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Review

Management zones in transboundary aquifers: A review of delineation methods under a new framework of cross-border groundwater impacts

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ABSTRACT

Attention on the use of transboundary aquifers (TBAs) and their cross-border impacts is growing as countries become increasingly concerned about their long-term water security. Cross-border impacts, in groundwater quality and quantity, tend to concentrate in specific parts of TBAs, as they largely depend on the transboundary flow dynamics where anthropogenic actions operate. Thus, there is a growing consensus that strategies intended to prevent or mitigate such impacts should be implemented in strategic zones rather than in the whole TBA. These transboundary groundwater management zones (TGMZs) are relatively recent but have become a prominent topic in TBA management. However, until now, limited effort has been put into exploring the concept of TGMZs and the methods for their delineation. This research aims to fill these gaps and provide a basis for the delineation of TGMZs, thus helping neighbouring countries meet international responsibilities regarding the right to use and enjoy groundwater in TBAs. By reviewing academic and grey literature accessible from public sources, we present an overview of the concept and terminology of TGMZs, the approaches proposed for their delineation, and current operating examples. Additionally, we build a conceptual framework for assessing cross-border groundwater impacts by identifying their typologies and causal factors. We then apply our framework to evaluate and compare three reported methods which identify and delineate TGMZs from distinct perspectives, thereby gaining insights into their principles, performances, and limitations. Finally, we provide recommendations for further research towards optimising methods for delineating TGMZs.

1. Introduction

A transboundary aquifer (TBA) is an aquifer or aquifer system whose parts are located in different countries (UNGA, 2008). The most recent global inventory has identified a total of 468 TBAs in 142 countries, showing that TBAs underlie almost every country in the world (IGRAC, 2021). A TBA contains groundwater that can flow between neighbouring countries (Puri and El Naser, 2002; Rivera et al., 2022; Wada and Heinrich, 2013) and be hydraulically connected to surface water bodies (e.g. streams, rivers, lakes) (hereafter referred to as connected SWB). This shared groundwater can sustain aquatic and terrestrial ecosystems and human populations, creating hydrological, social, and economic interdependencies between countries (UN-Water, 2008).

Human activities in a TBA (e.g. waste disposal, fertiliser application, groundwater abstraction) can cause impacts on the quality and quantity of both groundwater and connected SWB. These impacts can be felt in the country where the activities operate and in neighbouring countries. In principle, an impact could be either beneficial or adverse, i.e. increase or decrease the natural quantity and/or quality of the referred water resources. Throughout this article, the focus will be on adverse effects, as they can be causes for disputes (Eckstein and Eckstein, 2024). Accordingly, a cross-border groundwater impact (GWI) is defined hereafter, as any adverse effect on the quality and/or quantity of groundwater and/or connected SWB, that develops in a TBA country due to human activity located in another. For example, intense groundwater pumping in a country can cause a drop in the water levels that can expand beyond the

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international border into the neighbouring country, as occurred in the Irtysh-Obsky TBA (Kazakhstan-Russia) (ILEC et al., 2016). Likewise, groundwater contaminated with agrochemicals in one country can flow across the border into its neighbouring country, as reported in the Abbostdford-Sumas TBA (Canada-United States of America (USA)) (Council of Canadian Academies, 2009). Naturally, these impacts can create other adverse cross-border (sub)impacts on groundwater-dependent ecosystems (GDEs) (e.g. damage to the flora and fauna of wetlands) and on human groundwater needs (e.g. increase in the costs of drinking water supplies and treatments).

According to international law and current agreements and arrangements regarding TBAs, every country has the right to use and enjoy groundwater in its territory; still, this right can be subject to restrictions and liability if it interferes with the equivalent right of the neighbouring country (Eckstein and Eckstein, 2024).[2] Hence, in an era of increasing water stress and climate change (Munia et al., 2020), managing cross-border GWIs in TBAs is essential for sustaining GDEs and human groundwater needs, as well as maintaining stable relations between TBA countries. Ideally, the management of cross-border GWIs should rely on a unified and consistent conceptual hydrogeological model of the TBA (Puri and El Naser, 2002), requiring proper spatiotemporal data and, often, complemented with numerical modelling to assess ongoing and potential impacts. However, this is often challenging in TBAs, as data collection and harmonisation between different countries is elaborate and politically sensitive (Kukuric et al., 2013). Nevertheless, since groundwater movement is usually slow and fragmented into various flow systems, often only some parts of TBAs are relevant for controlling cross-border GWIs (Kukuric et al., 2013; Rivera and Candela, 2018). For example, in parts adjacent to the international border (hereafter referred to as frontier area) where significant human activities take place (Rivera et al., 2022).

For the reasons above, and as a way to move forward, there is a growing consensus in the literature that the management of transboundary groundwater use and impact should concentrate on smaller-scale zones rather than on the entire aquifer, especially in large TBAs (Fraser et al., 2020; Kettelhut et al., 2010; Kukuric et al., 2013; Rivera, 2021; Rivera et al., 2022; Rivera and Candela, 2018). The literature on these management zones is scattered and often vague, since they have been addressed with different and often inconsistent terminology. Although some directions and methods have been proposed to delineate these zones, no thorough analysis of their fundaments or feasibility has been conducted. Additionally, neither the typologies and causal factors of cross-border GWIs have been explicitly address in the literature, nor the use of methods to assess such impacts when relevant data are unavailable.

This paper aims to provide a foundation for delineating management zones concerning transboundary groundwater use and impact. First, section 2 presents a review of the conceptualisation and terminology of these management zones in the literature, the approaches for their delineation, and operational experiences. Section 3 presents a framework for assessing cross-border GWIs based on the recognition of typologies and causal factors of such impacts. Section 4 reviews specific methods that have delineated the management zones to gain insight into their principles, performances, and limitations. Furthermore, the framework of cross-border GWIs is used to compare the inputs and outputs of these methods and discuss trends. Finally, section 5 presents conclusions and provides recommendations for future research to optimise the delineation of management zones in TBAs.

2. Review of management zones in TBAs

This section reviews the academic and grey literature on management zones concerning transboundary groundwater use and impact, accessible from public sources in English and Spanish. Section 2.1 presents the literature that has referred to the characteristics and purposes of these management zones, to elaborate on their concept and terminology; section 2.2 shows the literature referring to approaches to delineate the zones; and section 2.3 presents operational experiences of them. Section 2.4 discusses considerations and limitations of the review.

2.1. Conceptualisation and terminology

Literature on management zones concerning transboundary groundwater use and impact is scarce, with currently only nine publications referring to their characteristics and/or purposes (Table 1). A review of the publications shows that the topic is relatively recent and has received limited attention in the academic literature. Of these eight publications, six were published during the last five years, five can be considered grey literature, and only three specifically focus on this subject.

An analysis of the names, descriptions, and purposes of these management zones in the literature reveals inconsistencies in their characterisation and terminology (see Table 1). Despite the inconsistencies, most of the publications describe them as specific zones within the territory of a TBA where ongoing or potential cross-border GWIs are a concern. The purpose of identifying such a zone is to achieve effective management of the shared groundwater resources, by implementing individual or joint countries' strategies. These strategies vary in scope but include: (1) conducting new or in-depth hydrogeological assessment and monitoring (Fraser et al., 2020; Pétré et al., 2022; Sanchez et al., 2020); (2) regulating groundwater abstraction and pollution activities (Kettelhut et al., 2010; Fraser et al., 2020); and, (3) establishing governance mechanisms such as international agreements and arrangements (Fraser et al., 2020; Kettelhut et al., 2010; Sanchez et al., 2020).

Particularly, different names have been used to refer to these management zones (see Table 1). Examples of them are: "zones of (potential) transboundary impacts" (Rivera and Candela, 2018), "regions for internationally shared management strategies", "effective transboundary aquifer areas" (Rivera, 2021; Sanchez et al., 2020), "vulnerable transboundary aquifer hotspots" (Fraser et al., 2020), and "transboundary groundwater management units" (Rivera et al., 2022). In general, these names consist of a combination of two or more terms from the following categories:

- Spatial designation within a TBA (e.g. *area, zone, frontier zone, region, unit, strip of land)* and related attributes (e.g. *key, priority, strategic, etc.*);
- Issue of international concern (e.g. *transboundary groundwater, transboundary impact, transboundary aquifer, transboundary aquifer hotspots, transboundary hotspots*) and related attributes (e.g. *potential, risk, vulnerable*);
- Strategy to control the concern (e.g. *shared management, cross-border management, joint management, management*) and related attributes (e.g. *local, efficient, effective, direct, practical, multi-scale*).

Based on the provided definition of the management zones, the name "Transboundary Groundwater Management Zone" is proposed as an

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[2] Today, international law instruments regarding TBAs such as the "Draft Articles on the Law of transboundary aquifers" (UNGA, 2008) and the "Model Provisions on Transboundary Groundwaters" made under the "Convention on the Protection and Use of Transboundary Watercourses and International Lakes" (UNECE, 2012), lack legal binding force (Burchi, 2018). However, it currently exists customary principles of international water law guiding the countries' behaviour, such as the "equitable and reasonable utilisation" and the 'no harm rule" (Burchi, 2018). Nonetheless, today it does not exit a universally accepted set of these customary principles ruling TBAs (Eckstein and Eckstein, 2024). Furthermore, the scope of the right to use and enjoy groundwater by the TBA countries has not been fully defined within international law (Eckstein and Eckstein, 2024).

