



ISSN: (Print) (Online) Journal homepage: <https://www.tandfonline.com/loi/rwin20>

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To cite this article: Christina M. Fraser , Robert M. Kalin , Modesta Kanjaye & Zione Uka (2020) A methodology to identify vulnerable transboundary aquifer hotspots for multi-scale groundwater management, Water International, 45:7-8, 865-883, DOI: [10.1080/02508060.2020.1832747](https://doi.org/10.1080/02508060.2020.1832747)

To link to this article: <https://doi.org/10.1080/02508060.2020.1832747>



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A methodology to identify vulnerable transboundary aquifer hotspots for multi-scale groundwater management

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ABSTRACT

Thirty-eight aquifer units are shared between Malawi and its neighbouring countries. It is essential to prioritize those transboundary aquifers that require immediate attention. A methodology of identifying hotspots in the transboundary aquifers of Malawi that may be at risk of depletion or contamination has been developed. There are 11 local-scale and three national-scale hotspots of transboundary concern in Malawi. Fiscal and planning measures can now be taken to assess these areas in more detail, fostering transboundary cooperation between stakeholders at both local and national scales.

ARTICLE HISTORY

Received 1 April 2020
Accepted 2 October 2020

KEYWORDS


Transboundary; aquifer; hotspots; management; Malawi

Introduction

Groundwater is a vital natural resource accounting for 97% of the non-frozen freshwater resources available across the globe (IGRAC & UNESCO-IHP, 2015). It provides almost half of the drinking water worldwide, alongside 40% of the water used for irrigated agriculture and 33% used in industry (Smith et al., 2016; UN-Water, 2018). It is essential for sustaining ecosystems and providing baseflow to rivers (Kelly et al., 2019a). Climate change and increasing human impacts on the environment are putting pressure on groundwater resources, causing quality and quantity issues (UN-Water, 2018). Over the last decade, groundwater abstraction has tripled and continues to increase at around 2% per year (Van der Gun, 2012). This issue is exacerbated in many parts of Africa, where groundwater is often the only reliable source of water. Up to 75% of the population on the continent relies on groundwater as their main source of drinking water (UNECA et al., 2000). Groundwater is also essential in these areas for rural livelihoods such as livestock rearing and agricultural crop cultivation (Villholth, 2013 and Foster et al., 2008 in Nijsten et al., 2018). The importance of water was recognized in the United Nations Sustainable Development Goals adopted in 2015. Goal 6 is dedicated to clean water and sanitation, including groundwater. Target 6.5 calls for the implementation of Integrated Water resources Management, at a transboundary level where appropriate (Mccracken, 2017).

Both surface waters and groundwater can be transboundary, meaning that rivers, lakes and aquifers have the ability to store and transmit water across a state or border (Fraser et al., 2020). Whereas transboundary surface waters have been extensively studied

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 Supplementary data for this article can be accessed at <https://doi.org/10.1080/02508060.2020.1832747>

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worldwide, transboundary aquifers have received much less attention (Rivera & Candela, 2018). Transboundary aquifer assessments have become more common across the globe since 2000 due to substantial efforts from the Internationally Shared Aquifer Resources Management initiative of the International Association of Hydrogeology and UNESCO (Rivera & Candela, 2018). There are currently 592 transboundary aquifers identified worldwide, 226 of which are groundwater bodies defined under the EU Water Framework Directive. There are 80 transboundary aquifers identified in mainland Africa (IGRAC & UNESCO-IHP, 2015). The identification and basic hydrogeological understanding of these aquifers has been driven by the need for transboundary aquifer management and agreements for these vulnerable shared resources (Fraser et al., 2018; Nijsten et al., 2018; Rivera & Candela, 2018).

A recent study that took a detailed and national-border-based approach to transboundary aquifer assessments in Malawi identified 38 transboundary aquifer units shared between Malawi and its neighbours, in contrast to a previous estimate of three (Fraser et al., 2020, 2018). It is likely that other countries, like Malawi, have many more transboundary aquifers than previously thought. As the number of such aquifers rises around the world, prioritizing which ones receive resources and funds for in-depth assessment and specialized management will become essential. Inherently, not all transboundary aquifers are at risk for reduced quality and over-abstraction. Identifying which aquifers require attention and which do not is essential under Integrated Water Resources Management and the Sustainable Development Goal agenda. Furthermore, assessing whether a transboundary aquifer requires local, national or international cooperation and management will allow the best policy instruments, legal agreements and management mechanisms to be selected.

This article presents a methodology for identifying hotspots in transboundary aquifers that may be vulnerable to groundwater quality and quantity issues. Asset management data collected as part of the Climate Justice Fund's Water Futures Programme were utilized in this study through a spatial analysis site selection technique to identify key areas in transboundary aquifers in Malawi that may be at risk. These areas of risk were then classified into local and national scale transboundary hotspots. Aided with this information, policy makers and governmental officials have the ability to select those transboundary aquifers (or areas of transboundary aquifers) that require further investigation, directed cross border management and potentially, transboundary agreements governing them.

