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Highlights:

- A national border based approach to transboundary aquifer assessments is proposed
- Transboundary aquifers must be conceptualized as hydraulically connected systems
- Conceptual models are an effective way to portray these complex systems
- Transboundary aquifer systems must be managed locally and regionally in Malawi

A National Approach to Systematic Transboundary Aquifer Assessment and Conceptualisation at Relevant Scales: A Malawi Case Study

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Abstract

Study region: Malawi

Study Focus: Integrated water resource management (IWRM) of transboundary aquifers (TBA's) is becoming increasingly important. Without adequate and accurate scientific knowledge of their extent and characteristics, uninformed policy creation could lead to unsustainable management of these vital resources. This is particularly important within the Southern African Development Community (SADC) where up to 85% of domestic water is supplied by groundwater. In this paper, Malawi is used as a case study to critically evaluate the current transboundary aquifer assessment frameworks within the region and their value in promoting IWRM. A series of illustrative conceptual models of TBA interactions pertinent to the Malawian national border are presented and we consider how TBA assessments may be integrated to national IWRM and strategic policy development.

New hydrological insights for the region: Current TBA assessments of Malawi and the wider SADC neglect multiple aspects needed for a national scale management plan. This includes full border TBA system identification alongside, given the geology of the region, consideration of the discontinuous nature of basement complex aquifers and localised alluvial deposits that both result in smaller scale aquifer units. Conceptualising such local scale complexity and encouraging countries to develop a strategy that systematically examines TBA systems along their national border at relevant scales will allow for more focused conjunctive policy creation and sustainable management of TBA's.

Key Words

Transboundary, Groundwater, Hydrogeology, Integrated Water Resources Management (IWRM), Africa, Malawi

1. Introduction

Groundwater has often been described as an invisible resource, yet it is important to recognise that almost 98% of the world's available freshwater resources is groundwater. Integrated water resources management (IWRM) acknowledges the important role of groundwater within frameworks that can sometimes be unduly surface water focused. The importance of IWRM is recognized in Sustainable Development Goal (SDG) 6 - 'to ensure availability and sustainable management of water and sanitation for all' (United Nations, 2017). Groundwater development is central to meeting SDG 6. A pressing need though IWRM is to recognize that many aquifers identified for resource use may cross national borders. It is then critical that transboundary cooperation comes into play to allow sustainable and equitable groundwater use by stakeholder nations involved.

Worldwide, water use is increasing due to growing water, sanitation and hygiene (WASH) demands. Africa is heavily reliant upon groundwater, including transboundary groundwater, with an estimated 75% of its population dependent on this resource for basic water supplies (Altchenko and Villholth, 2013). Investment in reliable water supplies will continue to depend on the development of groundwater resources. This may include the exploitation of transboundary aquifers (TBA's) (Giordano 2009, MacDonald and Calow 2009). This paper will focus primarily on Malawi, one of the 15 countries within the Southern African Development Community (SADC), a sub-continental region of Africa where widespread groundwater development is needed to address SDG 6. Effective groundwater management by some SADC member nations is faced by multiple challenges. These include little or no adherence to abstraction licensing legislation, low annual natural recharge in arid to semi-arid localities, low aquifer storage and vulnerability to climate-change; all of which provide critical impetus to the development of a science-based strategy for groundwater management (Smith-Carrington and Chilton, 1983).

The term 'transboundary water' is used to describe a water body that crosses two or more international country borders. This can be in the form of rivers, lakes and groundwater (UN Water, 2014). An aquifer is a hydrostratographic unit that stores and transmits groundwater. An aquifer becomes transboundary when it crosses one or more international political border and thus has the potential for groundwater exchange between neighbouring countries (Wada and Heinrich, 2013). The challenge faced by countries is to reliably define aquifer connectivity and groundwater movement at their borders. Often this is with limited data available, or data not shared. This knowledge then needs to be translated to accessible conceptual models that can underpin science based policy implementation clearly and accurately.

We propose that in order to meet SDG 6, there is a need for countries to develop strategies that systematically identifies and screens TBA units along its national border. This will allow countries to characterise TBA connectivity and transmission of groundwater over their entire national border length. This includes conceptualising how abstraction on one side of a border may influence groundwater and surface water availability on the opposing side. Where influence is judged to be significant, this should trigger development of joint data collation efforts to underpin TBA policy and agreements. We further advocate that systematic TBA screening along a national border should not only examine “major aquifer” systems where connectivity is already known, but also include “minor” aquifer systems. Whilst not as geographically extensive, individual minor aquifer TBA’s may be locally significance especially where relatively short distances separate neighbouring country communities. Furthermore, TBA connectivity of more major aquifer systems should not be assumed. Whilst extensive over tens of km scales or more, aquifers may still be locally discontinuous (e.g. due to structural faulting and weathering differences) and their local connectivity should be assessed.

Within the developing world context, technical data and financial resources are often limited. Here, desk-based screening using available data to conceptualise TBA connectivity is critical. Development of conceptual models of TBA interaction within a wider system, both generic and locally bespoke, is fundamental. Consideration of the TBA status of Malawi, a low-income developing country bordered by Mozambique, Tanzania and Zambia is made here as an example. A critical assessment of the current status of TBA’s in Malawi is presented with the overarching goal to contribute to the development of a Malawian national approach to systems-based TBA assessment and conceptualisation at relevant local scales. The aims are to:

- Critically review Malawi’s current status of TBA assessments that focus on more obvious major aquifer systems.

- Make a case for systematic TBA assessment along its national border length addressing minor, local aquifer systems and groundwater/surface water interactions.

- Develop conceptual models of TBA interactions relevant to its national border, but of generic value across the SADC.

- Consider how TBA assessments might be integrated to national implementation, strategic policy development and agreements with neighbouring countries.

2. Study Area

2.1 Malawi Study Setting

Africa is a continent challenged by limited water supply, poor quality of living, and economic uncertainty. Compared with Europe, cooperation over the management of Africa’s transboundary rivers, lakes and TBA systems is significantly less developed (Scheumann and Alker, 2009). The SADC (Figure 1) was established in 2004 to bring together countries within the south-eastern African continent to improve living situations for large populations of people. Malawi, one of the 15 countries within the SADC, lies between 9^{o}S and 17^{o}S (latitude) and 33°E and 36°E (longitude). It extends across an area of 118,484 km^2 stretching 853 km N – S and 257 km E – W (Chavula, 2012). Lake Malawi covers 23.6% of the country, the third largest freshwater lake in Africa. Malawi’s population is estimated to be 18.3 million (Worldometers, 2017) of which 90% live in rural areas. Its main economic income is generated from agriculture, with subsistence farming common amongst the rural population (Government of Malawi, 2012). With less than 1,400 m^3/year/person of available total renewable water resources, Malawi is one of the most water-stressed countries in the world (Government of Malawi, 2012). This is largely due to the lack of infrastructure within the country to support large-scale management of water resources and much of its rural population accessing groundwater through hand-dug wells or low-capacity boreholes fitted with hand pumps.

Tens of thousands of water points now exist across Malawi (Pavelic et al., 2012); and added to daily under the SDG 6 agenda efforts. With the population of Malawi set to rise to 26.5 million by 2030 and renewable water resources likely to decline due to deforestation and climate change impact, Malawi could become water scarce with available total renewable water falling below 1000 m^3 /year/person in the next 13 years. These valuable groundwater resources are vulnerable to pollution threats that may be poorly constrained (Back et al., 2018). Sparse monitoring of both groundwater quality and level can also lead to a poor knowledge base for management (Rivett et al., 2018a). Such factors, and others, indirectly influence the strategic development of TBA assessment and management (Rivett et al., 2018b).

2.2.1 Regional Geology and Hydrogeology

The geology of the SADC is varied. It is composed of a combination of crystalline basin complex rock units interconnected with younger orogenic belts of metamorphic rocks and large sedimentary basins underlain by basement. The east of the region is heavily influenced by structural tectonics creating a complex geological history (Ramoeli, 2009). The East African Rift System (EARS) runs 2100 km from Uganda to Malawi and formed during the onset of the Miocene. It can be seen at the surface as aligned tectonic basins forming rift valleys separated by uplifted continental blocks (Chorowicz, 2005) that extend from Mozambique to Ethiopia. The rifts of the Western Branch of the EARS, where Malawi resides (Figure 2), are often filled with sediments or water (Specht and Rosendahl, 1989).