Table 1
Appearance of groundwater management zones in TBAs in the literature.

	Publication			Management zones in TBAs		
	Authors	Type	Focus	Name	Description	Purpose
1	Kettelhut et al. (2010)	Conference article	Zones for groundwater management in TBAs	“Strategic strip of land, “Frontier management zone”	Strip of land in the frontier area of a TBA, in which an action in water use could cause an impact in the neighbouring country	Establishing minimal and effective management mechanisms that will contribute to the protection and management of groundwater
2	Kukuric et al. (2013)	Report of guidelines on TBAs assessment	General assessment of TBAs	Not specified	Zones of the aquifer that are likely to cause or receive transboundary impacts within a reasonable time	Implementing transboundary management
3	Agreement Al-Sag/Al-Disi Layer (2015)	International agreement	Management and utilisation of groundwater in a TBA	“Protected area”, “Management Area”	Zones demarcated in the frontier area between Jordan and Saudi Arabia	Establishing rules for groundwater abstraction and pollution activities
4	Rivera and Candela (2018)	Scientific article	Outcomes from the UNESCO ISARM initiative	“Zones of (potential) transboundary impacts”, “Regions for internationally shared management strategies”	Zones within TBAs where there may be transboundary groundwater impacts	Implementing a joint management plan to prevent or mitigate cross-border conflicts
5	Sanchez et al. (2020)	Scientific article	Zones for groundwater management in TBAs	“Effective Transboundary Aquifer Areas (ETAAs)”	Priority hotspot areas of groundwater productivity in TBAs	Implementing “more efficient and effective transboundary groundwater assessment, management options at a more regional and local scale”
6	Fraser et al. (2020)	Scientific article	Zones for groundwater management in TBAs	“Vulnerable transboundary aquifer hotspots”, “Hotspots of transboundary risk”	Hotspot areas in TBAs at risk of groundwater quality and quantity transboundary issues at multi-scales	Implementing immediate actions such as “further investigations, directed cross-border management and potentially transboundary agreements”
7	Rivera (2021)	Journal editorial	Management of TBAs	“Groundwater management units under the TBA context”, “Effective TBA areas”	Not specified	Managing groundwater under a transboundary context
8	Pétré et al. (2022)	Conference article	Assessement of Milk River TBA	“Transboundary groundwater management unit”	Not specified	Prioritising “future study and monitoring, to support joint management”.
9	Rivera et al. (2022)	Journal essay	Key elements of TBAs issues	“Transboundary groundwater management units”	Unit where transboundary implications are important (e.g. groundwater flow across the border, presence of well fields or pollution)	Implementing appropriate management

Table 2
Appearance of methodological approaches for delineating TGMZs in the literature.

	Authors	Name	Description	Methodological Proposal	Approach
1	Kettelhut et al. (2010)	Not specified	Estimates the most distant point from the international border in which any human action could cause a cross-border groundwater impact, through a method that uses the aquifer hydraulic characteristics of the frontier area, a time frame, and the groundwater flow direction	Concrete method for delineation	**Cross-border Flow Zoning**
2	Kukuric et al. (2013)	“Zoning”	Divides the TBA into a number of zones, considering the hydraulic characteristics, flow direction and type of transboundary interaction expected	General direction towards delineation	
3	Rivera and Candela (2018)	“Time-scale and Space-scale factors”, “Scale factor”, “Zoning”	Defines zones within the TBAs by considering groundwater flow systems	General direction towards delineation	
4	Rivera (2021)	Not specified	Divides the TBA into groundwater flow systems and identifies the relations based on scientific, social, economic and political needs and issues	General direction towards delineation	
5	Pétré et al. (2022)	Not specified	Defines zones in the TBA based on groundwater flow directions	Concrete method for delineation (not described in detail)	
6	Sanchez et al. (2020)	“Identification of hotspots of groundwater productivity”	Identifies zones with intense groundwater pumping along the frontier of TBAs by a method that uses the location, quantity, and depth of active pumping wells, topography and hydrography features	Concrete method for delineation	**Cross-border Hotspots Identification**
7	Rivera (2021)	Not specified	Identifies priority zones in TBAs by using pumping hotspots	General direction towards delineation	
8	Fraser et al. (2020)	“Risk hotspot analysis”	Identifies zones at risk of quality and quantity GWIs by a method that uses anthropogenic pressures and aquifer conditions as criteria	Concrete method for delineation	

appropriate denomination as it encompasses the purpose of such areas (i.e. the management of the shared groundwater resources). Therefore, this name, and its acronym TGMZ, are used hereafter. This term is preferred over the term “Transboundary Groundwater Management Unit”, used by Pétré et al. (2022) and Rivera et al. (2022), as the word *unit* could be confused with a physical spatial designation (e.g. geological/hydrogeological unit), an institutional designation (e.g. department, section), or even a measure parameter (e.g. impact per m^2/year). Nevertheless, it should be noted that management unit, zone, and area are all widely used and exchangeable terms in natural resources management literature and practice.

2.2. Delineation of TGMZs

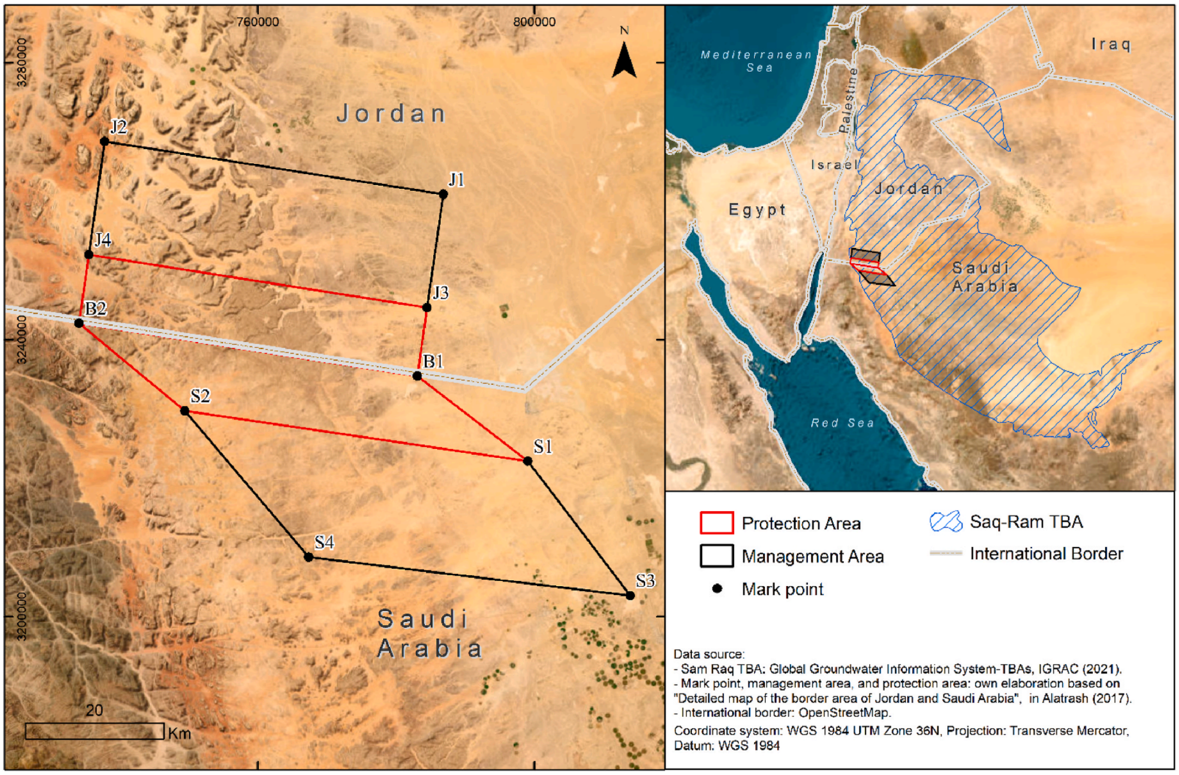
2.2.1. Methodological approaches

Directions and methods towards the delineation of TGMZs have appeared in seven publications in the literature (Table 2), distinguishing between two main methodological approaches. The first approach, followed by five of the publications, consists of zoning the TBA based primarily on the direction and/or spatial-temporal scales of groundwater flow across the international border. This approach has been named in the literature “time-scale and space-scale factors” (Rivera and Candela, 2018), “scale factor” (Rivera and Candela, 2018) and “zoning” (Kukuric et al., 2013; Rivera and Candela, 2018). In this article we refer to these approaches as *cross-border flow zoning*. The second approach followed by four publications (as the study of Rivera (2021) describes both approaches) refers to the identification of significant human pressures on groundwater within the frontier area of TBAs. This approach has been named in the literature as “Identification of hotspots of groundwater productivity” (Sanchez et al., 2020) and “risk hotspot analysis” (Fraser et al., 2020) and adapted in this article to *cross-border hotspots identification.*

The publications proposing concrete methods for delineating TGMZs are Kettelhut et al. (2010), Fraser et al. (2020), Pétré et al. (2022), and Sanchez et al. (2020). These four methods emerged from studies motivated by different aims, problems/gaps, and application contexts. Despite their differences, three of them (Kettelhut et al., 2010; Sanchez et al., 2020; Fraser et al., 2020) consist of spatial analysis techniques designed for TBAs where hydrogeological data is limited. The method by Pétré et al. (2022) has not been explained in detail in the literature, but, in contrast with the other methods, relies on unified conceptual, geological, and numerical flow models of a TBA. These methods are described and analysed in **Section 4**. Further information about the research and application context of the methods are provided in additional material (**Appendix A**).