Methodology

Study area

Malawi is a small country in south-eastern Africa and is part of the Southern African Development Community (SADC). It is landlocked by Tanzania, Mozambique and Zambia. Groundwater is a vital resource in Malawi, providing 82% of drinking water in rural areas as well as agriculture and industry needs (Chavula, 2012). Malawi has many challenges and limitations for its groundwater supply, particularly in rural areas (Kalin et al., 2019). Threats to aquifers include decreasing groundwater levels, high salinity levels in alluvial deposits, contamination from pit latrine location and -agricultural runoff, an increasing population and the effects of land degradation and climate change

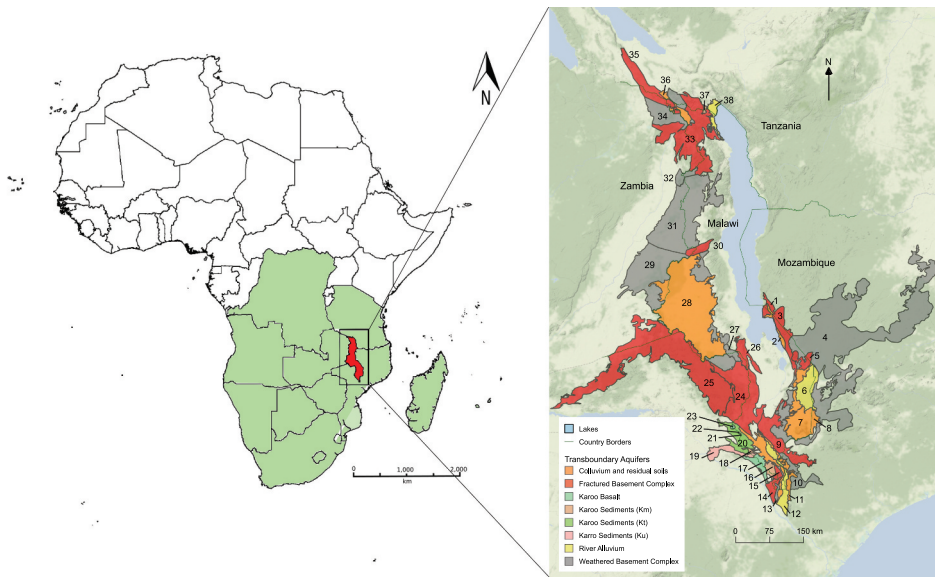


Figure 1. Transboundary aquifers shared between Malawi and its neighbours in the wider SADC (adapted from Fraser et al., 2020, 2018).

on groundwater recharge (Addison et al., 2020; Back et al., 2018; Bath, 1980; Kelly et al., 2019b; Monjerezi et al., 2011; Rivett et al., 2019, 2018a, 2018b; Smedley, 2004; Smith-Carrington & Chilton, 1983).

Three transboundary aquifers in Malawi were first identified by the Global Environment Facility's Transboundary Waters Assessment Programme, which aimed to provide the first global-scale assessment of all transboundary waters (Fraser et al., 2018; ILEC et al., 2016). More recently, Fraser et al. (2020) increased this number to 38 by including smaller, more locally significant aquifers in their assessment. Figure 1 illustrates the current understanding of transboundary aquifers shared between Malawi and its neighbours.¹ Aquifer lithologies include widespread weathered and fractured basement complex, Karoo sediments and basalts, and quaternary alluvium and colluvium. Not all of these transboundary aquifers will be at risk to over-abstraction or reduced water quality. The method presented in this article seeks to identify which of these 38 aquifers, and indeed which areas in these aquifers, pose a potential risk.

Methodological approach

The method presented here is based on the concept of fuzzy logic first developed by L. A. Zadeh in 1965. It is based on the assumption that people do not think in exact variables ('yes' or 'no') but distinguish a range of 'blurry' values (for example 'very', 'somewhat', 'perhaps', or 'yes and no'). Fuzzy logic can be used as an overlay analysis technique in geographical information systems (GIS) to solve traditional overlay analysis applications such as site selection and suitability models. The fuzzy logic method assigns membership values from 0 to 1. Fuzzy logic site selection is different from other site selection methods because it represents the possibility of an ideal site. Fuzzy overlay allows the user to overlay the various

reclassified layers to analyze the possibility of a specific occurrence. This can then be used to identify a site based on a series of criteria.

Spatial analysis of transboundary aquifers in Malawi was undertaken using fuzzy logic and GIS overlays to generate 'hotspot maps' of areas with the greatest risk of transboundary mismanagement. The hotspot map is generated using multiple input raster layers that each have weighted attributes attached to them based on the parameter being modelled, which are then summed to produce a combined raster layer. The higher the cell weight, the worse the case. From this, a heat map is produced where the areas of greatest accumulation of highly weighted categories are shown as 'hotspots'. Then shapefiles of the known transboundary aquifers in Malawi were overlaid and eliminated based on their local or national hotspot significance. Although this method is relatively common, it has never been applied to a transboundary aquifer context to assess areas of risk due to diminished water quality and quantity.

The spatial co-location of areas of higher risk for reduced quality and quantity of water corresponding to transboundary aquifers provides a first indication that the aquifer requires further evaluation. A hotspot that spans across the majority of a transboundary aquifer is deemed to be of a national scale. If it is only focused along the border, then it is considered to be of local scale. Hotspots not within a transboundary aquifer, or within a transboundary aquifer but not directly linked to the border, were not considered.