2.2.2 Malawi Geology and Hydrogeology

The EARS large-scale rifting heavily influenced the topography and morphology of Malawi (Monjerezi and Ngongondo, 2012). This is through the creation of four main physiographic areas; the plateau, the uplands, the rift valley escarpment and rift valley plains. The plateau area represents the largest proportion of the topography of Malawi and is comprised of highly faulted basement gneiss (Smith-Carrington and Chilton, 1983).

The rift valley, where the Shire River Basin is located, forms the most significant structural feature of Malawi. It comprises a series of half-grabens that section into 60-100km long extensional basins formed by faulting offset from the EARS. This is bordered on one side by steep normal faults and by en-echelon step-faults with minor vertical offset on the other side of the valley (Ebinger et al., 1987; Ring and Betzler, 1995) (Figure 2). These rift events have played a significant role in the distribution of the aquifer lithologies within Malawi and the SADC (Smith-Carrington and Chilton, 1983).

Differing lithologies in Malawi provide varying productive water-bearing units theoretically allowing a large proportion of Malawi access to groundwater. Accurate knowledge of the geology and hydrogeology is important to determine the aquifers that may be transboundary. The main water bearing geological units in Malawi are summarised below in order of increasing importance (Bradford, 1973):

(1) Precambrian to Lower Palaeozoic weathered and (2) fractured basement rocks; composed of metamorphic rocks of varying lithology but primarily gneiss and granulites. These are Malawi's most abundant geological units and account for 96% of the total land cover. These are low storage and low transmissivity aquifers with borehole yields between 0.5 and 0.8l/s (Government of Malawi, 2006. Upton et al, 2016).

(3) Permian to Triassic Karoo sedimentary rocks; units exhibit low porosity and intergranular permeability due to calcite cementation. Groundwater flows through fractures and thus aquifers have low to moderate productivity; although this may be increased in the south of Malawi where more heavily faulted (Smith-Carington and Chilton, 1983; Upton, 2016).

(4) Cretaceous sedimentary rocks; outcrops tend to be limited and of infrequent occurrence across Malawi. The units tend to exhibit good storage and high permeability, and tend to be highly fractured. There are extensive deposits across the southern extent of the SADC that are significant sources of water (Government of Malawi, 2006; Upton et al, 2016).

(5) Lower Jurassic weathered Karoo basalts; outcrops are limited to small regions within Malawi. These can form a valuable localized resource due to spaces at contacts between lava flows and vesicular cavities providing a flow path for water alongside jointing and faulting of the lava. Permeability within the units is hence high which provides a high quality and low mineralized water source (Smith-Carrington and Chilton, 1983).

(6) Quaternary unconsolidated alluvial deposits; found across the flood plains of rivers. These form Malawi's most productive aquifers. They are spatially variable across the country with highest quality water being available within gravel beds where permeability is high (Smith-Carrington and Chilton, 1983).

Malawi's groundwater resources are representative of the east of the SADC and parts of the south of the SADC where the basement complex is exposed. Similarities can also be seen throughout the world where large proportions of the groundwater come from basement rocks that tend to support only low yielding boreholes and provide only local water supplies. Parallel cases of large scale basement complex aquifers can be seen in South Asia, South America and Australia (Wright and Burgess, 1992).

3. Review of Malawi's Current Status of TBA Identification

3.1 Regional Context

The main driving force for international TBA assessments is the UNESCO-IHP (United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme) through the Internationally Shared Aquifer Resources Management (ISARM) initiative and the International Groundwater Resources Assessment Centre (IGRAC). IGRAC publishes a 'Transboundary Aquifers of the World' map with all known TBAs displayed based on the most recent inventory results from many projects globally. This compilation of all international data constitutes a valuable starting-point for governments. There are 592 TBA's currently identified worldwide. 80 of these are located within Africa (Figure 3) (IGRAC, 2015a; IGRAC, 2015b) accounting for 43% of the continental land surface (Altchenko and

Villholth, 2013). A large proportion of TBA's within Africa were identified through the 'Global Environment Facility Transboundary Waters Assessment Program' (GEF-TWAP) regional assessments (ILEC et al, 2016). The aim of the GEF-TWAP was to provide the first global scale assessment of all transboundary waters. GEF-TWAP regional assessments were carried out by an appropriate representative from each country and then collected and streamlined by the project.

3.2 Malawi Context

The GEF-TWAP and the most recent 'Transboundary Aquifers of the World' map of the world map identify three TBA's shared between Malawi and its bordering neighbours (Table 1; Figure 3) (ILEC et al, 2016; IGRAC, 2015a; IGRAC, 2015b). Malawi and its surrounding neighbours possess geological and hydrogeological maps (Geological Survey of Malawi, 1970; Government of Malawi, 1987). These data were used via the GEF-TWAP in 2014 (ILEC et al, 2016) to assist in the reinterpretation of the extent of a TBA previously identified as crossing the Malawi-Tanzania and Malawi-Zambia border. Further information was also collected on two other identified TBA's shared between Malawi and Zambia, and Malawi and Mozambique.

3.3 TBA Assessment Gaps

A number of gaps have been identified that must be addressed in order for Malawi to manage their aquifers on a local scale, as well as nationally. Firstly, the Shire Valley Alluvial Aquifer (Table 1) is not the only potential alluvial transboundary unit within Malawi. Other small scale unconsolidated alluvial deposits can be found across the flood plains of other rivers throughout the country, some of which are likely to be transboundary. These have not been recognised on a regional scale most likely due to their limited extent and thickness. Although these smaller 'minor' aquifers may not contribute large quantities of water to Malawi and its neighbours, small communities situated relatively close to the national border may rely exclusively upon them for local drinking water, irrigation and other agricultural supply use. The identification of small scale aquifers is also important in countries like Malawi as they may provide baseflow to hydraulically connected river systems (Kingdon et al, 1999).

Karoo sedimentary units and basalts also outcrop in Malawi. Most of these units lie on the south west border of Malawi and are transboundary with Mozambique. In many other parts of the Southern African region, the Karoo Super Group has been seen to yield excellent quality and quantities of groundwater (Woodford & Chevallier, 2002; Cheney et al., 2006). This is potentially another TBA shared between Malawi and Mozambique that could be a valuable groundwater resource locally.

Within the TWAP regional assessment, the complexity of the basement complex that underlies the sand and gravel TBA (Table 1) is not considered (ILEC et al, 2016). It is composed of multiple complex, non-uniform lithologies that are important when considering water storage and flow, particularly close to the border. These different lithological units are discontinuous and subject to fracturing by faults; groundwater units of limited size are formed along these fracture zones, which vary locally in their yield potential depending on lithology (Wright and Burgess, 1992). Fractured basement aquifers often exhibit low transmissivity values and thus cross border groundwater flow may not be that significant. Still, the extent of local flow regimes should be considered and in particular the potential for cross-border flow and influence of abstraction from one border side upon the opposing side. Where local flow systems are more restrictive than previously thought, limited groundwater present may be supplying larger populations than it can realistically support. Local assessments at national borders of the hydrogeological unit are hence needed to ensure that communities, either side of a border, sustainably and equitably use the local groundwater available.

Storage within the basement complex is dependent on secondary porosity, available due to weathering and fracturing which is also spatially variable (Upton et al, 2016). Weathering usually declines with depth and therefore higher yielding units occur nearer the surface (Smith-Carrington and Chilton, 1983). Fracturing, however, forms along fault zones primarily within the rift valley of the southern limbs of the extensive EARS. Given the local differences between the degree of weathering and fracturing within the basement complex lithologies, these units cannot be considered as a single aquifer system and instead must be recognised to constitute multiple smaller systems dependent on the local conditions where local fracturing or weathering is significant enough so that groundwater can be stored. There are therefore large 'non-aquifer' areas of the basement complex not capable of groundwater storage, and other small local areas with intensive fractures or significant weathering providing sufficient yields (Upton et al, 2016). These aquifers are hence more discontinuous in nature than the alluvial or sand and gravel systems making them less of a transboundary issue in some places. Again, these factors point to the need for more local driven assessments of TBA systems at national borders.