2.2.2. TGMZs within the general assessment of TBAs

The delineation of TGMZs has been proposed as a recommended step within the general joint assessment of TBAs, in two methodological guideline reports (Kukuric et al., 2013; IGRAC and UNESCO-IHP, 2015). Both guidelines propose the delineation of TGMZs after having a base understanding of the TBA. Kukuric et al. (2013) present a methodology in which the delineation of TGMZ (named zoning) is recommended as the fifth of a six-step process: 1. Delineation of the aquifer geometry, 2. Description of the aquifer main properties and components, 3. Classification of relevant characteristics for revealing patterns (e.g. aquifer size, hydraulic properties), 4. Diagnostic analysis that ranks criteria to select TBAs for priority management, 5. Zoning, and 6. Data harmonisation and information management. IGRAC and UNESCO-IHP (2015) present a methodology with a four-step process: 1. Data collection, 2. Harmonisation and aggregation, 3. Aquifer characterisation, 4. Data management. The third step (aquifer characterisation), which assesses the aquifer dynamic and the environmental, socioeconomic, legal and institutional aspects, suggested mapping TGMZs (named zones of priority) as part of the proposed activities. Building the knowledge of TBA systems and their conceptual functioning is paramount to a proper assessment and management of these water resources. During the implementation of the EU Water Framework Directive, for instance, priority was given to the delineation and characterisation of groundwater bodies, before proceeding with the development of status



Data source:
- Sam Raq TBA: Global Groundwater Information System-TBAs, IGRAC (2021).
- Mark point, management area, and protection area: own elaboration based on "Detailed map of the border area of Jordan and Saudi Arabia", in Alatrash (2017).
- International border: OpenStreetMap.

Coordinate system: WGS 1984 UTM Zone 36N, Projection: Transverse Mercator, Datum: WGS 1984

Fig. 1. Map of the TGMZs implemented in the west section of the Saq-Ram TBA by Jordan and Saudi Arabia (adapted from Agreement Al-Sag/Al-Disi Layer (2015)) .

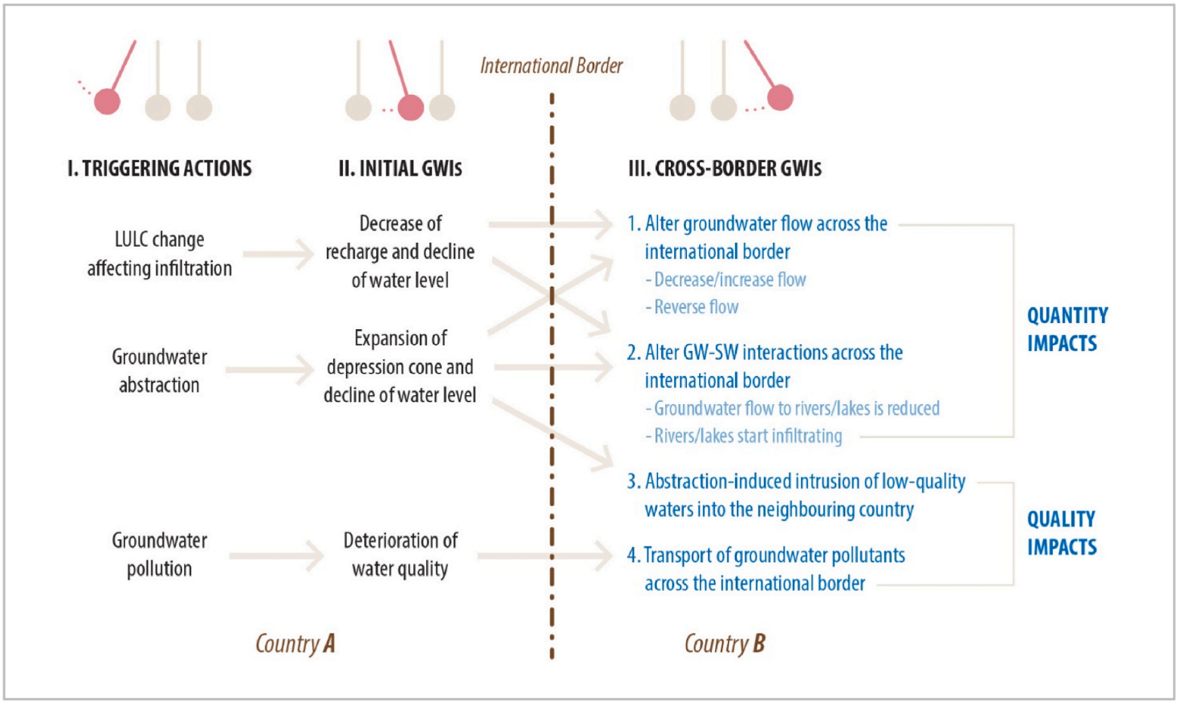


Fig. 2. Typologies of cross-border GWIs in TBAs.

assessment methodologies and management strategies (European Commission, 2004). Similarly, in a technical manual for the integration of groundwater management into transboundary basin organisations in Africa (AGW-Net and CapNet, 2015), the characterisation of groundwater systems and their GW-SW interactions, is a pre-requisite for any management strategy of the transboundary resources.

2.3. Operational experiences of TGMZs

The only reported experiences of operational TGMZs are found in the western section of the Saq-Ram TBA, namely Al-Sag/Al Disi layer, shared by Jordan and Saudi Arabia (Fig. 1). The TGMZs were settled by the countries within a legally binding agreement (Agreement Al-Sag/Al-Disi Layer, 2015). In this agreement, two zones were delineated at the frontier area of this TBA. First, a "Protected area" in which all groundwater abstraction activities had to be eliminated, and where the drilling of any monitoring well requires the coordination with the "Technical Joint Committee". Second, a "Management Area" in which groundwater abstraction is only granted for municipal purposes, the drilling of any well is subject to technical standards, and horizontal and tilted wells are prohibited to avoid groundwater pollution. As shown in Fig. 1, the "Protection Area" is located within the "Management Area". The "Protected Area" extends over approximately 400 km^2 within each country, while the "Management Area" covers around 1,000 km^2 (Eckstein, 2015). How these TGMZs were delineated was neither reported in the agreement nor in other literature accessible from public sources. Still, before the agreement, Puri et al. (1999) and Puri and El Naser (2002) mentioned that several studies had been conducted to assess the impacts on human activities in both countries, and the long-term yield and reliability of groundwater (e.g. hydrogeological numerical modelling, groundwater risk assessments).

2.4. Considerations and limitations of the literature review

The literature review on TGMZs had as its main difficulty in the different terminology employed to name and/or describe them. Therefore, the strategy to find relevant literature on electronic search engines (e.g. Scopus, Google Scholar) consisted of using a wide range of terms in English and Spanish arranged in different ways. Additionally, we reviewed literature on assessment and management of TBAs published

Table 3
Triggering factors of cross-border GWIs.

1. Location	A. Intersection of changed LULC with recharge areas and its proximity to the international border B. Not applicable C. Position of changed LULC within groundwater flow systems that cross the international border	A. Proximity of the abstraction source to sensitive elements, i.e. international border, connected SWB, and lower-quality water body (WB) B. Depth of the abstraction source (shallow, medium, deep) C. Position of the abstraction source in relation to the direction of groundwater flow across the international border (upgradient/downgradient)	A. Proximity of the pollution source to sensitive elements, i.e. international border and connected SWB B. Proximity of the pollution source to the aquifer saturated zone C. Position of the pollution source in relation to the direction of groundwater flow across the international border (upgradient/downgradient)	Triggering factors
2. Duration	Duration of the LULC change that is affecting infiltration (permanent/ temporal)	Abstraction duration and frequency	Pollutant discharge duration and frequency	
3. Intensity	Infiltration/recharge reduction rate due to changed LULC	Abstraction rate	Pollutant load	
4.Characteristic	Not applicable	Abstraction infrastructure type and quality to prevent pollution during construction/operation	Pollutant behaviour and fate	

by UNESCO, UNECE, Internationally Shared Aquifer Resources Management (ISARM) programme, International Groundwater Assessment Centre (IGRAC), Transboundary Water Assessment Programme (TWAP), Transboundary Aquifer Assessment Programme (TAAP), as well as the international agreements and arrangements pertaining TBAs. The review, therefore, considered the academic and grey literature published in the referred languages and accessible from the mentioned sources. Nevertheless, we acknowledge that reviewing literature in other languages and from non-public sources, such as TBA country reports and working documents, could uncover new relevant literature on TGMZs.