Three important characteristics of the method should be noted. First, any data or criteria could be used. This means that each user (or country, or community, etc.) can define what they believe the biggest transboundary risks to be and how they should be weighted. This empowers countries to make their own decisions about their transboundary resources. If arsenic contamination, for example, is deemed to be an issue, it can be added as a layer. Second, the map is data-driven, but given its flexibility, as described above, a user can have as few as two layers, or as many as needed to define the risks. The more data, the more accurate the result, but even with little available data, results can still be achieved. This makes the method inherently flexible and accessible to data-limited countries. Third, although this is a transboundary context, the method was only applied to one country, rather than two or more. This was chosen to show that previous transboundary cooperation is not necessary for countries to start to look at their own transboundary circumstances; on completion of the hotspot analysis, a country could then approach its neighbours with a mandate for future cooperation.

Data collection

The case study and the chosen area should dictate what data are used for the creation of the hotspot maps. The data layers for this study were selected in consultation with the government of Malawi's Ministry of Agriculture, Irrigation and Water Development, based on groundwater quality and quantity concerns. Malawi, like most of Southeast Africa, had limited data for certain parameters on which to base groundwater assessments (Adelana & MacDonald, 2008). Instead, we used proxies for these parameters which we believe to be suitable.

The primary data source for this assessment is from the Futures Programme asset management data set of the Climate Justice Fund (CJF), hosted on the mWater platform (www.mwater.co). Data were collected through a series of water point functionality and

household-level surveys using a method often called ‘water point mapping’. The information gathered included water point functionality, geographical location, accessibility, reliability and communities served. In total, 120,935 water points, 278,045 sanitation points and 10,297 waste sites were assessed, with five pieces of site data collected per water point, 81 questions per water point functionality survey and up to 23 questions per sanitation survey. A total of 93,000 water and sanitation points (and data from four of the specific questions) were used in this study, supplemented by two open source shapefiles for hydrology and land use (MASDAP, 2019; Persits et al., 2002; Upton et al., 2018)

Data selection and weighting

The hotspot spatial analysis used six combined raster files. Each data point in these six files was given a weigh between 0 and 1 based on a selected criterion. The higher the weight, the worse the case and thus the higher the risk rating. Table 1 summarizes the parameters selected for this study and the weight selected for each attribute.

Layer 1 is water point type. These data were collected through observation during the CJF water point functionality survey. Water point type is used here as a proxy for water supply reliability. The attributes are (1) hand-dug well, which are considered to have the lowest water supply reliability and thus are given a weight of 1, indicating high risk; (2) mechanically drilled borehole, which are considered more reliable and given a weight of 0.5 (MacDonald et al., 2019); and (3) piped supply, which is considered to have the highest reliability in this scenario and is given a weight of 0, indicating low risk.

Layer 2 is the hydrogeology of the aquifer. This is open source shapefile data from the British Geological Survey (Upton et al., 2018). Hydrogeology is used as a proxy of water supply availability, as some aquifer types provide better yields of water than others (Upton et al., 2018). Attributes in this layer are (1) basement lithology, which has low yields and thus is given a weight of 1, indicating high risk; (2) Karoo sediments and basalts, which have higher yields and so are given a weighting of 0.5; and (3) alluvial and colluvial lithologies, which have the highest yields and therefore a weight of 0, indicating low risk (Smith-Carrington & Chilton, 1983).

Table 1. Input layers for hotspot map.

Layer	Attribute	Weight	Data type / location
Water point type	(1) Hand-dug well	1	mWater point data
	(2) Hand pump/borehole	0.5	
	(3) Piped supply	0	
Hydrogeology type	(1) Basement	1	GIS shapefile
	(2) Karoo	0.5	
	(3) Alluvial/colluvium	0	
Users per water point	(1) Above Malawi guidelines (> 250 per borehole, 120 per tap)	1	mWater point data
	(2) At or below Malawi guidelines	0	
Proximity to pit latrine	(1) Outside Malawi guidelines (<30 metres)	1	mWater point data
	(2) Within Malawi guidelines (>30 metres)	0	
Land Use	(1) Settlement/cropland/industry	1	GIS shapefile
	(2) Forest/grassland/wetland	0	
Seasonal fluctuations	(1) Yes	1	mWater point data
	(2) No	0	
No data		0.5	

Layer 3 is number of users per water point. The data were collected during the CJF water point functionality survey through questioning of a local community representative. This layer is used as a proxy for stress on the aquifer's water supply. When a water point exceeds the recommended number of users, this can cause stress on the aquifer. In layer 3, when the number of users is above the government guidelines of 250 users per borehole or 120 per tap (Stoupy & Sugden, 2003), a weight of 1 is given; otherwise a weight of 0 is given.

Layer 4 is proximity to a pit latrine. The pit latrine and water point GPS data were collected through observation during the CJF water point functionality survey. GIS was then used to represent the data spatially and determine the distance between water point and pit latrine. Drinking water sources close to a pit latrine are more susceptible to faecal contamination, so distance from a pit latrine is a proxy for water quality (Back et al., 2018). The government guideline is that pit latrines should not be within 30 metres of a water point (Ministry of Irrigation and Water Development, 2008). In layer 4, water points within 30 metres of a pit latrine are given a weight of 1, indicating the highest risk; otherwise they are given a weight of 0.

Layer 5 is land use. This is open source shapefile data obtained from Malawi's Spatial Data Platform (MASDAP, 2019). Different uses of land can cause a variety of pressures on groundwater. Here, we use land use as a proxy for potential nitrate contamination, as heavy industry and agricultural land use can raise nitrate concentrations in the environment (Lapworth et al., 2017; Wick et al., 2012; Wongsanit et al., 2015). In layer 5, areas of settlement, cropland or industry are given a weight of 1, indicating a high risk of nitrate contamination; forest, grassland and wetland are given a weight of 0.