3.4 Legal Provisions

Though transboundary surface water governance is regularly practiced nowadays, transboundary groundwater governance has received comparatively little attention to date (Eckstein, 2015). Globally, only six TBA's have a governing agreement in place compared to over 3,600 treaties relating to the use of transboundary surface waters (UNEP, 2002; cited by Eckstein and Sindico, 2014). This deficiency has prompted our work under the Climate Justice Fund - Water Futures Programme to support a country-wide evaluation of all groundwater resources within Malawi including TBA potential (Scottish Government, 2017). There are currently no legally binding agreements between Malawi and its neighbouring countries relating to the management of shared groundwater resources. There is, however, some cooperation between Malawi and Mozambique concerning the management of the Shire River Basin. In 2003 a treaty was signed by both parties on 'The agreement on the establishment of a Joint Water Commission' to improve responses to flooding in the basin (IWMI, 2015). A World Bank-funded project focused on the Shire River Basin is also on-going, but is primarily focused on the Malawi side of the border. It does not assess potential TBA issues (The World Bank, 2010).

There are multiple protocols and policy instruments within the SADC that include groundwater and transboundary management within their scope. These include the Regional Water Policy adopted in 2005, the Regional Water Strategy adopted in 2006 and the Regional Strategic Action Plan on Integrated Water Resources and Development Management. The most relevant to TBA management is the Revised Protocol on Shared Watercourses (SADC, 2000). This protocol recognises that many watercourses within the SADC are shared among several member states. It aims to foster closer cooperation amongst these states for the protection, management and use of these shared watercourses within the region (e.g. Article 2(a); Article 3, 8(a)). Member states agree to cooperate on projects and exchange information on shared watercourses, consulting with each other and collaborating on initiatives. Within Malawi's own Water Resource Act (2013), a provision states that Malawi must consider its "obligations relating to shared waters" (Part 4, Section 41 (e) (ii)) when granting an abstraction licence and issuing a permit to discharge effluent into a watercourse. Clarity is required in the forthcoming policy on how this provision binds Malawi to uphold the SADC Revised Protocol on Shared Watercourses (2000) and customary international water law principles such as no significant harm, or whether the provision is just a placeholder for any future obligation regarding shared waters that Malawi might legally accept to be binding on it.

Within international water law, the UNILC Draft Articles on the Law of Transboundary Aquifers, 2008 (ILC, 2008) and the Convention on the Law of the Non-Navigational Uses of International Watercourses 1997 (UNECE, 2014) are two instruments available to countries looking to foster agreement over the management of their transboundary resources. The Watercourses Convention is limited by its narrow and restricted definition of a 'watercourse' which suggests that not all types of aquifers come under the regulations of the Watercourse Convention, including fossil groundwater (Martin-Nagle, 2016). Furthermore, the Watercourse Convention does not have a standard definition of what constitutes a TBA alongside suggested criteria for the management of these resources.

The UNILC Draft Articles on the Law of Transboundary Aquifers in contrast facilitate an international legal framework that focuses on all shared groundwater resources and conjunctive management of both groundwater and surface waters (Sanchez, 2016). It does this by including both natural recharging and non-recharging (i.e. fossil) TBA's within its scope and recognising that TBA's can be hydraulically linked to surface waters. However they do have limitations of their own, particularly within the exact definition of an 'aquifer' and the exclusion of 'recharging-only' states (i.e. those states from which recharge comes from but who hold not proportion of the aquifer within its border) from the scope (Eckstein 2007). As Draft Articles, they can only provide direction for member states and consequently only hold legal obligations if all involved states agree to utilize them. If localised and regional TBA management is to be supported by international law, adopted instruments will need to recognise the complexity of the hydrogeological systems governed.

4 Discussion

4.1 A case for systematic national border-based assessments

Many countries are now recognising the importance of TBA identification as a contribution to IWRM. They are assessing key TBAs, most often identified through regional initiatives such as the GEF-TWAP as previously described. This includes Western Europe, Kazakhstan, Russia and the United States of America (European Commission, 2015; Puri & Aureli, 2005; Zektser, 2010). Sanchez et al. (2016) describe known TBAs along the Mexico-USA border with a significant collation of available hydrogeological data. The aquifer systems are laterally extensive and this mode of assessment may fail to resolve the potentially more local transboundary issues where more local minor aquifer assessments become more valid. This need for greater resolution is alluded to by Rivera (2015) who reviews the ten main identified TBA systems along the Canada-USA border, but acknowledges that more TBAs likely remain to be resolved.

Individual TBA system assessments are more common, for example, the detailed assessment of the Milk River Formation between Canada and the United States (Petre et al, 2016; Petre et al, 2015). The study establishes a geological and hydrogeological conceptual model of the TBA system characterising flow directions, recharge zones and abstraction rates. The conceptualisation underpins the development of effective strategies to sustainably manage the resource. Such dedicated aquifer system-focused assessments, whilst critical, do not represent the whole transboundary circumstances of a country. Such detailed assessments also require extensive data and financial resources that may not be available to many developing countries.

Our premise is that there is a need for countries to develop a TBA assessment strategy that systematically screens its entire national border at relevant scales. For some countries, this may include local scales where more minor aquifers may form important resources that are relied upon by rural communities. Overall abstraction volumes may not be that large, but still could be significant locally, especially in SADC arid-semi-arid environments where recharge may be low. This drives the need for relatively local TBA assessment, albeit within the context of the wider geological/hydrogeological systems. A flow diagram is developed in Figure 4 to illustrate the fit of such a national border-based TBA assessment within an overall TBA assessment framework.

The transboundary connectivity of the more major aquifer systems should not be assumed and requires consideration within the strategic approach (Figure 4). Their potential locally discontinuous nature due to faulting and lithology variation (heterogeneity) needs to be understood. Detailed hydraulic functioning at local scales in the vicinity of national borders should be assessed with particular emphasis on assessing evidence for barriers to groundwater flow. This may be aided by improved recording, archiving and computer access to geological log, water level and geophysical monitoring data than is often not practiced in the developing world.

For both minor and major aquifer systems, the potential complicating influence of surface water flows hydraulically connected to these aquifer systems also needs to be explicitly recognised at relevant scales (Figure 4). Groundwater – surface water interactions may result in groundwater flow to surface water and vice versa. These may alter seasonally and groundwater abstraction variation. Conditions may likewise vary upstream and downstream of a country border.

The aim of national border based assessments will be to allow for identification of a country's groundwater resources that are most vulnerable to TBA influence and cross-border flows. Whilst a desk-based study may frequently lack data and resources to make a complete assessment, it should enable some prioritisation and selection of higher risk TBA scenarios that warrant further analysis and targeted (field) data collection (Figure 4).

Contributing metrics to evaluating the at-risk status may include not only TBA hydraulic connectivity, but also consideration of near-border population levels and relative water abstraction rates either side of a border. Such an approach helps to address SDG 6 - Target 6.5 requiring IWRM with transboundary cooperation where necessary (UN Water, 2015).

Our on-going TBA assessment work in Malawi seeks to account for the expected discontinuous nature of the basement complex arising from lithologies, and will consider the differences between the weathered and fractured zones within the basement complex to evaluate the significance of transboundary groundwater exchange. The first results of the reinterpretation of the hydro-stratigraphic units shared with Mozambique in the southern extent of Malawi (Figure 5) illustrate the complexity that can be lost in a regional scale assessment. Whereas the TWAP (ILEC et al, 2016) Southern and Eastern Africa sub-region recognises only one TBA system, the Shire Valley Alluvial Aquifer, in reality exists a multilayer sedimentary aquifer and a discontinuous basement complex system that dominates a large proportion of the border.

4.2 Conceptual models for TBA interactions

A series of illustrative conceptual models of TBA interactions applicable to the Malawian national border are developed below. They are anticipated to be of generic value elsewhere, particularly across the SADC. These models assume low thickness alluvial or basement complex aquifers with low to moderate transmissivity/hydraulic conductivity at or near the border.