3. Conceptual framework of cross-border GWIs

The delineation of TGMZs requires a prior understanding of cross-border GWIs. Currently, knowledge on these impacts in TBAs is very limited. Only three publications have elaborated on their relevant characteristics (Eckstein and Eckstein, 2024; Puri and El Naser, 2002; Rivera, 2015), while there is only little evidence of reported cross-border GWIs cases in the literature (Fraser and Sterckx, 2022). Although the latter could be linked to the controversial nature of these impacts, it may also reveal the blind spots to recognise and assess them with the same approach as domestic GWIs (i.e. entirely located within one country). Therefore, by building on the existing knowledge in domestic and cross-border GWIs, and fields with analogous transmissions and causalities (i.e. cross-border climate impacts and landslide assessments), a framework of typologies and causal factors of cross-border GWIs has been developed.

3.1. Typologies of cross-border GWIs

Typologies of cross-border GWIs are framed on the basis of the impacts descriptions made by Puri and El Naser (2002) and the cross-border climate impacts types proposed by Carter et al. (2021) (adapted to the specifics of this research). The typologies of cross-border GWIs are thereby built through the recognition of three elements: triggering actions, initial GWIs, and types and categories of cross-border GWIs, as represented in Fig. 2. Here, a triggering action refers to the specific anthropogenic act that initiates a cross-border GWIs, commonly, abstraction of groundwater, introduction of pollutants into groundwater, and changes in land use and land cover (LULC) that affect infiltration and reduce recharge. Examples of the latter action are pavement of natural areas for urban development, and deforestation for intensive agriculture.

A cross-border GWI starts with a triggering action that induces initial GWIs in the country in which the action is conducted. This leads to subsequent GWIs that can propagate and subsequently cross the international border, originating in four types of cross-border GWIs:

1. Alter groundwater flow across the international border, particularly by decreasing/increasing the flow magnitude or reversing the flow direction;
2. Alter groundwater-surface water (GW-SW) interactions across the international border, mainly in two ways: i) groundwater flow to rivers/lakes is reduced, causing baseflow/inflow to drop in the dry season; ii) rivers/lakes start infiltrating or becoming influent, thereby reducing surface flow/water level in the wet season;
3. Abstraction-induced intrusion of low-quality water (e.g. polluted, saline) into the neighbouring country, from SWB (e.g. oceans, rivers) and/or other aquifers (sometimes through vertical leakage);
4. Transport of groundwater pollutants across the international border (not induced by groundwater abstraction).

These types of cross-border GWIs can be classified into two major categories: quantity or quality. Quantity impacts refer to a decline or a long-term depletion of the groundwater and/or connected SWB in the neighbouring country. Similarly, quality impacts refer to the

Table 4
Conditioning factors of cross-border GWIs.

	Conditioning factors	LULC change affecting infiltration	Groundwater abstraction	Groundwater pollution
Aquifer conditions	**1. Recharge** *Rate and location of recharge*	Determines the rate of groundwater recharge reduction (from the land surface) and subsequent decline of the water level	Determines the rate and magnitude of the water level drawdowns and subsequent alteration of the groundwater flow systems	Promotes leaching and transport of pollutants or attenuates pollutant concentrations through dilution
	2. Confining layer *Presence and degree of confinement*	Allows/restricts the effects of LULC change on groundwater recharge	Determines the rate and magnitude of the water level drawdowns and the potential of recharge/leakage	Allows/restricts the possibility of introducing/attenuating pollutants
	3. Geometry *Area and thickness of the aquifer*	Influences the effects (magnitude/time) on storage and discharge rates	Influences the aquifer storage and transmissivity	Influences the pollutants' residence times
	4. Hydraulic properties *Porosity, permeability, storativity*	Influences the effects (magnitude/time) on storage and discharge rates	Determines aquifer transmissivity, storage and release potential	Influences the travel times and the related attenuation potential of pollutants
	5. Contact with lower-quality WB *Presence and proximity of saline or contaminated water body such as oceans, rivers, and other aquifers*	Determines the potential of lower-quality WB becoming influent and affecting the water quality of the aquifer	Determines the potential of lower-quality WB becoming influent and affecting the water quality of the aquifer	Determines the potential of polluted groundwater further altering the lower-quality WB
Flow conditions	**6. Spatial-temporal scale** *Location, depth, and velocity of groundwater flow systems*	Determines where and when the effects of recharge decrease will be felt (local, intermediate or regional flow scale)	Determines the spatial extent and timing of the expansion of the depression cone across the border	Determines the spatial extent and timing of pollutants transport across the border
	7. Hydraulic Gradient *Hydraulic gradient of groundwater flow with respect to the international border*	Determines the changes in the magnitude and directions of groundwater flow across the border	Determines the changes in the magnitude and directions of groundwater flow across the border	Determines the magnitude and directions of pollutants transport across the border
	8. GW-SW interaction *Presence of hydraulically connected SWB such as streams, rivers and lakes*	Determines the potential to alter the magnitude and direction of GW-SW interactions across the border	Determines the potential to alter the magnitude and direction of GW-SW interactions across the border	Determines the potential to pollute a groundwater-fed SWB across the border

deterioration of the neighbouring country groundwater and/or connected SWB quality.

3.2. *Causal factors of cross-border GWIs*

Causal factors of cross-border GWIs are framed on the basis of the concepts of triggering and conditioning factors, used in landslides assessments (Wubalem, 2021), which were adapted to the specifics of this research. Triggering factors are thereby defined as the characteristics of the anthropogenic-triggering actions that are most influential to the occurrence of cross-border GWIs; and conditioning factors, as the characteristics of the natural environment that either prevent or promote these impacts. Triggering and conditioning factors both shape cross-border GWIs, as they play a role in the development of initial GWIs and their subsequent transmission towards a neighbouring country.

3.2.1. *Triggering factors*

There are several triggering factors that could influence the

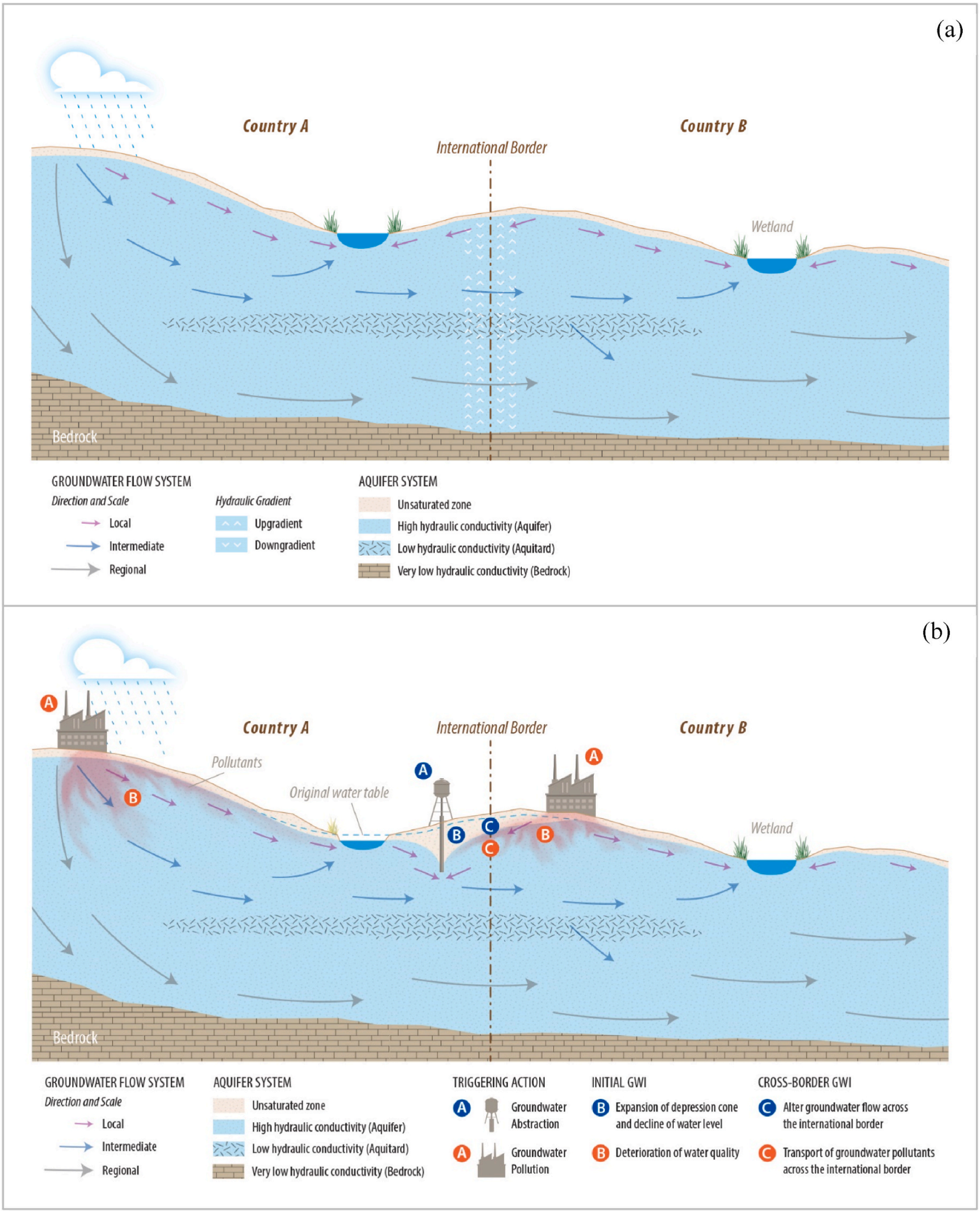


Fig. 3. Groundwater flow systems in a TBA shared by two countries with different spatial-temporal scales and hydraulic gradients with respect to the international border. A) TBA under natural conditions. B) TBA under anthropogenic activities.

