At the same time, four cases of joint management interventions were adopted under domestic agreements. However insightful these cases are, cooperation in domestic TBAs does not meet the same level of complexity than international TBAs (Puri, 2021). The example of the Pretashkent Aquifer is telling: a water sharing agreement existed between Kazakhstan and Uzbekistan, when the two

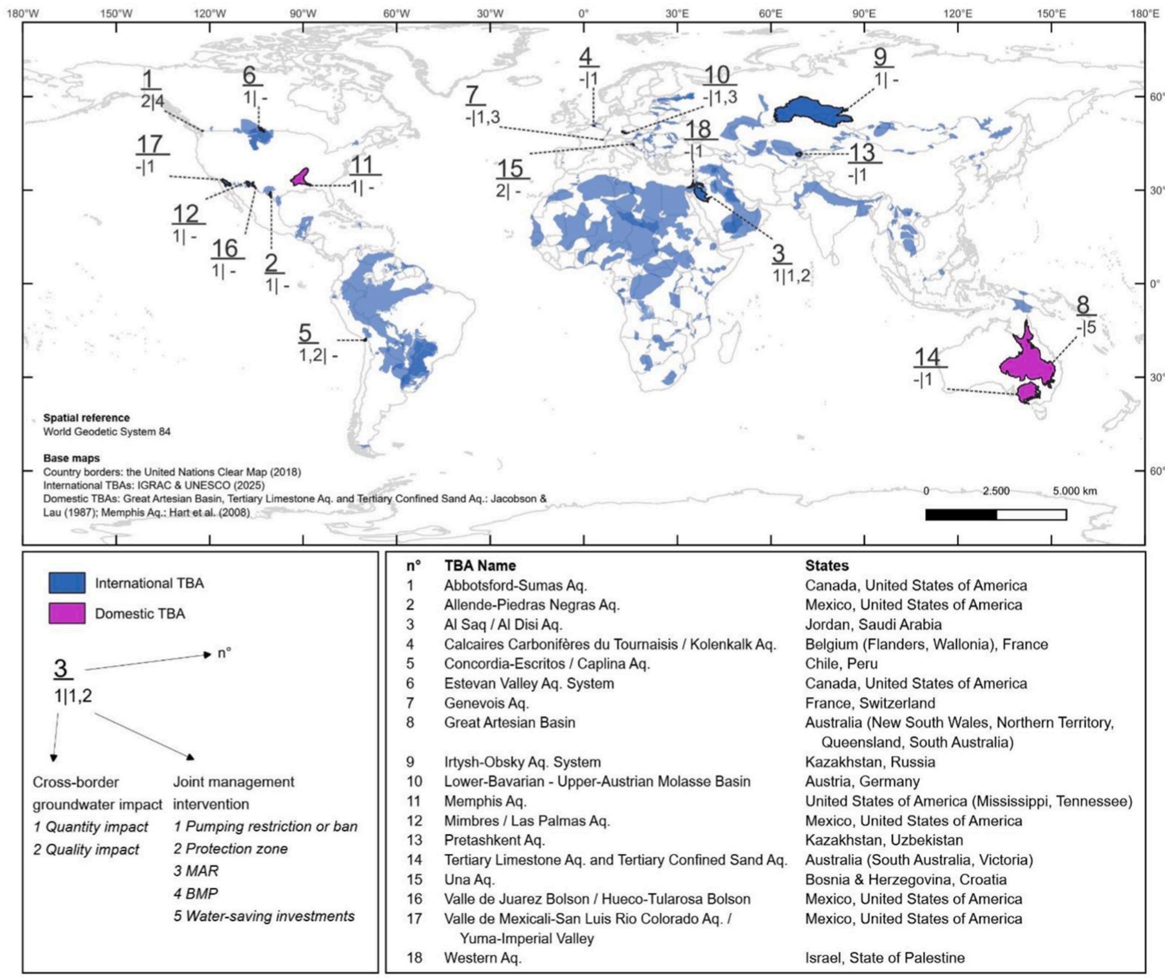

Fig. 4. Location map of the TBAs where cross-border groundwater impacts and/or joint management interventions have been identified.

countries were republics of the USSR. This agreement ended at independence. Since then, significant efforts have been invested to revive cooperation on this TBA and, despite promising achievements, more efforts will be needed in the future.