Figure 6 portrays an idealised low thickness, symmetric (i.e. the national border lies in the middle of the aquifer). Figure 6(a) illustrates the aquifer’s natural conditions and Figure 6(b) shows the addition of a sustainable abstractions either side of the border. The flow divide remains central with the resource equally shared. Increased groundwater abstraction may still result in an equal resource share either side of the border but a non-sustainable use (and ultimately a loss) of groundwater and negative impacts on surface water (losing rivers) on both sides of the border. Figure 6d illustrates unequal abstraction which shifts the groundwater flow divide resulting in the share of groundwater becoming unequal and considerable surface water impact due to a drop in the water table. The final scenario is particularly pertinent to Malawi where local villages close to the border are heavily reliant on groundwater supplied from thin but abundant alluvial aquifers, some of which are transboundary. Equally, the reverse is also possible if a neighbouring state has a higher abstraction rate.

Figure 7 conceptualises a low thickness alluvial aquifer with the country border in an asymmetric position; a better representation of reality. The recharge across the border is not equal and a larger proportion of the aquifer resides within one country. Abstraction (b) on one side of the border complicates the situation by shifting the flow divide away from the border and this impacts surface water within the abstracting state. Importantly, the abstraction also increases the speed at which the groundwater is moving across the border, as a steeper gradient across the border causes an increase in transboundary flow. Climate change or deforestation within the scenario could also reduce recharge significantly within the system, as is the case for Figures 6, 8 and 9.

Figure 8 conceptualises a semi-confined system where the TBA is not receiving natural recharge on one side of the border due to an overlying low permeability aquitard. Recharge to the confined aquifer occurs to one side of the border. During natural conditions (Figure 8(a)) the confined section of the aquifer on the other side of the border is under artesian pressure resulting in upward leakage through the aquitard and into the aquifer above. This leakage hence provides some support to river flow to the right of the border contributing to baseflow. Adding an abstraction on either side of the border could cause leakage to be reversed resulting in a losing river scenario (Figures 8b and 8c). Increased abstraction may result in complete loss of baseflow to the river. Such cases are illustrative of TBA connectivity on the management of both surface and groundwater resources.

The final conceptual model (Figure 9) is of basement complex, with an overlying discontinuous alluvial aquifer; a common scenario across the SADC. Assuming a natural flow regime, there are a variety of transboundary implications based on where the border sits (Borders A-E). Borders A and E for example result in transboundary groundwater flow through both unconsolidated alluvial sediments and fractured basement rock. Borders B and D would exhibit just fractured rock groundwater flow, and border C, close to the groundwater flow divide, would have fairly limited groundwater contributions from the opposing border side contributing to aquitard leakage and the shown spring discharge. This conceptualization highlights how variable aquifer lithologies and discontinuities throughout the basement complex can cause different transboundary system types that need to be considered on an individual and local basis. Figure 9 could have been developed to portray a different basement complex lithology or a weathered zone instead of a no fracture zone; this again could result in the unit being broken up into smaller aquifer units.

4.3 Integrated Water Resource Management (IWRM)

Although widely recognised that groundwater is an integral part of many hydrological systems, many IWRM schemes still omit transboundary groundwater from their scope. Whilst some groundwater resources may appear to have weak hydraulic connectivity to other system compartments or contain fossil groundwater (Martin-Nagle, 2011), many systems do display significant connectivity between groundwater and surface water systems (Rivera, 2015). It is critical to recognise this connectivity within any TBA assessment and IWRM framework adopted.

'Water Resource Units' (WRUs) have long been defined in Malawi that sub-divide the country into 17 separate physiographic regions and 66 sub-region units based upon surface water catchments (Smith-Carrington and Chilton 1983). More holistic IWRM at a national level needs to recognize that many aquifers cross these units and thereby allow water transfer between them. This may result in IWRM tensions as neighbouring unit officials could manage their connected groundwater resources differently. This scenario may be further complicated where transboundary issues also arise. IWRM of TBAs requires consideration of not only recharge sources and abstraction areas, but also surface water (recharge/discharge) connectivity to these aquifer systems. Future water resource policy in Malawi will need to increasingly recognize that linkage of physiographic regions and groundwater (including transboundary groundwater) is required to achieve IWRM and SDG

6. It is not unreasonably surmised that similar challenges (with local variation) to those faced by Malawi are likewise faced by other countries.

Various foundations for IWRM and hence TBA management beyond Malawian borders are provided for by surface water catchment based initiatives. Within Africa, 'River Basin Organizations' (RBOs) have been developed to foster joint water cooperation between stakeholder countries built upon the African Water Vision 2025 (UN Economic Commission for Africa, 2001). Malawi is part of the Zambezi Watercourse Commission (ZAMCOM), one of six River Basin Organizations within the SADC region. Similar to the Malawian WRUs, these are surface water catchment management based, often without mandate to manage transboundary groundwater or coordinate its management between the stakeholder basin states. Where mandates do exist (e.g., Orange-Senqu River Commission), technical skill or financial resource limitations inhibit the progress of groundwater management. Consequently, the groundwater aspect of the river basin is often managed indirectly to the rest of the hydraulic system.

Fostering institutes that cooperate conjunctively on hydraulically linked surface and groundwater management on both the local, national and international scale is advocated to move forward with IWRM within the SADC. Recent progressive effort to account for groundwater management within SADC member states is evident through establishment of the SADC Groundwater Management Institute (SADC-GMI) hosted by the Institute for Groundwater Studies in Bloemfontein, South Africa. Their aim is to support the sustainable management of groundwater at national and transboundary levels across SADC member states (SADC-GMI, 2016). Our national border-based TBA assessment approach is seen to support this initiative.

5 Conclusion and Recommendations

Integrated water resource management of transboundary groundwater is becoming increasingly important and can vitally underpin international achievement of SDG 6. This paper has critically assessed previously identified TBAs in Malawi and introduced the need for Malawi and other countries to more generally develop a TBA strategy that systematically examines its entire national border at relevant scales in order to establish and prioritise TBA connectivity. It is fundamentally built around conceptual models of TBA connectivity and interaction that are presented here and offer generic value elsewhere.

Within the African developing world context personified by Malawi, an entire national border approach may initially require local-scale desk-based assessments driven by the presence of rural low-density populations, dispersed community water points, frequent minor aquifer systems and the potential for disconnected aquifer units (e.g., by faulting or weathering). Whilst aquifers are often minor, they are nonetheless critically important to life and livelihoods in most cases. Our proposed approach outlined, and on-going in terms of detailed assessments throughout the Malawian national border length, is necessarily desk-based due to resource constraints in the developing world. It is nonetheless expected to vitally steer where future TBA efforts may be targeted.

Our border based TBA assessment approach is vitally overarched by an IWRM framework that recognises the connectivity of groundwater and surface water as a single hydraulic system. Such an approach is critical to informing and developing appropriate national management policies, international cooperation, and the development and implementation of science-informed TBA agreements that are workable. International law and policy guidance will need to recognise the complexity of hydrogeological-hydrological systems. Although the Draft Articles as indicated are moving in the right direction, limitations must be addressed in order to facilitate a framework that promotes IWRM of TBA systems. It is anticipated that such recognitions and approaches will pave the way for appropriate local/regional scaled sustainable and equitable management of the TBAs identified and safeguard water resources for all stakeholder nations involved.