occurrence of cross-border GWIs, from which four factors are proposed as the most relevant: (1) location of the action, (2) duration of the action, (3) intensity of the action, and (4) characteristic of the action. These factors and their subcategories for each triggering action (i.e. LULC change affecting infiltration, groundwater abstraction, groundwater pollution) are described in Table 3. Overall the table is self-explanatory.

3.2.2. *Conditioning factors*

There are multiple conditioning factors of the natural environment in which triggering actions operate that can be relevant for cross-border GWIs. Of these, eight factors are proposed to be the most influential. Five of these factors refer to conditions of the aquifer: (1) recharge, (2) confining layer, (3) geometry, (4) hydraulic properties, and (5) contact with lower-quality WB. Three further factors deal with the conditions of groundwater flow within the aquifer: (6) spatial-temporal scale and (7) hydraulic gradient, and (8) GW-SW interaction. These conditioning factors and their implications for each triggering action are presented in Table 4, and have been defined following basic hydraulic and hydrogeological principles such as those described by Kruseman et al. (2000). As with the triggering factors (Table 3), most of the conditioning factors are self-explanatory and can be understood by studying Table 4. Here we choose to elaborate on the flow conditions, since they have been highlighted in the literature as fundamental for controlling cross-border GWIs (Kukuric et al., 2013; Puri and El Naser, 2002; Rivera, 2015, 2021; Rivera and Candela, 2018).

3.2.2.1. Flow Conditions: spatial-temporal scales, hydraulic gradients and GW-SW interactions. Cross-border GWIs in a TBA largely depend on the transboundary flow dynamics where the triggering actions operate. The spatial-temporal characteristics of groundwater flow (e.g. locations, depths, lengths, velocities, ages) in an aquifer can be categorised, based on the Groundwater Flow Theory (Tóth et al., 2016; Toth, 1963), into three scales: local, intermediate, and regional. For a TBA, these groundwater flow systems-scales are illustrated in Fig. 3a (following the previous illustration by Puri and El Naser (2002)). On the local scale (purple arrows), groundwater recharge and discharge areas are adjacent; on the intermediate scale (blue arrows), these areas are separated by one or more local flow systems; and on the regional scale (grey arrows), the recharge and discharge areas are located at the highest and lowest elevation zones of the watershed, respectively. Consequently, flow paths are the shortest and shallowest in local systems, and longer and deeper in intermediate to regional systems. The present-day hydrological cycle mostly interacts with the local and intermediate flow systems (de Vries, 2007), even though discharge areas of deep flow systems can contribute to some extent. Therefore, groundwater ages (time since recharge) and velocities are, respectively, youngest (i.e. days to years) and fastest in local flow systems, whereas they are older and slower in intermediate to regional systems, reaching residence times of thousands of years (Alley et al., 1999).

Not all flow systems necessarily cross the international border in a TBA. Those that do, may occur from the highest-altitude country to the lowest-altitude country, but locally can also occur in the opposite direction (Puri and El Naser, 2002). For example, in Fig. 3a, the intermediate and regional flow systems cross the border from country A to country B, while one of the local flow systems crosses the border in the opposite direction.

Generally, the scales of the flow systems that cross the border will determine the timing and spatial extent of cross-border GWIs. Therefore, triggering actions in local-scale flow systems will cause initial GWIs and, eventually, cross-border GWIs, faster than in the intermediate and regional systems. Additionally, the hydraulic gradients of these flow systems, as well as their connection with SWB will determine the magnitude and directions of cross-border GWIs. Of course, these impacts will also depend on triggering factors (e.g. abstraction rates, pollution load, distance of the abstraction/pollution source to the border) and other conditioning factors (e.g. aquifer hydraulic properties, natural recharge).

For example, in Fig. 3b, an industrial effluent (pollution-triggering action) in country A, at a large distance from the border, has caused water quality deterioration in the same country (initial GWI) but not yet in country B. Transport of pollutants towards country B is faster in the local-scale flow system than in the intermediate and regional systems. Here, the local flow system does not cross the international border. Thus, the pollutants can only reach country B through the intermediate-scale and regional-scale flow systems, taking a much longer time (e.g. hundreds of years). Still, these pollutants (through the intermediate system) will eventually reach and deteriorate the water quality of a wetland in country B. Additionally, an industrial effluent in country B, but this time near the border, has polluted local-scale flow systems. This has caused water quality deterioration in country B and, subsequently, in country A (as here, the local flow direction is towards country A). Similarly, intense pumping (abstraction-triggering action) near the border in country A has developed a depression cone and declined the water level in the country (initial GWIs), causing the increase of groundwater flow towards country A (cross-border GWI).

3.3. *Considerations and limitations of the framework*

The developed framework relies on a definition of cross-border GWIs that particularly considers the transboundary adverse effects of human actions on the quantity and quality of groundwater and connected SWB and, thus, indirectly on the GDEs. Moreover, this framework does not consider neither the transboundary beneficial effects of human actions (e.g. increase of groundwater levels due to managed aquifer recharge (MAR)), nor the transboundary effects of climate actions (e.g. decrease of flow in streams that recharge TBAs due to a decline of rainfall, as described by Shamir et al. (2021)).

The formulation of typologies of cross-border GWIs was developed on the basis of the transmission of impacts in a TBA from country A to country B (Fig. 2). This is a simplification of the reality since the propagation of these impacts can occur in multiple directions across the border and with triggering actions operating on both countries (as shown in Fig. 3B). In addition, this framework does not encompass all the possible triggering actions of cross-border GWIs. We selected the ones that have been recognised as common potential triggers of these impacts in the literature (AGW-Net et al., 2015; Eckstein and Eckstein, 2024; Puri and El Naser, 2002). Similarly, when formulating the triggering and conditioning factors, we included a selection of relevant causal factors, not of all the possible ones. Furthermore, the relative importance of these factors to the generation of cross-border GWIs has not been presented in this framework, as this is to a large extent context-specific, and requires testing through case studies.

4. Delineation methods

The criteria, procedure, and results of the TGMZs delineation methods identified in section 2.2.1 (Kettelhut et al., 2010; Sanchez et al., 2020; Fraser et al., 2020) are described and analysed to gain insight into their underlying principles, performances, and limitations. The method by Pétré et al. (2022) is not included in this analysis as it is not been described in detail in the literature.

4.1. *Kettelhut et al. (2010)*

Kettelhut et al. (2010) developed a procedure to delineate a TGMZ at the frontier area of a TBA (called “Physical and Technical Strip of land” or PTS). The width of the TGMZ is established with a linear equation calculating the farthest distance from the international border at which any human activity located on one side of the international border may cause GWIs on the other side within a specific time period. The equation uses two criteria: the aquifer hydraulic conductivity (K) and the

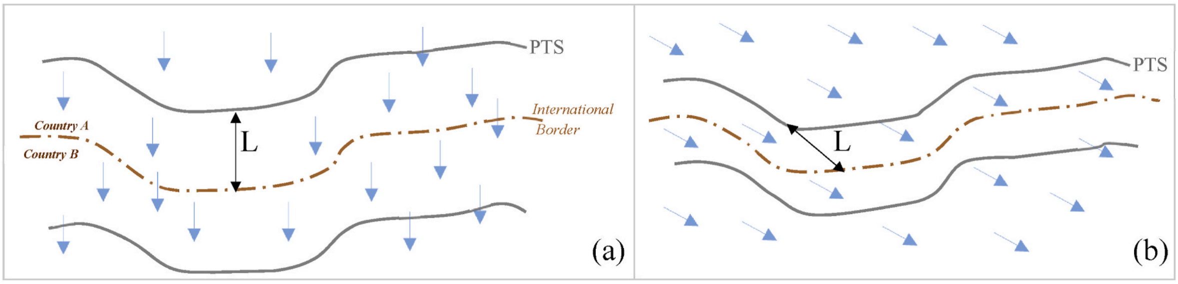


Fig. 4. Scheme of TGMZ (named PTS) delineated using the method by Kettelhut et al. (2010) under two different transboundary flow directions (adapted from Kettelhut et al., 2010).

management time (MT) of the groundwater resource. The K value is used as a measure of the aquifer ability to transmit water, and the MT value as a time frame to evaluate this "ability". As K can vary in order of magnitudes for the same aquifer, the highest K value (denominated *Critical Conductivity Rate)* is used as a proxy of the "fastest" flow scenario. Regarding the MT, the advice is to consider a "*suitable planning time horizon in which the countries can plan and have management governability*". Here, 1,000 years is given as an example of an unreasonable time. Still, it remains unclear if the MT value refers to the time to implement mitigation/remediation actions or to the time that it takes to restore impacts by these actions. On this basis, the equation to estimate the width of the TGMZ is constructed as follows:

$$L = CCR \text{ x } MT \tag{1}$$

Where:

L: Horizontal distance from the international border to each country (e.g. meters)

CCR: Critical conductivity rate that is the highest K value of the frontier area (e.g. meters/year)

MT: Management time for the groundwater resource (e.g. years)

Finally, the TGMZ is delineated using the L value and the groundwater flow direction between countries, as illustrated in Fig. 4. In the example, the TGMZ is delineated using the same L value under two transboundary flow directions: (a) perpendicular and (b) diagonal to the international border.