4.7. Proactive TBA cooperation

The framework used to characterize cross-border groundwater impacts (Maass-Morales et al., 2024) relies on the propagation of impacts from triggering actions in one country to a neighbouring country. However, the authors of the framework recognize that in reality, there might be triggering actions in both countries, whereby several cross-border groundwater impacts could occur, in both directions. In this inventory, cases of cross-border groundwater impacts caused by groundwater abstraction often show abstraction in more than one country. Similarly, one of the cases of quality impacts has polluting activities on either side of the border (i.e. Abbotsford-Sumas Aquifer; case n°1). Moreover, there are several cases where the groundwater flow pattern changed over time, or cases in multi-layer aquifer systems. This is an important difference with transboundary river basins, where cross-border impacts are typically caused by upstream countries on downstream countries (Puri and El Naser, 2002). In TBAs, searching for individual responsibilities might be unproductive. Instead, there is a scope for countries to cooperate on shared impacts. This is illustrated by several cases of joint management interventions that were adopted without identifying cross-border groundwater impacts, but with initial groundwater impacts reported on both sides of the border.

Joint management interventions can help not only to mitigate or remediate existing cross-border groundwater impacts, but also to prevent emerging ones, if implemented upon the identification of triggering actions or initial impacts. Transboundary Environmental Impact Assessments (EIA), among others, can help identify potential cross-border groundwater impacts before activities are granted a permit. For instance, it was reported that a gold mining project in Ukraine was abandoned after joint studies identified risks of cross-border groundwater impacts (Szucs et al., 2013).

Finally, a small number of cases of joint management interventions have been identified in comparison with the results of the last SDG Indicator 6.5.2 reporting phase (UNECE and UNESCO-IHP, 2024), which show that operational arrangements have been implemented or partially implemented in several TBAs globally. As this study set out to demonstrate, activities covered under operational arrangements, such as data sharing, joint meetings or aquifer management plans, are essential to design joint management interventions, where necessary and prevent cross-groundwater impacts, or even disputes (Puri and El Naser, 2002; Eckstein, 2021a). The Stampriet Transboundary Aquifer System (STAS) illustrates this well. For more than 10 years, the three aquifer states (Botswana, Namibia and South Africa) have developed a cooperation mechanism over this strategic water resource, without identifying cross-border groundwater impacts or imminent risks of cross-border groundwater impacts. However, this mechanism is currently proving instrumental to evaluate, in a timely manner, the proposal for exploiting uranium through in-situ leaching in the Namibian part of the aquifer, an activity raising concerns of groundwater contamination, including for