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Figures

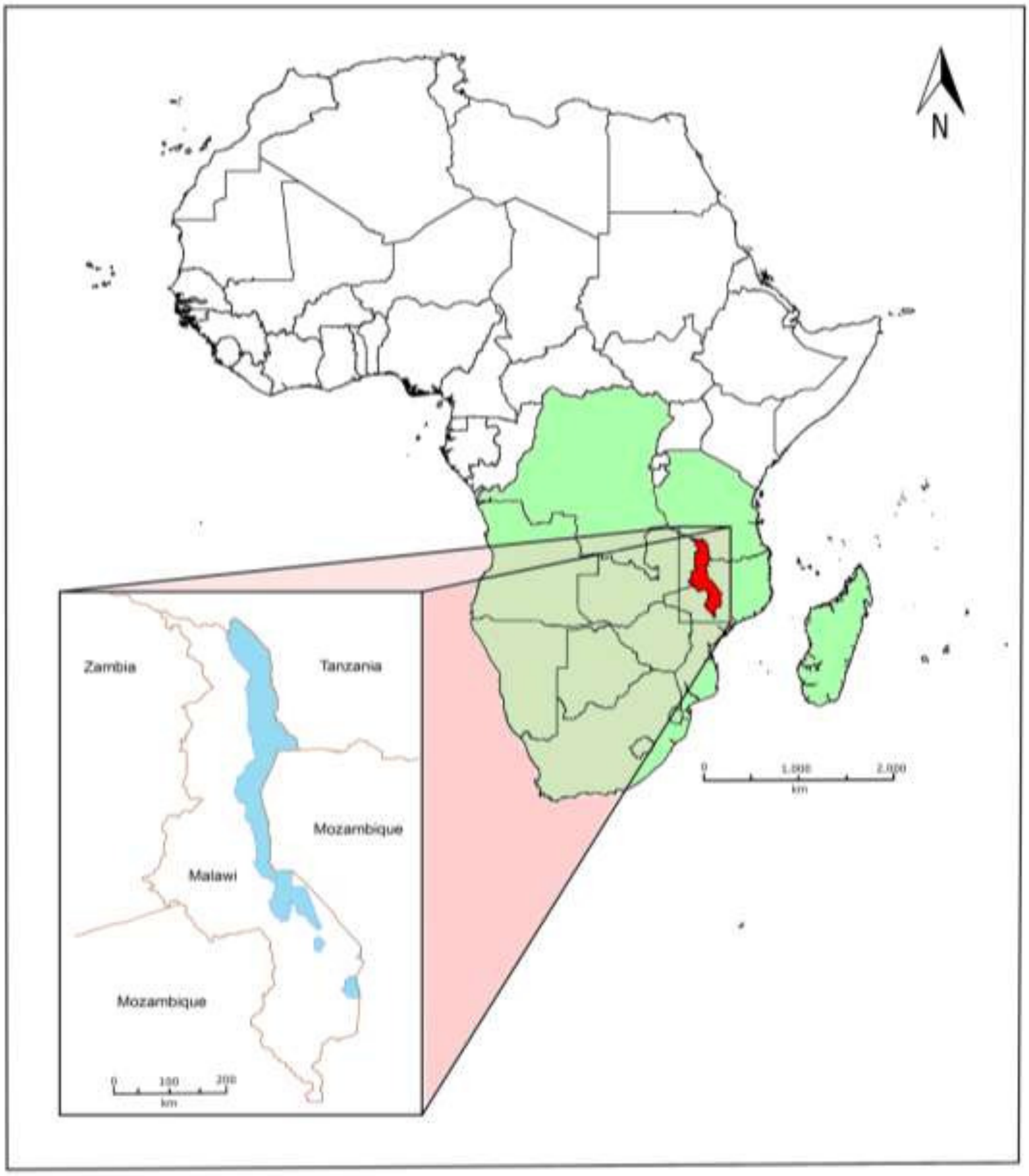

Figure 1 - Map of Malawi surrounded by Zambia, Mozambique and Tanzania illustrating Malawi's position (red) in relation to the African continent and the SADC (green)

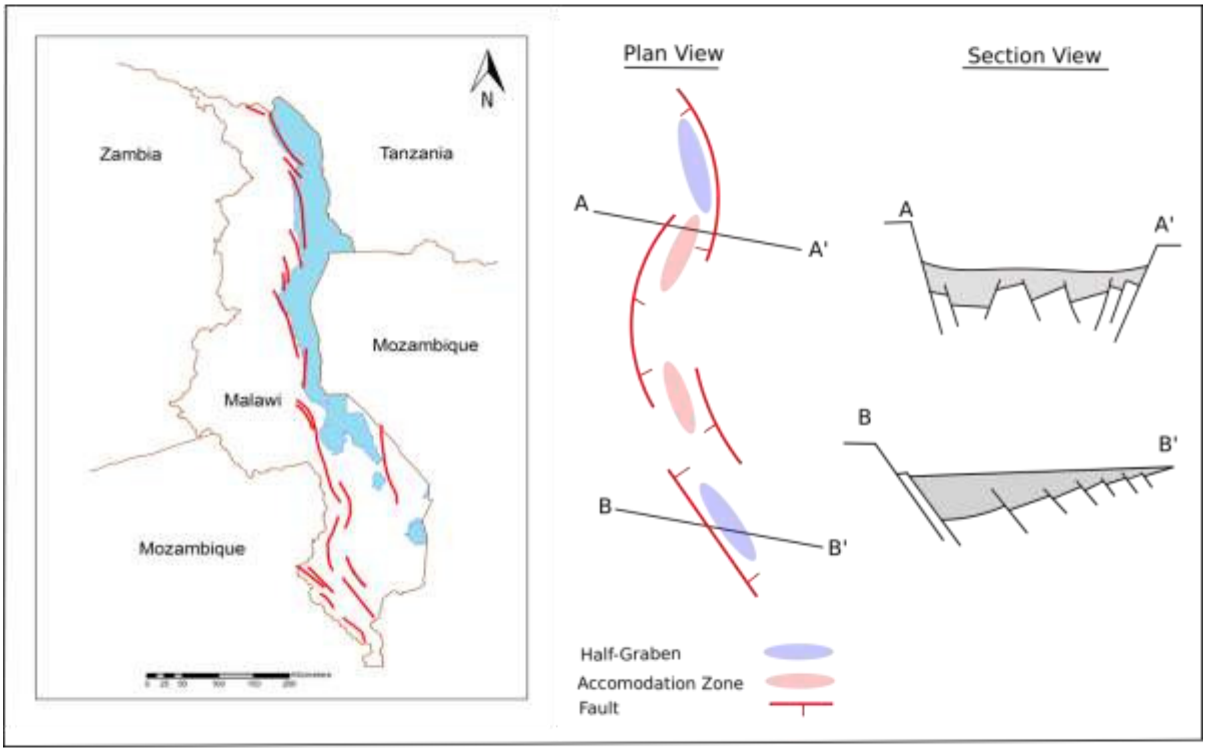

Figure 2 - *Malawi's Rift faults and basin structure (left) with a plan and cross section view through the southern region (right). Modified from (Delvaux, 1991)*