The proposed equation relies on two main assumptions. First, the faster the water can flow through the geological formation, the faster the impacts in one country can propagate to the neighbouring country (e.g. pollutant transport across the border). Therefore, where the CCR value is higher, the TGMZ is wider. Second, the longer the MT considered, the farther away a human-triggering action from the international border can cause cross-border GWIs. Thus, when the MT value is higher, the TGMZ is also wider. The idea of this equation, although not entirely explained by the authors, is that distance L should be larger than the distance travelled by groundwater during the MT (as time is needed to implement actions to control impacts). However, using the aquifer K as a proxy of travel time/velocity, omitting other factors that play a role in groundwater flow, seems oversimplified. In terms of flow velocity (based on Darcy's law), K holds no significance until it is linked to the hydraulic gradient and the porosity of the formation. Although this omission could relate to data restrictions (e.g. hydraulic gradients require water level measurements at both sides of the border), the cross-border flow directions used in the method would already need to rely on the same hydraulic gradient data. Moreover, topographic gradients could serve as a proxy where data is absent. Examples of L value calculations under the original equation by Kettelhut et al. (2010) and its modification using flow velocity are provided in the suplementary materials (**Appendix A**).

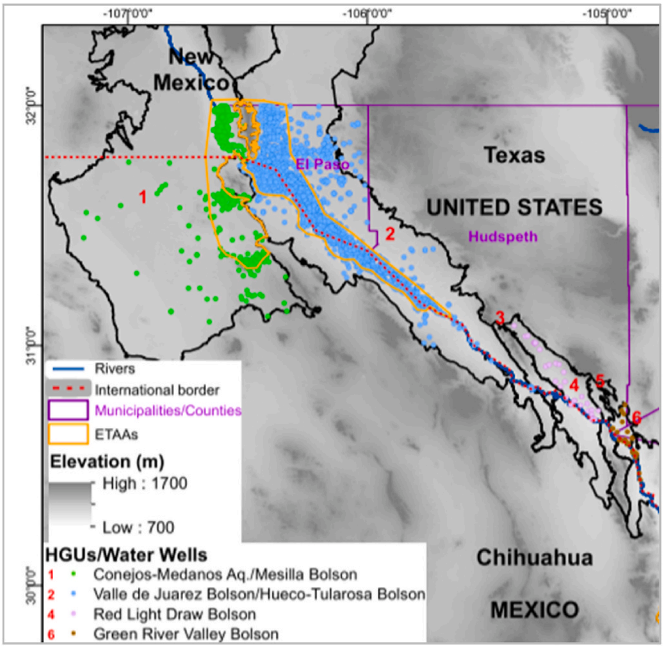


Fig. 5. Map of part of the TGMZs (named ETAAs) proposed by Sanchez et al. (2020) in part of the frontier area between Mexico and the USA (modified from Sanchez et al., 2020). *The ETAAs (orange polygons) circumscribe areas with high densities of active pumping wells (dots) located near and on both sides of the international border (red dotted line), that pump water from a same geological formation (dots of same colour), despite the limits of the existent hydrogeological units (black polygons).*

4.2. Sanchez et al. (2020)

Sanchez et al. (2020) developed a procedure to delineate TGMZs (termed Effective Transboundary Aquifer Areas or ETAAs) based primarily on hotspots of groundwater abstraction. The process is conducted in a Geographical Information System (GIS) for a frontier area between Mexico and the USA and consists of a spatial analysis of the location of active pumping wells. The TGMZ is delineated for an area with a high density of active pumping wells abstracting water from the same aquifer formation, close to the international border. A cluster of wells is used as a proxy for intensive groundwater abstraction, as pumping rate data is often limited in TBA countries. The exact well density and distance to the border are not stated. In addition, as a cluster of wells could be pumping groundwater from different aquifers, the TGMZ is delineated considering the well hydrogeological formation from which water is drawn. If this information is missing, this formation is inferred based on the well's total depth and the surface map of hydrogeological units (HGUs). Finally, since the locations where groundwater flow paths divide often coincide with the locations where surface water also separates, the topography and the stream network data are used to refine the limits of the TGMZ. How these corrections were performed is not entirely explained.

This method is built on available pumping well data and, thus, also on a series of assumptions. As data of abstraction volumes per well is limited, the method assumes that wells have similar abstraction rates. High abstraction rates from only a few wells (in the frontier area of a TBA) will therefore not result in a TGMZ, while, in reality, it could lead to cross-border GWIs. Similarly, as the method was developed for aquifers whose boundaries and transboundary nature are not totally clear, TGMZs are delineated only if well clusters are located in both countries. As a result, a cluster of active pumping wells located in one country of the TBA would not result in a TGMZ even though it could certainly generate cross-border GWIs.

Fig. 5 shows examples of two TGMZs (ETAAs) delineated by Sanchez et al. (2020) along the Mexico-USA border. The dots represent pumping wells, with colours indicating the specific hydrogeological formations pumped. Here, the TGMZs only enclose wells of the same formation (green and blue dots) located at both side of the borders, as the other wells (pink and brown dots) are located only in one country. Notably, the well location criteria (i.e. density and distance to the border) for delineating these TGMZs look dissimilar. For instance, why are certain “blue” wells at “El Paso” (USA) excluded from the TGMZ on the right, and what distinguishes them from the “green” wells on the Mexican side that are included in the TGMZ on the left? Clarification of used criteria are not provided or discussed by the authors, limiting the replicability of this method.

According to the authors, the aplicability of this method relies on the availability of borehole data (i.e. location, depth, geological/hydrogeological formations). Furthermore, they acknowledge that the proposed TGMZs may not be helpful in TBAs that are already overexploited, which could be addressed by including recharge conditions into the assessment. Additionally, the authors propose potential improvements, suggesting the inclusion of pumping rates and water quality data. One possible enhancement could be to consider the available screens depth as well location criterion. For instance, TGMZs that enclose clusters of “shallow wells” could be delineated considering a larger distance to the border than “deep wells”. This is because, in general, groundwater abstraction in shallower flow systems (local-scale) cause GWIs faster than in deeper flow systems (regional/intermediate-scale) (section 3.2.2.1).

Table 5
Layers used by Fraser et al. (2020) as factors of risk to assess TGMZs in TBAs of Malawi.

Layer	Classes		Risk score (0–1)	Risk Criterion
1. Water point[a] type	1	Hand-dug well	1	Influences water supply reliability
	2	Hand pump/ borehole	0.5	
	3	Piped supply	0	
2. Hydrogeology type	1	Basement	1	Influences the water supply reliability due to the yields of water
	2	Karoo	0.5	
	3	Alluvial/ colluvium	0	
3. Users per water point[a]	1	Above Malawi guidelines (>250 per borehole, 120 per tap)	1	Influences the water supply reliability due to the stress on the aquifer
	2	At or below Malawi guidelines	0	
4. Proximity of a water point[a] to a pit latrine	1	Outside Malawi guidelines (<30 m)	1	Influences the groundwater quality due to faecal pollution
	2	Within Malawi guidelines (>30 m)	0	
5. Land use	1	Settlement/ cropland/industry	1	Influences groundwater quality due to nitrate pollution
	2	Forest/grassland/ wetland	0	
6. Seasonal water level fluctuation[b]	1	Yes	0	Influence groundwater supply reliability
	2	No	0.5	

[a] Water point: groundwater source of drinking water (e.g. well, pipe).
[b] Water level fluctuation due to recharge/base flow impacts.