Finally, layer 6 is seasonal fluctuation. These data were collected during the CJF water point functionality survey through questioning of a local community representative. Groundwater levels in Malawi fluctuate due to seasonal recharge and baseflow impacts (Kelly et al., 2019b). At times, the levels can drop below borehole and shallow dug well depths. Seasonal fluctuation of water availability from a water point is used as a proxy for groundwater reliability. A source that is seasonally fluctuating is considered less reliable than a source that supplies water year round. In layer 6, water points that fluctuate seasonally are given a weight of 1; otherwise, they are given a weight of 0.

These weights were summed, so each data point had a range from 0 to 6. This overall weighting was then presented spatially in GIS.

Existing methodologies

Methods to prioritize transboundary aquifers for directed management already exist. Davies et al. (2013) sought to identify the transboundary aquifers in most need within the Southern African Development Community. The method aimed to classify 14 transboundary aquifers in the region based on how 'troublesome' they are. The criteria included groundwater flow and vulnerability/susceptibility, groundwater knowledge and understanding, governance capability, socio-economic/water-demand capability and environmental issues. Only two of the 14 aquifers assessed were classified as

troublesome. Curiously, neither has been subject to any further study. Instead, three of the other 12 aquifers have had projects dedicated to their assessment and management: the Shire Valley Alluvial Aquifer through the Shire CONWAT project, the South West Kalahari/Karoo Basin Aquifer through the GGRETA project, and the Zeerust-Ramotswa-Lobatse Dolomite Basin Aquifer through the Ramotswa Project (International Water Management Institute, 2019; Southern African Development Community-Groundwater Management Institute, 2018; UNESCO-IHP, 2016). This method is limited by its applicability to only entire transboundary aquifers. Often, large parts of transboundary aquifers are not utilized, especially those that expand across large areas or are not at risk due to their small population (Fraser et al., 2018). This method also risks misrepresenting parts of transboundary aquifers based on data from potentially only one area.

The term ‘transboundariness’ was coined by Sanchez et al. (2018a) to describe a method that identifies and prioritizes transboundary aquifers based on a political and socio-economic criteria. The data used include population metrics, water quality, data/research availability, political recognition as transboundary, cooperation efforts and other issues governing the agenda. The approach was applied to the Texas–Mexico case, where transboundary aquifers are fairly well understood and often recognized constitutionally (Sanchez & Eckstein, 2017; Sanchez et al., 2016, 2018b). The results split the aquifers into priority groups based on their ‘transboundariness’. The more ‘transboundary’ an aquifer is, the higher the priority it is given. ‘Priority’ refers to the level of attention or importance given to an aquifer. Thus, the approach gives the highest priority to those aquifers with the most attention and the best data availability. The approach does not prioritize aquifers based on need but rather highlights those which have been given priority until now (Sanchez et al., 2018b). Although effective in identifying which aquifers are already receiving the most attention, this method does not identify which may be at risk of contamination or reduction in water quantity in the future. Furthermore, the method is not applicable in countries where transboundary aquifers are not as well studied, understood or recognized.

Finally, Sanchez et al. (2020) developed an approach to identify the priority areas within a single aquifer using pumping well locations and density as indicators. Areas with a high density of wells are termed ‘effective transboundary aquifer areas’. These areas can be considered priority zones by both local and national governments for more specific and specialized transboundary management between riparian states. In focusing only on abstraction, this method does not consider the water quality in transboundary aquifers and thus makes it unsuitable for areas where transboundary aquifers are at risk of reduced water quality, as in the Malawi case.

Our method seeks to highlight the importance of both water quantity and quality in the SADC transboundary aquifer context, where financial resources and groundwater data are often limited. Water point mapping is common practice in the region, and through an alternative use of these data we can fill the gap left by the lack of comprehensive aquifer studies in the region. Furthermore, we can single out individual problematic water points for rehabilitation.

Results

Hotspot analysis

Figure 2 shows the results of the hotspot analysis. Darker spots indicate a higher risk to groundwater. The inset gives more detail. Each of the over 93,000 water points has an individual rating. The spread of the higher-risk areas can be said to be directly related to population. The population is much higher in the central and southern regions of the country than in the north. These areas inherently require a greater number of water points for access to groundwater. This however does not mean the northern areas may not be at risk. Many areas in the north have smaller but equally at-risk water points. Here, pressure from contamination may be more of a driving factor than over-abstraction risk.

It is important to highlight that this risk analysis is confined to within Malawi. Where hotspots are indicated along the border in Malawi, it cannot be assumed that the situation is the same across the border. However, it provides Malawi's government reasons to responsibly notify a neighbour that they share a transboundary aquifer that has been highlighted as at risk for groundwater contamination or over-abstraction. In areas where the groundwater flow direction is from Malawi to a neighbouring country, the risk for that neighbouring country can be deemed just as high as in Malawi. This is because (1) any contamination of the aquifer in Malawi has the potential to travel across the border