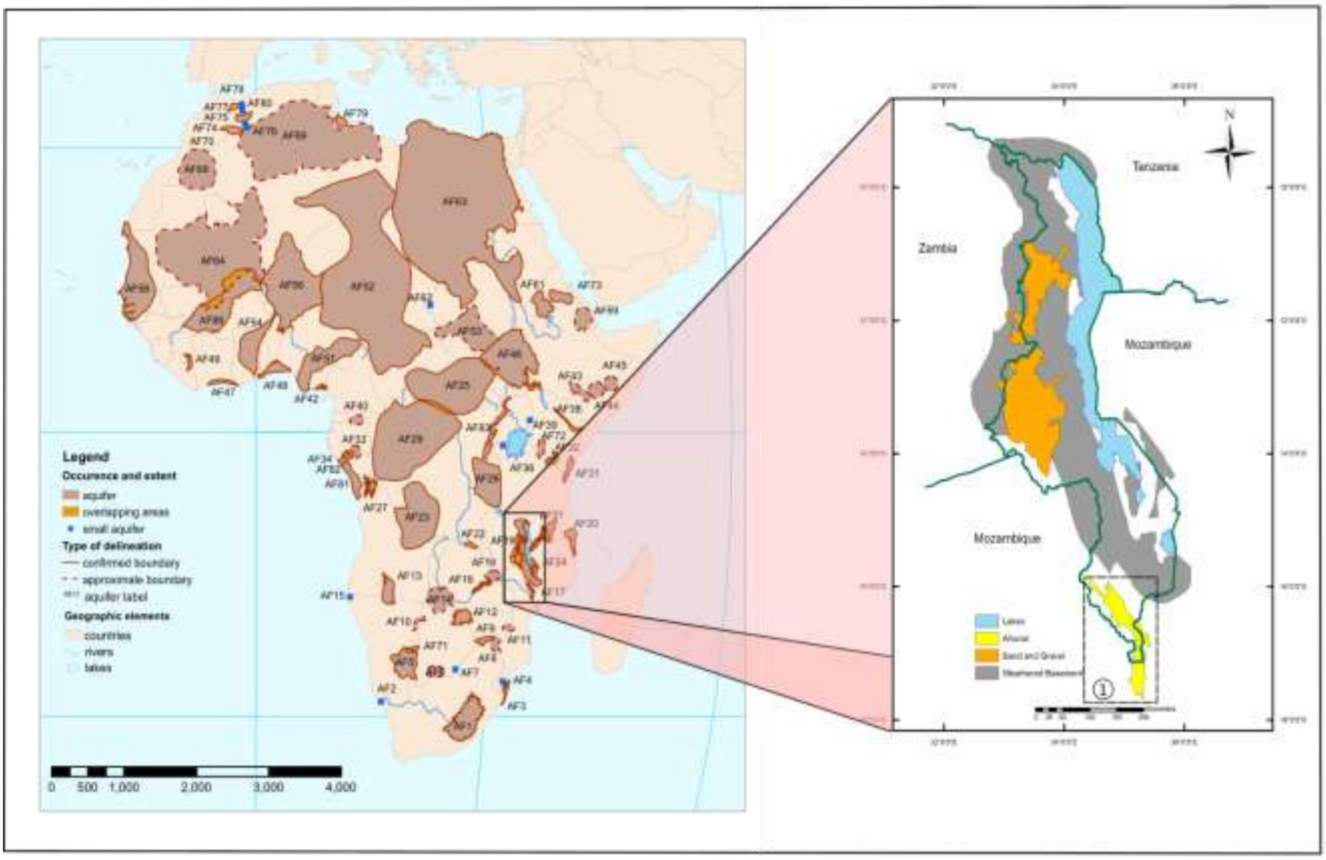

Figure 3 - *Map of the African continent illustrating the current known transboundary aquifers highlighting current identified transboundary aquifers of Malawi shared with surrounding countries (modified from IGRAC, 2015). See figure 5 for a reinterpretation of the south of Malawi transboundary aquifers, area illustrated in point 1*

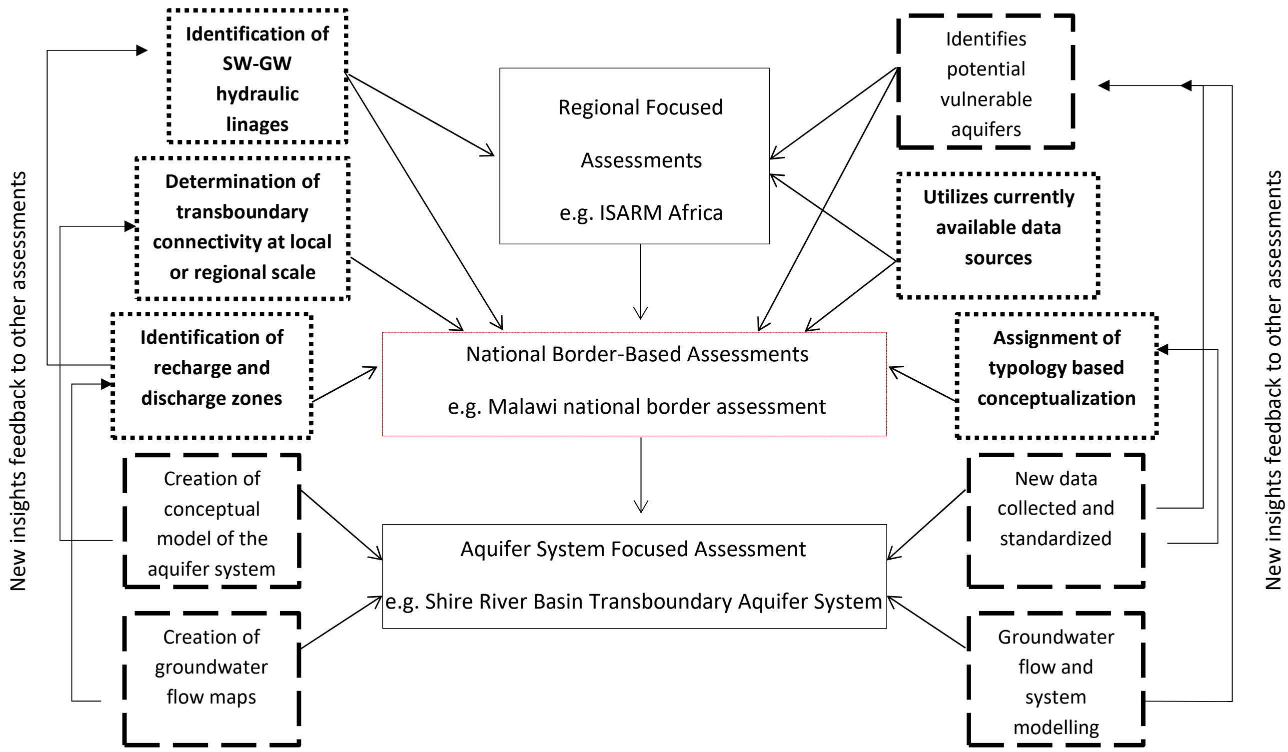

Figure 4 - Flow diagram illustrating the place for national based boundary assessment within an overall framework. Gathered information from regional assessments can feed in to inform the national border based assessments. These can then be used to identify key aquifers that require a more detailed system-focused assessment. New data and insights can feed back to other assessments in a looped system

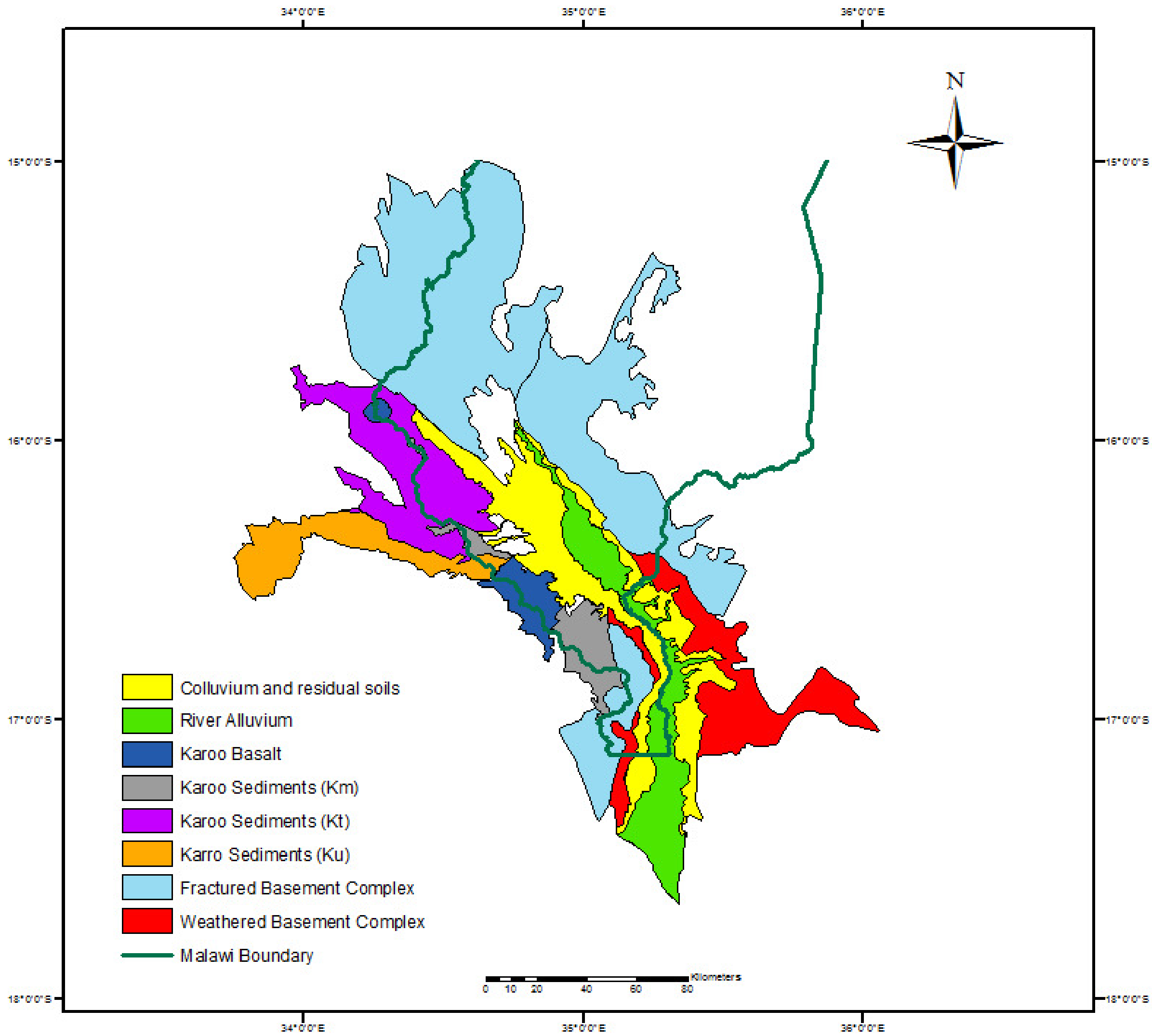

Figure 5 - A reinterpretation of the transboundary aquifer units of Southern Malawi shared with Mozambique. For reference of location see point 1 on figure 3