4.3. *Fraser et al. (2020)*

Fraser et al. (2020) propose a method to delineate TGMZs (termed “hotspots of transboundary risk”) by finding areas within TBAs with potential cross-border GWIs in quality and quantity. The procedure can be summarised in four steps: (1) identification of factors that represent a threat for reducing water quality and quantity in a TBA (e.g. land surface activities); (2) ranking each factor with a score on a scale of 0–1, with 0 being no risk, and 1 being the highest risk; (3) estimation of “combined risk value” by summing the different risk scores previously assigned to the factors; (4) analysis of the results considering the flow directions across the international border. This method is conducted through a GIS multicriteria spatial analysis, where the factors are represented by GIS layers. The choice of layers and their ranking depends on the specific threats and characteristics of the assessed TBA, and data availability. The GIS layers are overlaid and summed creating a “combined risk” map. This method relies on the assumptions that GWIs within the territory of a country have the potential to propagate such impacts into the neighbouring countries. Due to data limitations, the risk assessment is conducted only in the Malawian sides of 38 TBAs shared with Zambia, Mozambique, and Tanzania. The GIS layers, scores, and related evaluation criteria used in Malawi are shown in Table 5.

From the six GIS layers employed in Malawi, two are used as a proxy of reducing the quality of groundwater due to faecal pollution (layer 4: water points located nearby pit latrines), and nitrate pollution (layer 5: land uses likely to introduce nitrates into groundwater such as cropland). The other four layers are used as a proxy of reducing the groundwater quantity due to a reduction in the reliability of its supply rather than due to its depletion). Therefore, for instance in layer 1 (water point type), a drilled well is considered a more reliable water source (lower risk) than a hand-dug well (higher risk), as the latter often tap shallow groundwater that is more prone to contamination or water levels fluctuations. If layer 1 would have been used as a proxy of groundwater quantity depletion, the risk score of the drilled well should be higher than the hand-dug well (as the former has typically higher yield). Similarly, in layer 2 (hydrogeology type) an alluvial formation is considered a more reliable source to supply water (lower risk) than the aquifer basement (higher risk), as the alluvial material provides better yields of water. If considering risk of depletion, the score should be the opposite.

According to the authors, while the method’s flexibility in layer selection and rating makes it accessible to TBAs with limited data, it also makes its results very data-driven (the more data, the more accurate the results) and dependent on the user’s knowledge of the TBA (in order to select the layers and rate them properly). Furthermore, the absence of a clear criterion to select and rate the layers relevant to cross-border GWIs introduces subjectivity into the assessment with the reliability of the results heavily dependent on the user perspective (e.g. groundwater depletion vs. the groundwater supply reliability).

Examples of the combined risk maps of Malawi are shown in Fig. 6. The areas on the maps with high-risk values (represented with colours from red to black) are considered hotspots at risk of reducing both groundwater quality and quantity. When such hotspots fall within the limits of a TBA (ligh blue and light green polygons), they are considered hotspots of “combined transboundary risk” of national or local scale depending on whether they cover most of the TBA or the frontier area, respectively. It is worth noting that assessing the risk of GWIs as a proxy of cross-border GWIs, by considering only one TBA country while

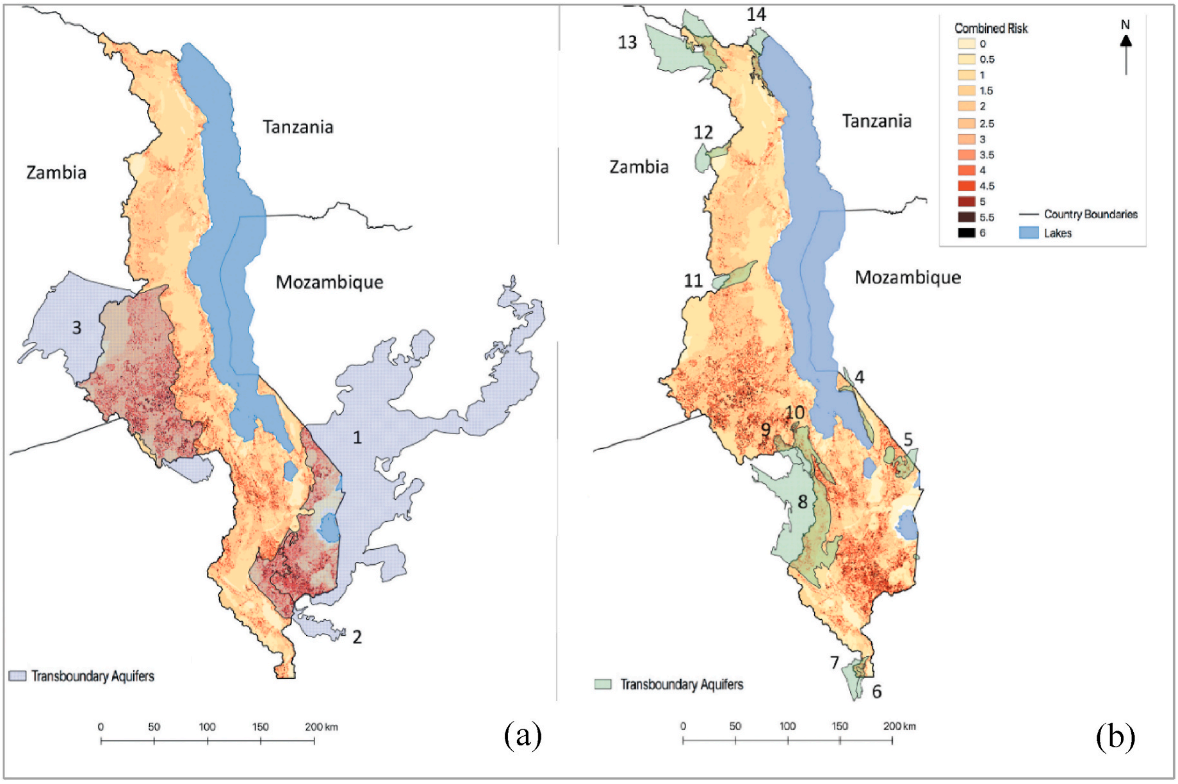


Fig. 6. Map of TGMZs proposed by Fraser et al. (2020) (named hotspots of transboundary risk) in Malawi. (adapted from Fraser et al., 2020). *The TGMZs are the areas on the map with high combined risk values (colours red to black) located within a TBA (light blue/light green polygons). A TGMZ of national-scale has high risk values within most of the TBA* (3a). *A TGMZ of local-scale has high risk values covering mostly the frontier area of the TBA (3b).*

Table 6
Triggering actions, causal factors, and initial and potential cross-border GWIs tackled by each method.

Method	Triggering actions	Triggering Factors	Conditioning Factors	Initial GWIs	Cross-border GWIs
	1. LULC change affecting infiltration. 2.Abstraction. 3. Pollution.	1. Location. 2. Duration. 3. Intensity. 4. Characteristics.	1. Recharge. 2. Confining layers. 3. Geometry. 4. Hydraulic properties. 5. Lower-quality WB 6. Flow scale 7. Flow gradient 8. GW-SW interactions	1. Decrease of recharge and decline of water level. 2. Expansion of depression cone and decline of water level. 3. Deterioration of water quality.	1. Alter groundwater flow across the international border. 2. Alter GW-SW interactions across the international border. 3. Abstraction-induced intrusion of low-quality waters into the neighbouring country. 4. Transport of pollutants across the international border.
Kettelhut et al. (2010)	–	–	4, 7	–	1, 4
Sanchez et al. (2020)	2	1, 3	–	1	1
Fraser et al. (2020)	2 3	1, 3 –	– –	1, 2 2	1, 3 4

omitting the border flow conditions, seems to be a simplistic assumption. Although, the flow directions across the border were analysed by Fraser et al. (2020) to interpret the results, this factor was not included as part of the GIS multicriteria analysis. Here, the authors stated that where hotspots are located near the border, the same situation could be assumed on the other side if the groundwater direction is from Malawi to the neighbouring countries.

4.4. *Comparative analysis*

A comparative analysis of the methods is carried out using the framework of cross-border GWIs presented in section 3. Particularly, the inputs and outcomes of the methods (i.e. criteria and resulting TGMZs) are evaluated based on the recognition of the causal factors and typologies of cross-border GWIs, as presented in Table 6.

4.4.1. *Inputs of the methods*

Table 6 presents the triggering actions *(LULC change affecting infiltration, groundwater abstraction, groundwater pollution)* and related triggering factors (*location*, *duration*, *intensity*, and *characteristics)* used by each method to delineate the TGMZs, according to the categories framed in section 3.2.1**.** The detailed assessment is presented in the supplementary materials (Appendix C, Table 4S).

The assessment shows that Kettelhut et al. (2010) do not consider any triggering action explicitly in their method, nor any triggering factor, while Sanchez et al. (2020) and Fraser et al. (2020) both use triggering actions and factors. The triggering action considered by Sanchez et al. (2020) is groundwater abstraction, and the triggering factors are *location* (specifically, in terms of proximity to the international border) and *intensity* of abstraction (represented by well density). According to this method, clusters of wells necessarily need to abstract groundwater from the same hydrogeological formation and be located on both sides of the international border (see section 4.2), but it does not use the depth or the upgradient/downgradient position of the abstraction wells as explicit *location* triggering factors. Instead, they are used to ensure that TGMZs are not delineated mistakenly with well clusters pumping groundwater from different or non-transboundary aquifers. The method of Fraser et al. (2020) uses groundwater abstraction (for domestic supply, referred to as water points) and groundwater pollution (from settlement, cropland, and industry land uses, associated with nitrate contaminants) as triggering actions. In addition, the method considers two abstraction-triggering factors: *location* (proximity to lower-quality WB represented by the distance of water points to pit latrines) and *intensity* (represented by the number of users per water point). It must be noted that Fraser et al. (2020) consider the “water point type” criterion that refers to abstraction infrastructure type (e.g. hand pump, borehole, piped supply). However, this criterion is used as a factor that influences the groundwater supply reliability and not the quality to prevent pollution during the construction/operation of the pumping wells.