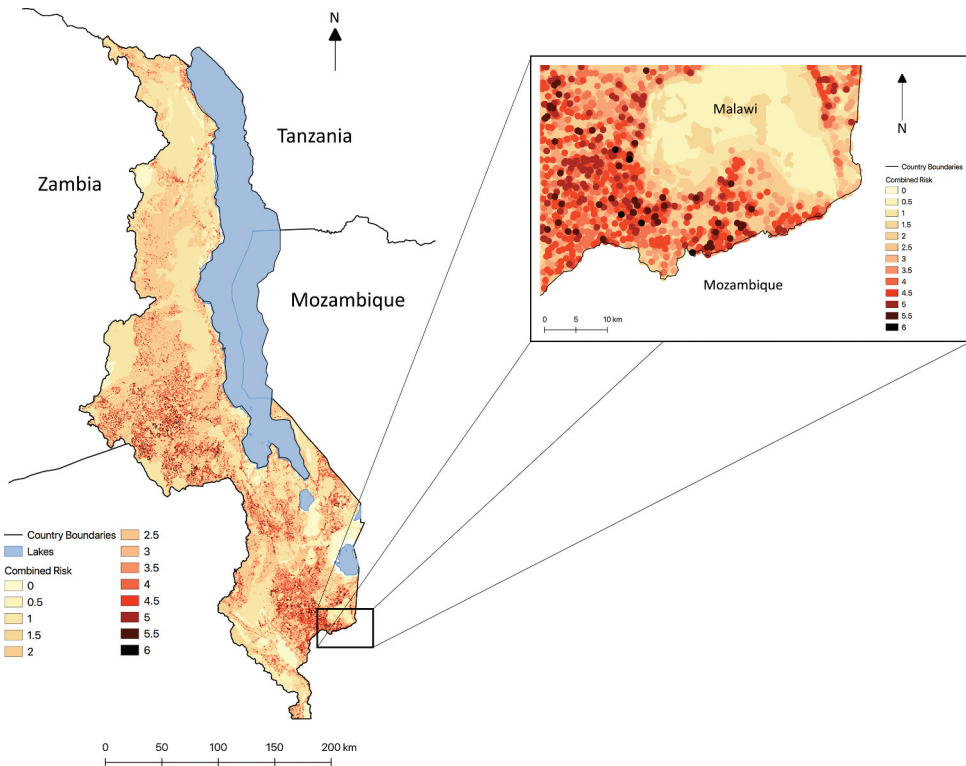


Figure 2. Risk hotspot analysis results.

into the neighbouring country, and (2) over-abstraction from an aquifer in Malawi could change the groundwater flow pattern or even reverse it. These would cause groundwater quality and quantity issues in the neighbouring country.

The hotspot analysis also highlights areas in Malawi where groundwater is not currently being used. Areas lacking water point data indicate that either surface water or a piped supply system, likely from a surface reservoir, is in place. This information could be useful to the government, as these areas could be exploited in the future for greater water availability and thus water security, especially in areas with high-yielding aquifers.

The insert in [Figure 2](#) covers the Mulanje district of Malawi, which borders Mozambique. At this scale, individual water points can be seen. This can help identify the exact location of the water points at the most risk. Isolating these water points and ensuring they are managed effectively could greatly reduce the risk to the overall aquifer.

The next two sections will illustrate which of the 38 previously identified transboundary aquifers ([Figure 1](#)) have potential national and local-scale hotspots of transboundary risk. Transboundary aquifers that do not exhibit any sign of national or local-scale hotspots are dropped from further discussion. Although these transboundary aquifers should continue to be monitored, we deem them not to pose a current transboundary risk.

National-scale hotspots

[Figure 3](#) shows the hotspot map overlaid with selected transboundary aquifers from [Figure 1](#) that have national-scale hotspots, which span the majority of a transboundary aquifer. Just three transboundary aquifers exhibit a national scale of risk. The largest is 37,000 km², and the smallest is 3800 km². Due to the large spread and high density of the water points in these hotspots, they must be considered and dealt with at the national, not the local level.

The national-scale hotspots are all in the central or southern region of Malawi, where the population density is greatest. This emphasizes that as the population rises, the risk to aquifers' water quality and quantity also rises. Also, the transboundary aquifers aligned with these hotspots are all of basement complex lithology, so large populations are relying on low-yielding aquifer types in these areas. Descriptions of the national-scale aquifers are given in Section 1 of the online supplemental material.

Local-scale hotspots

[Figure 4](#) shows the hotspot map overlaid with transboundary aquifers that have local-scale hotspots, which are focused along the border and do not spread further inland into the aquifer. There are 11 of these. Due to their isolated and smaller nature, they can be considered a more local risk and managed as such.

The local-scale hotspots are spread fairly evenly throughout Malawi. They range in size from 230 km² to 8600 km². Their lithology varies from basement complex to colluvial and alluvial superficial deposits. The hotspots in these aquifers are all much more isolated than the national-scale hotspots. There could be multiple reasons for this:

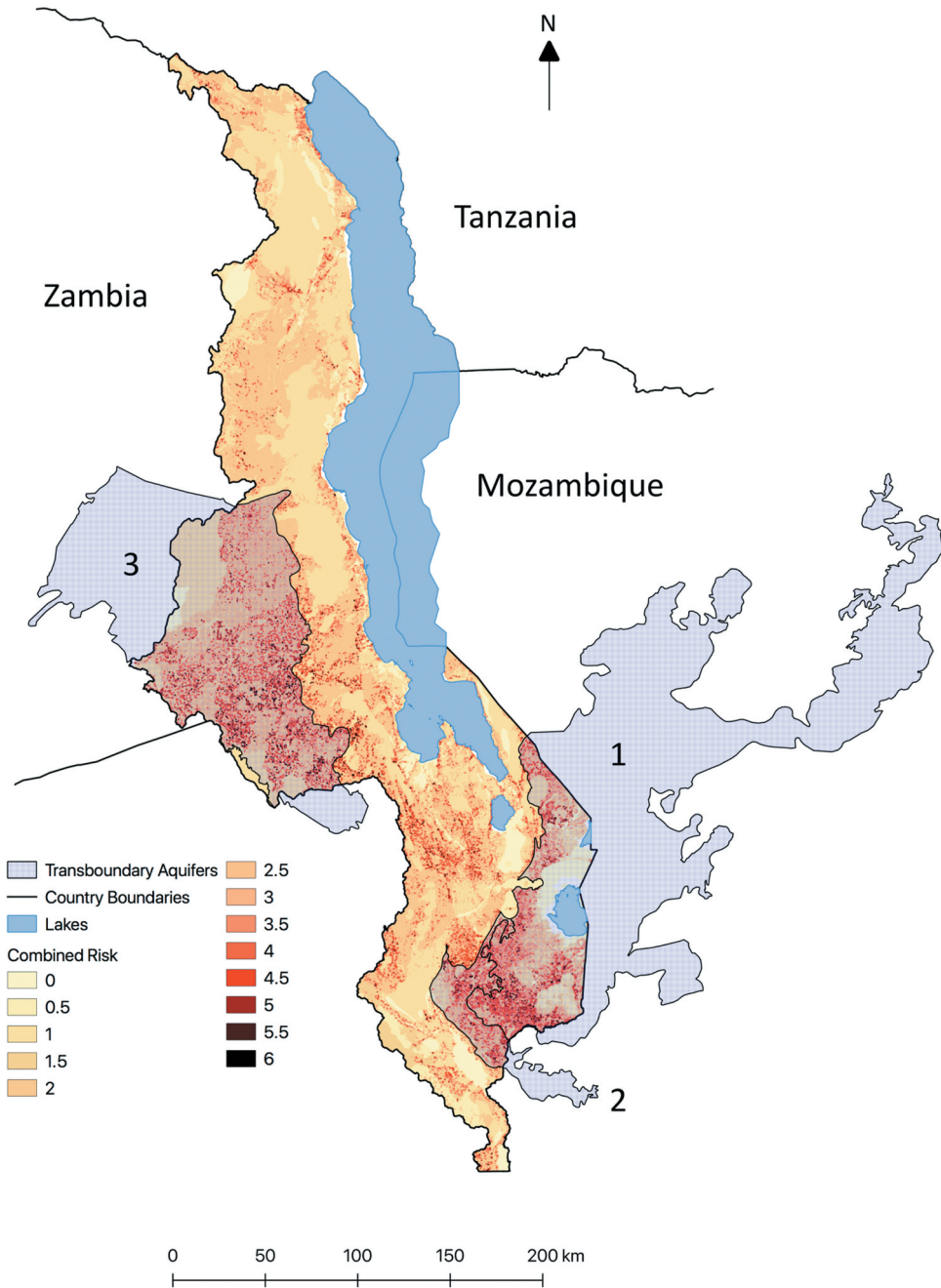


Figure 3. National-scale hotspots and corresponding transboundary aquifers.

these areas tend to be more rural and secluded, with no large populations close to the hotspots; and specific issues relating to particular communities could influence them, such as poor pit latrine location planning, location on a low-yielding aquifer, or a specific land use type, such as agriculture.