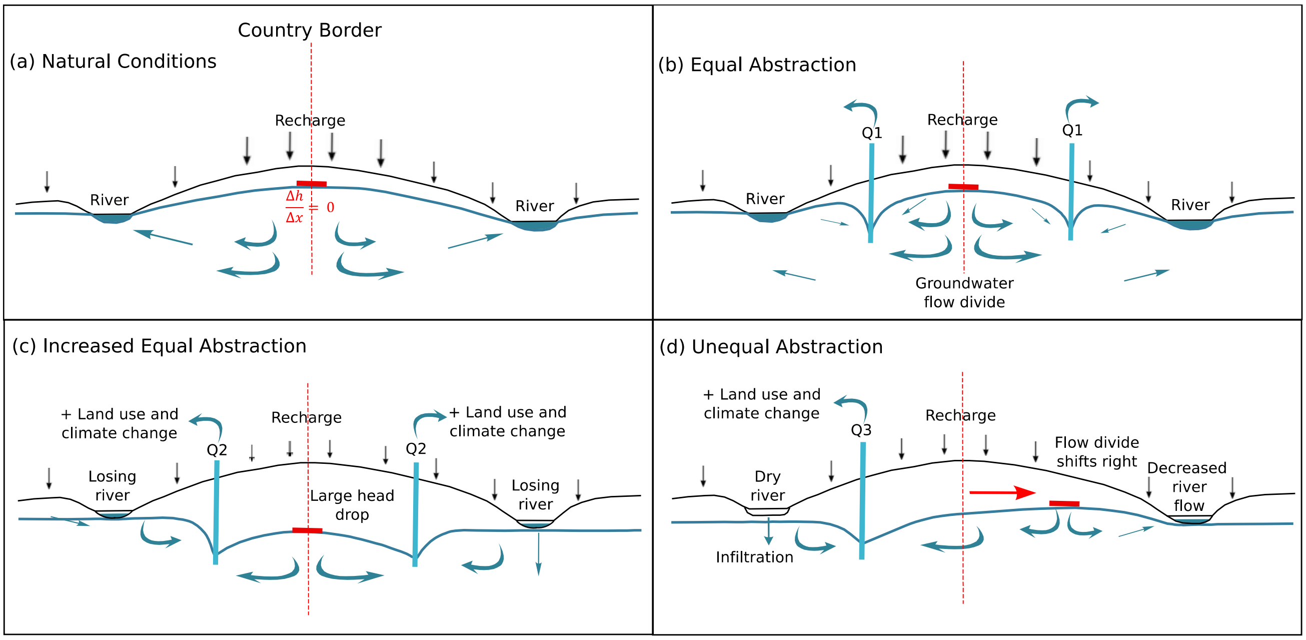

Figure 6 – Equal and unequal abstraction from an equally shared transboundary aquifer between two states and sustainability implications

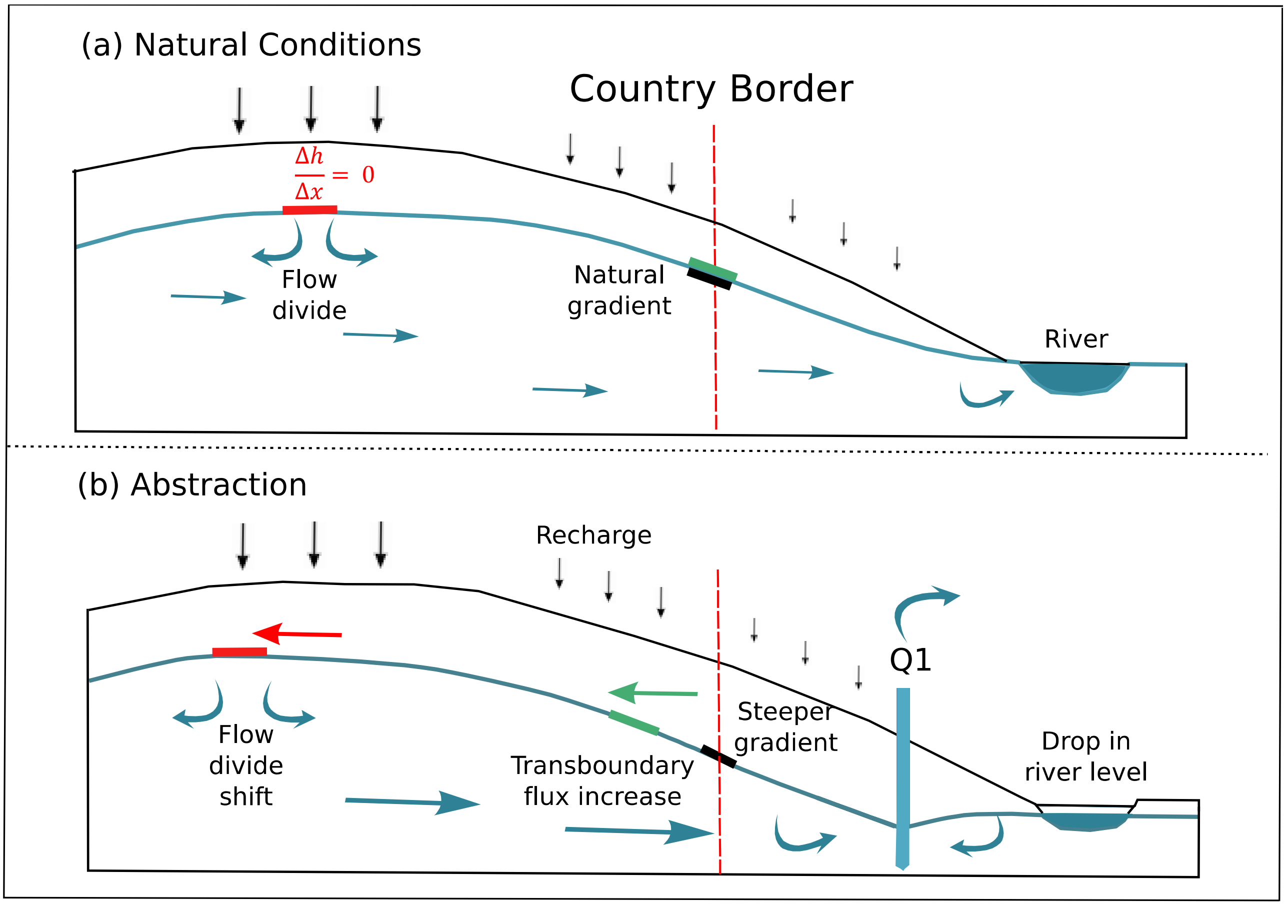

Figure 7 –Sustainable and non-sustainable transboundary abstraction within an unequally shared transboundary aquifer system