Table 6 presents the conditioning factors used by each method to define the TGMZs regarding the aquifer conditions (*recharge, confining layer, geometry, hydraulic properties, contact with lower-quality WB)* and the flow conditions (*spatial-temporal scale, hydraulic gradient, GW-SW interaction*) (section 3.2.2**).** The detailed assessment is presented in the supplementary materials (Appendix C, Table 5S).

The assessment shows that only Kettelhut et al. (2010) consider conditioning factors in their method, namely the aquifer *hydraulic properties* (aquifer (critical) hydraulic conductivity) and the *hydraulic gradient* (flow direction across the international border). Sanchez et al. (2020) and Fraser et al. (2020) do not include any of them. It must be noted that Fraser et al. (2020) consider two criteria that relate to natural factors (the “seasonal water level fluctuation” that could relate to the *recharge* factor, and the “hydrogeology type” that could relate to the *hydraulic properties* factor). Still, once again, they are used as factors that affect groundwater quantity due to a reduction in the reliability of its supply rather than due to its depletion.

These assessments clearly reveal that the methods take two distinct approaches to delineate the TGMZs. On the one hand, the method by Kettelhut et al. (2010) is built on natural conditioning factors and, thus, it takes a preventive approach (still, it relies on only two factors out of the eight identified in section 3.2.2). On the other hand, the methods by Sanchez et al. (2020) and Fraser et al. (2020) are founded on triggering actions and triggering factors, representing reactive approaches. Although only Fraser et al. (2020) consider the pollution-triggering action, but not its pollution-triggering factors. Also, none of the methods consider the LULC change affecting infiltration as a triggering action.

4.4.2. *Outcomes of the methods*

The TGMZs of each method are evaluated by relating the input criteria of the methods with the elements of the impact transmission (i.e. triggering actions, initial GWIs, and cross-border GWIs) according to the categories framed in section 3.1, as presented in Table 6.

The TGMZs delineated by Kettelhut et al. (2010) using only conditioning factors of cross-border GWIs can be implemented to prevent the occurrence of cross-border GWIs. This preventive approach is about anticipating cross-border GWIs by implementing management strategies in zones vulnerable to such impacts due to natural (aquifer and flow) conditions. These TGMZs could be established to prevent the types of cross-border GWIs one and four (alter groundwater flow and transport of pollutants, across the international border). It is concluded that the TGMZs of this method could not be used to prevent impacts two and three (*alter GW-SW interactions* and *abstraction-induced intrusion of low-quality waters*), as the conditioning factors used are limited to the hydraulic conductivity and flow direction.

The TGMZs delineated by Sanchez et al. (2020) using triggering actions and factors can be implemented to mitigate ongoing initial GWIs and cross-border GWIs derived exclusively from groundwater abstraction. This reactive approach is about implementing management strategies where GWIs (initial and/or cross-border) have already originated. In principle, the TGMZs delineated by Sanchez et al. (2020) could be established to mitigate the three types of cross-border GWIs triggered by groundwater abstraction (*alter groundwater flow across the border, alter GW-SW interactions across the border,* and *abstraction-induced intrusion of low-quality waters*). However, the last two impacts are discarded as this method does not use causal factors that could influence them (e.g. *presence of GW-SW interactions, proximity of the abstraction wells to lower-quality WB)*.

Finally, the TGMZs delineated by Fraser et al. (2020), also using a reactive approach, can be used to mitigate ongoing GWIs (initial and/or cross-border) derived from abstraction and pollution actions. These TGMZs could be established to mitigate the four types of cross-border GWIs. However, impact two (*alter GW-SW interactions across the border)* is discarded as this method also not use causal factors that could influence it. However, unlike the other methods, Fraser et al. (2020) include a triggering factor (proximity of the abstraction source to lower-quality WB) that can influence the occurrence of impact four (*transport of pollutants across the border*). Still, impact four might not be totally addressed by the TGMZs as the conditioning factors that determine this type of impact are not used in the analysis (e.g. flow scale, flow gradient, proximity of the source to the international border).

5. Conclusions and way forward

This study offers an overview of TGMZs and provides a conceptual framework of cross-border GWIs to contribute to the definition and delineation of such zones. The review of the characteristics and terminologies of TGMZs allowed us to connect existing literature on the subject and establish the first comprehensive definition of these management zones. The review of TGMZ experiences showed that they are scarce and limited. Currently, there are TGMZs proposed for TBAs shared by Mexico and the USA (Sanchez et al., 2020), for TBAs of Malawi (Fraser et al., 2020), and for the Milk River TBA (Canada-USA) (Pétré et al., 2022). One operating experience of TGMZs exists in part of the Sam-Raq TBA shared by Jordan and Saudi Arabia (Agreement Al-Sag/Al-Disi Layer, 2015). Furthermore, the literature review showed that three publications have provided general directions to delineate TGMZs (Kukuric et al., 2013; Rivera, 2021; Rivera and Candela, 2018), while four publications have proposed concrete methods (Fraser et al., 2020; Kettelhut et al., 2010; Pétré et al., 2022; Sanchez et al., 2020). These directions and methods show two distinct approaches, which have been differently named in the literature (e.g. zoning, time-scale factor, hotspots identification, etc.). We proposed to denominate them as “cross-border flow zoning” and “cross-border hotspots identification”. The delineation methods of TGMZs were found to have essential differences in their principles, techniques, criteria, and outcomes, as they emerge from studies with different motivations and data realities. These methods consist of spatial analysis techniques that rely on limited data and, thus, on a series of assumptions, that sometimes are too simple to define appropriate TGMZs. The development of a conceptual framework of typologies and causal factors of cross-border GWIs enhanced the comparison and the understanding of these methods. The comparative analysis revealed that the method by Kettelhut et al. (2010) is grounded in (natural) conditioning factors adopting a preventive approach (anticipates cross-border GWIs). Meanwhile, the methods by Fraser et al. (2020) and Sanchez et al. (2020) rely on (human) triggering actions and factors, taking a reactive approach (mitigates cross-border GWIs). Nevertheless, the causal factors of cross-border GWIs used by the three methods remain limited. Therefore, the types of cross-border GWIs that the TGMZs of these methods can prevent or mitigate are limited as well. It is worth noting that none of the methods use the three flow conditions factors (*spatial-temporal scale*, *hydraulic gradient, GW-SW interaction*) directly in their assessments, even though the literature has acknowledged them as central for controlling cross-border GWIs.

5.1. Future research

Moving forward, testing the elements of the conceptual framework on cross-border GWIs is crucial for optimising methods to delineate TGMZs. Several opportunities exist to test the proposed typologies and causal factors. The typologies of cross-border GWIs can be compared with reported cases of these impacts in the literature. Although such cases are scarce, analysing the triggering actions, initial GWIs, and types and categories of cross-border GWIs of the existing examples (as done by Carter et al., 2021 with examples of cross-border climate impacts) can help to verify, improve and even expand the typologies of impacts.

Regarding the causal factors of cross-border GWIs, future research should encompass the assessment of the significance and sensitivity of the (human) triggering factors and the (natural) conditioning factors, for instance through conceptual and numerical modelling. Ideally, this assessment should be applied to data-rich regions with well-established hydrogeological conceptual models. This will allow an understanding of the relative importance of the causal factors and how they vary under different hydrogeological and climatic conditions. The most relevant factors could subsequently be prioritised in data collection and in the development of simple but robust methodological tools to assess cross-border GWIs and delineate TGMZ accordingly. Such tools could encompass risk-based methodologies to evaluate the hazard, vulnerability, and risk of these impacts. Impact risk-based methodologies and their applications to delineate management zones, have not yet been developed for cross-border GWIs, although examples for domestic GWIs are available (Li et al., 2015). Furthermore, cross-border GWI risk-based methodologies and their applications to delineate TGMZs could benefit from considering environmental and socioeconomic factors in the analysis (e.g. TBA total population, its dependency on groundwater, and the ecological features of GDEs). Examples of such factors have been used in the Mexico-USA border (Sanchez et al., 2018a) and in the Southern African Development Community (SADC) region (Davies et al., 2013) for identifying TBAs for priority management. Although the aim of these methods is prioritising between TBAs (not zones), they can serve as examples to include other relevant dimensions in the methodological development of TGMZs.

CRediT authorship contribution statement

Constanza Maass-Morales: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tibor Stigter:** Writing – review & editing, Supervision, Conceptualization. **Christina Fraser:** Writing – review & editing, Supervision. **Boris M. Van Breukelen:** Writing – review & editing. **Graham Jewitt:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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Appendix A. Supplementary data

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