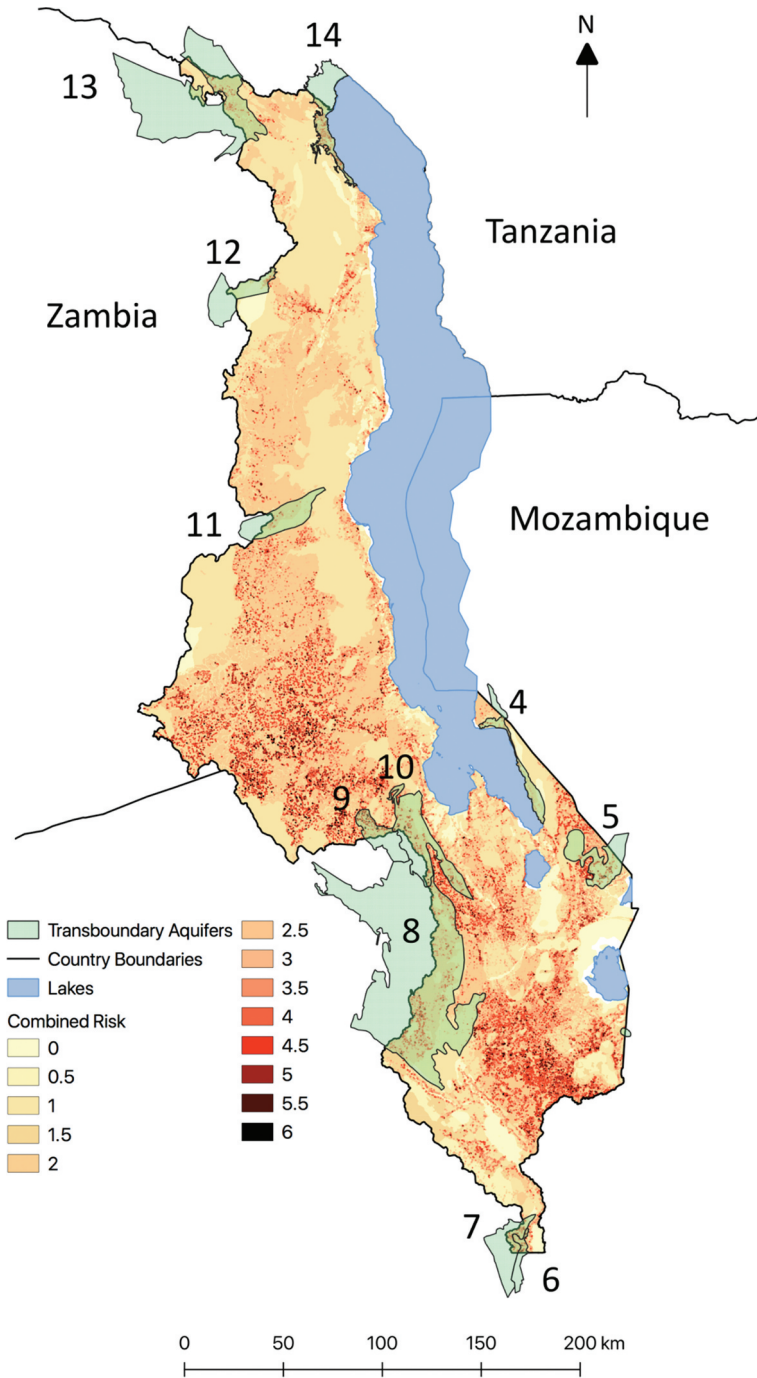


Figure 4. Local-scale hotspots and corresponding transboundary aquifers.

Transboundary responsibility

Of the 14 aquifers identified as exhibiting risk hotspots, only four have groundwater flowing from Malawi into a neighbouring country. The other 10 have groundwater flowing into Malawi from a neighbouring country. Groundwater flow direction can influence transboundary impacts and thus management. Aquifers 2, 6, 7 and 14 are considered high-risk transboundary aquifers with transboundary flow from Malawi to a neighbouring country (see Section 2 of the online supplemental material). The Malawi government must recognize that impacts on these aquifers will affect their downstream neighbours. Ensuring good water quality and sustainable abstraction rates will help prevent negative impacts on bordering countries. Conversely, it is also in Malawi's interest to ensure that the other 10 transboundary aquifers, which flow into Malawi from neighbouring countries, are managed sustainably to prevent any contaminated groundwater from crossing into Malawi's portion of the transboundary aquifer, alongside ensuring that groundwater levels do not fall over time.

Multi-scale management

No two aquifers, including transboundary aquifers, are the same (Eckstein, 2013). Lithology, transmissivity, storage capability, abstraction rates, population dependency and seasonal fluctuations are just some of the factors that may affect how a transboundary aquifer is used. The use of an aquifer should then inform how it is managed (Eckstein, 2013). For example, a small aquifer in a highly productive lithology used by a limited number of people will require a different management strategy from a large aquifer with a low recharge rate used by a large population. Classifying what type of management is required of an aquifer is particularly important in countries like Malawi, where resources and financial reserves are limited. In a transboundary context, it is even more essential to ensure that the selected management type is established in cooperation with neighbouring countries. Available resources should be directed to the aquifers in the most need of management on a case-by-case basis, but there are limited methods currently to identify which aquifers in a country like Malawi should get the highest priority. It is difficult to identify which aquifers may require a specific level of management (e.g., local vs. national) or which currently are not at risk for over-abstraction or contamination and can be left as is.

National-border-based assessments (Fraser et al., 2020) generate data that allow governments to evaluate their transboundary aquifers in detail. Hotspot analysis of these identified transboundary aquifers, as conducted in this study, highlight which aquifers require immediate attention and at what scale. But what management is appropriate for these transboundary aquifers? [Figure 5](#) highlights the relationship between the information generated from different transboundary aquifer assessment types and transboundary management they could inform.

Regional assessments are useful in identifying large transboundary aquifers that may be impacted on a regional scale. For example, the Global Environment Facility's Transboundary Waters Assessment Programme identified 80 transboundary aquifers that are of high importance across south-eastern Africa (ILEC et al., 2016). These aquifers are best managed under intergovernmental organizations, like the river basin

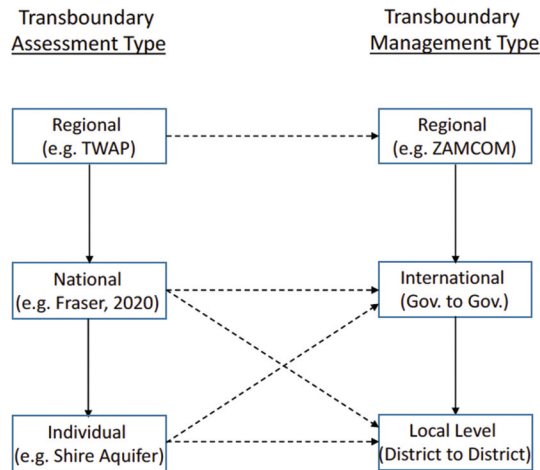


Figure 5. Flow diagram illustrating the relationship between different transboundary aquifer assessments and management types.

organization ZAMCOM, that bring together riparian states to facilitate and promote the sustainable management of water resources in the region, in view of their large scale and regional importance (ZAMCOM, 2019).