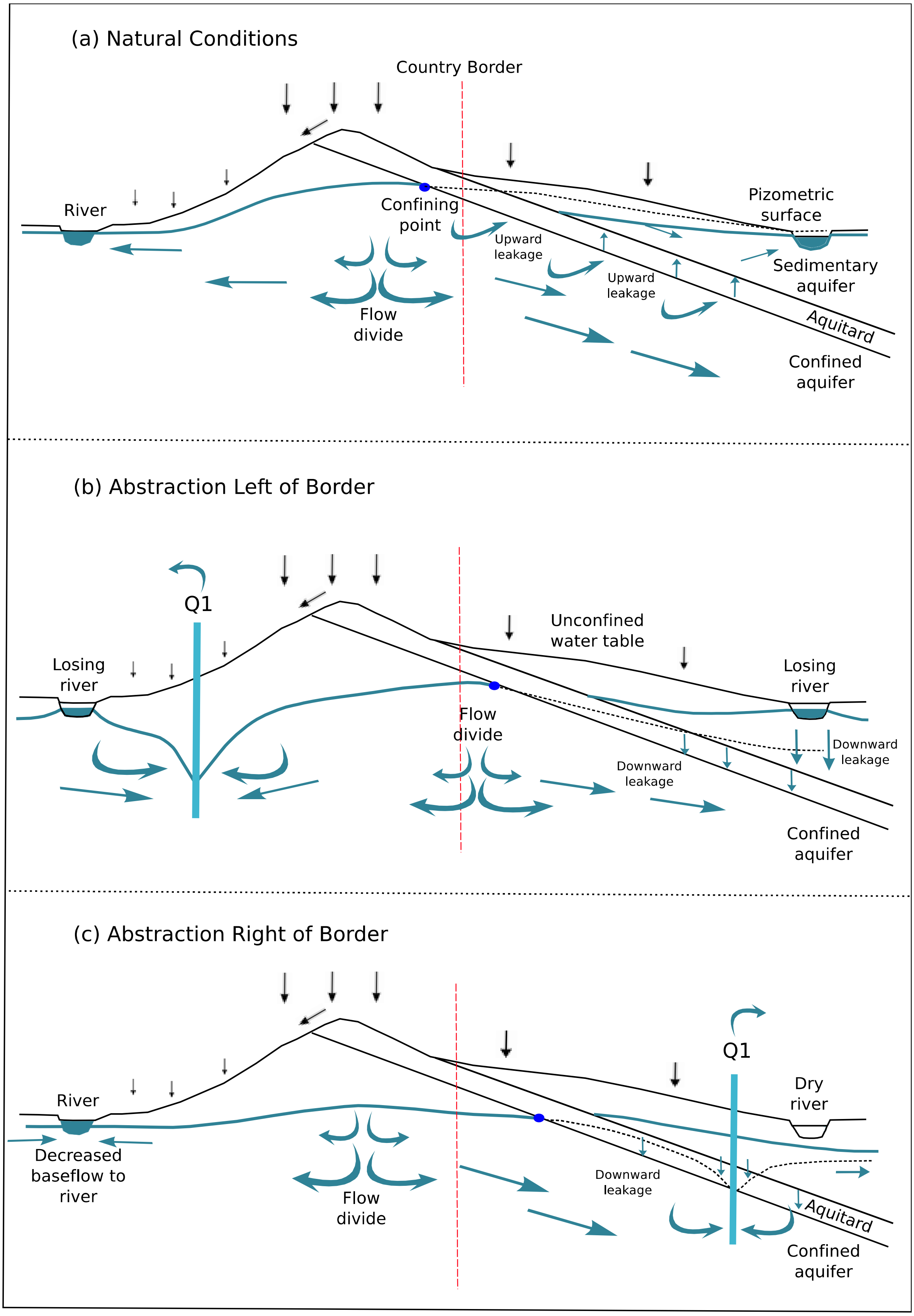

Figure 8 – The implications of abstraction from a confined transboundary aquifer system

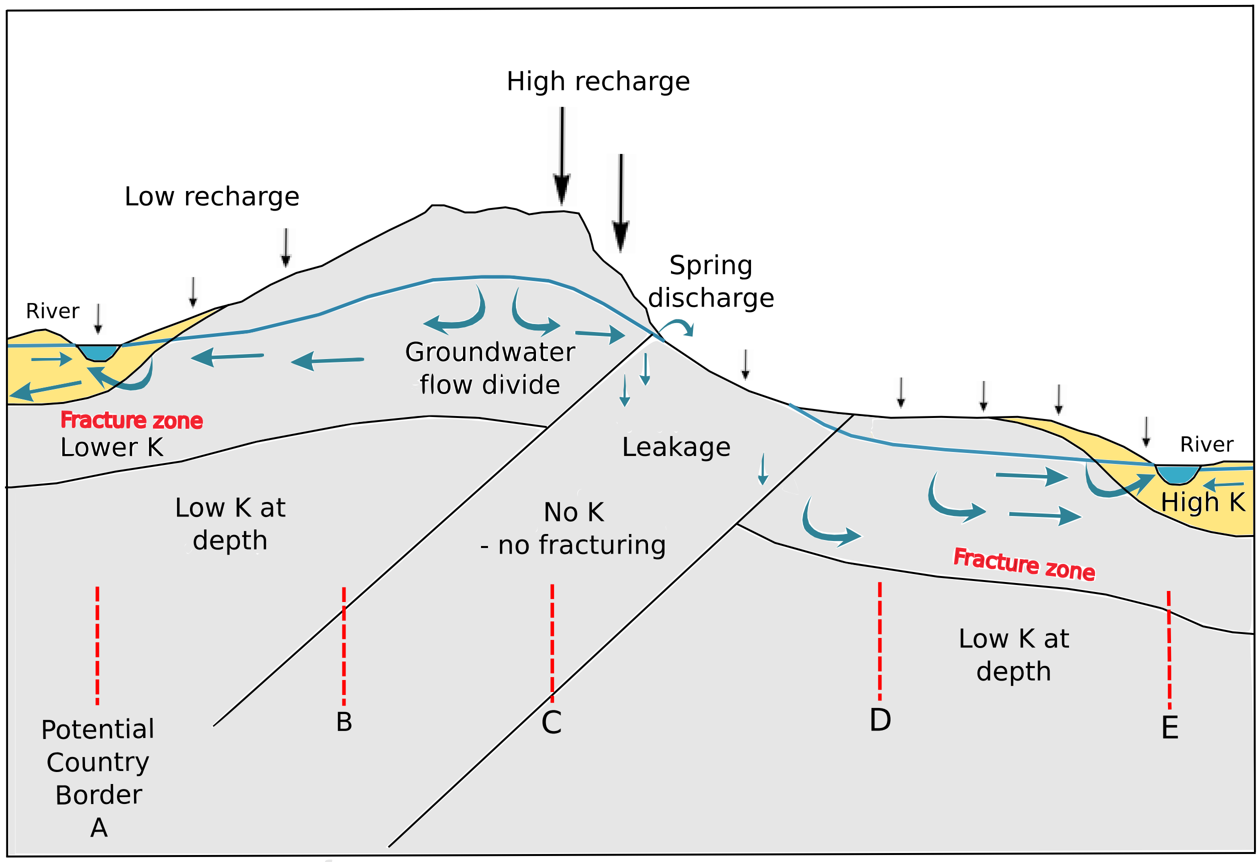

Figure 9 – Discontinuous fractured rock aquifer and boundary implications for transboundary groundwater flow

Tables

Table 1: Summary of current identified TBA's within Malawi (ILEC et al, 2016; Upton et al, 2016; Davies et al, 2013). For aquifers extent and location see Figure 3

Aquifer Name	Lithology	Transmissivity (m^2/day)	Total area extent (Km^2)	Aquifer Thickness (m)	Aquifer Productivity	Aquifer Type	Confinement	Involved Countries
Weathered Basement	Crystalline-metamorphic basement rocks	<5-6	110,000	30-45	Low to moderate	Mainly single-layered, multi-layered in north	Semi-confined to confined	Malawi Tanzania Zambia Mozambique
Sand and Gravel	Colluvium overlying weathered metamorphic basement gneiss	<5-26	23,000	20-60	Low to moderate	Single-layered system	Unconfined to semi-unconfined	Malawi Zambia Mozambique
Shire Valley Alluvial	Tertiary/Quaternary sediments	50-300	6223	30-150	High to very high	Single-layered system	Unconfined to semi-unconfined	Malawi Mozambique