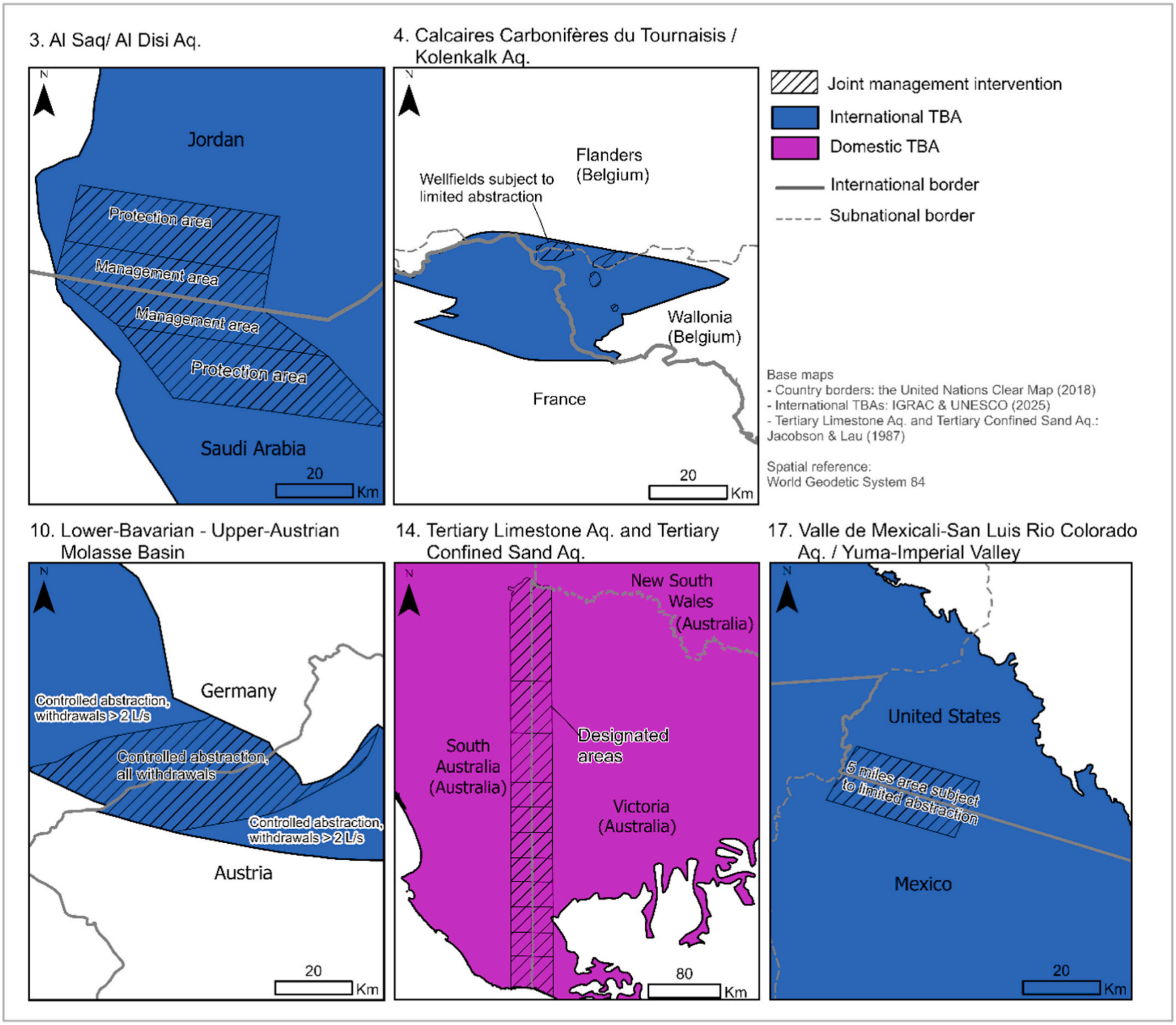

Fig. 5. Cases where joint management interventions are restricted to specific zones adjacent to the border.

downstream aquifer states (UNESCO, 2024).

5. Conclusion

This inventory of cases of cross-border groundwater impacts and joint management interventions provides empiric evidence that groundwater depletion and contamination do cross borders and can have significant impacts on neighbouring states. It also illustrates how such cross-border groundwater impacts can be prevented, mitigated or remediated, and demonstrates the need for aquifer states to develop transboundary institutional mechanisms and engage in cooperation activities that make joint management interventions possible. It shows that the spatial extent of cross-border groundwater impacts and joint management interventions is usually limited to the border area, which suggests that transboundary cooperation efforts could be prioritized over these areas. It also suggests that local institutions should play a leading role in TBA cooperation mechanisms. The need for data and hydrogeological studies to identify cross-border groundwater impacts means that cross-border groundwater impacts are likely more prevalent than the number of cases that was found, and there would be a value in mapping initial groundwater impacts in TBAs to identify where joint management interventions could be relevant. It is also likely that a thorough review of grey literature in other languages would reveal additional cases. It is hoped that more cases will be brought to light in the upcoming years, with the participation of national or regional experts, bringing additional insight on cross-border groundwater impacts and joint management interventions.

CRediT authorship contribution statement

Arnaud Sterckx: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Constanza Maass-Morales:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Christina M. Fraser:** Writing – review & editing, Investigation, Conceptualization. **Kevin Pietersen:** Writing – review & editing. **Oleg Podolny:** Writing – review & editing. **Lucía Samaniego:** Writing –

review & editing. **Rosario Sanchez:** Writing – review & editing.

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Declaration of competing interest

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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