On the other hand, national-border-based assessments can inform international (government-to-government) and local (district-to-district) management (Figure 5). The transboundary aquifers in Malawi that have been identified as having national-scale hotspots are good candidates for international management. These aquifers present a significant enough risk at the national level to warrant the government of Malawi to notify and cooperate with its neighbouring-country governments to ensure management of these shared aquifers. This is best done through an international transboundary agreement or an international institutional governance mechanism. International agreements over shared groundwater are however still in their infancy; globally, there are only six transboundary aquifer agreements governing the use and management of shared groundwater (Rivera & Candela, 2018), for only 1% of identified transboundary aquifers worldwide. Each is unique to the aquifer in question. They include the Genevese Aquifer agreement, which governs the management and allocation of water from the aquifer on the French–Swiss border (De Los Cobos, 2018); the Nubian Sandstone and North-Western Sahara Aquifer agreements, which facilitate data sharing between parties (Nubian Sandstone Aquifer System, 2002; SASS, 2002, in Eckstein, 2011) and the Al-Sag/Al-Disi agreement, which created a protected area of 10 km on either side of the border for the fossil (non-recharging) aquifer (Burchi, 2018). Most recently, the UN Draft Articles on the Law of Transboundary Aquifers were developed to provide guidelines for countries wanting to foster agreements over the management of their transboundary aquifers. They cover all aspects of potential transboundary scenarios, including transboundary recharge and fossil aquifers (Sanchez et al., 2016; United Nations, 2008). The draft articles assisted in development of the Guarani Aquifer Agreement, which draws from the draft articles covering equitable and reasonable use, the obligation to

cause no harm, and the exchange of technical data (Sindico et al., 2018; Villar & Ribeiro, 2011). A transboundary agreement over any of the identified nationally at-risk aquifers in Malawi could build on the lessons learnt from these agreements. There are currently very few institutional mechanisms that act to govern the use and management of transboundary aquifers in place of a formal agreement at the international and binational level, particularly in the African context (Fraser et al., 2020). Moving forward, Malawi could look to set up a binational commission to govern the use and management of the three national-scale transboundary hotspots we identified, but this would require a strong mandate and willingness to cooperate from all involved stakeholders, which can take time to develop.

The transboundary aquifers in Malawi that have been identified as having only local-scale hotspots are probably too small to justify a full international agreement or binational commissions. These issues could be addressed locally particularly because Malawi's water regulations are decentralized to the district level (Truslove et al., 2020). This approach has been successful in other countries. Local-scale agreements include the Hueco Bolson Aquifer underlying the cities of El Paso and Juárez on the Mexico–US border (Juárez-El Paso MoU, 1999 in Eckstein, 2011), the Abbotsford–Sumas Aquifer between the US State of Washington and the Canadian province of British Columbia (Abbotsford–Sumas MoA, 1996), and the 1999 Memorandum of Understanding between the Municipal Water and Sanitation Board of the City of Juarez, in Chihuahua, Mexico (Eckstein, 2013). Local-scale management has also been suggested as an alternative to fostering formal agreements along the border between the US and Mexico (Eckstein, 2013). A local agreement could be informal or in the form of a memorandum of understanding, but there is nothing to stop parties creating an official agreement on a smaller scale.

Local-scale management can be advantageous for multiple reasons. Local communities often have the biggest stake in good transboundary management; small changes to a local aquifer can have large impacts on the community that depends on it. Communities are often best informed about local issues. Local communities along the border region are also more likely to have links to individuals, communities or businesses on the other side of the border (Eckstein, 2013). In Malawi, for example, many communities close to the border speak the same language and practice the same religion as their cross-border counterparts, due to precolonial tribal connections (Kaspin, 1997).

There is already evidence of local-scale transboundary cooperation in Malawi. The district of Mulanje, on the south-east border of Malawi, is party to semi-regular meetings with the neighbouring district, Milange, in Mozambique. Representatives from the two districts meet and discuss shared issues such as trade, border control and management of their shared river, the Ruo, which forms the border between the two districts. One could make a case for the addition of transboundary groundwater to this working group's mandate. A local-scale agreement over the use and management of transboundary aquifers in Malawi might include clauses for regular exchange of data, joint monitoring of boreholes, and the inclusion of local stakeholders such as communities and local businesses.

Conclusions and recommendations

This study has identified transboundary aquifers in Malawi that are at risk of over-abstraction or reduced water quality (hotspots). Using fuzzy logic and GIS overlays, we

pinpointed specific areas in the country that may be at transboundary risk. The method provides the Malawi government with a tool to prioritize which transboundary aquifers require management and international agreements. In Malawi, where water management is decentralized, it also gives an opportunity to identify areas where local-scale transboundary management can play an important role in managing cross-border water resources.

The results of this study can inform the Malawi government where to direct resources for transboundary groundwater management. We highlight three transboundary aquifers thought to be at high risk of over-abstraction and contamination and which require consideration for transboundary agreements. Another 11 hotspots on smaller-scale transboundary aquifers could be managed at the local level. A transboundary diagnostic analysis and coherent conceptualization of these transboundary aquifers could improve our understanding of what management practices are needed. This should ideally be done in cooperation with neighbouring local stakeholders and governments.

Notes

1. Readers of the print article can view the figures in colour online at <https://doi.org/10.1080/02508060.2020.1832747>.

Acknowledgments

The authors would like to acknowledge financial support from the Scottish government, through the Climate Justice Fund's Water Futures Programme (research grant HN-CJF-03), and the University of Strathclyde. They would also like to acknowledge their partners in the government of Malawi and BASEflow for their support of this research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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