Identifying transboundary aquifers in need of international resource management in the Southern African Development Community region

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Abstract Transboundary aquifer (TBA) management, in part, seeks to mitigate degradation of groundwater resources caused either by an imbalance of abstraction between countries or by cross-border pollution. Fourteen potential TBAs were identified within a hydrogeological mapping programme based on simple hydrogeological selection criteria for the Southern African Development Community (SADC) region. These have been reassessed against a set of data associated with five categories: (1) groundwater flow and vulnerability (which is perceived as the overarching influence on the activity level of each TBA), (2) knowledge and understanding, (3) governance capability, (4) socio-economic/water-demand factors, and (5) environmental issues. These assessments enable the TBAs to be classified according to their need for cross-border co-operation and management. The study shows that only two of the 14 TBAs have potential to be the cause of tension between neighbouring states, while nine are potentially troublesome and three are unlikely to become problematic even in the future. The classification highlights the need to focus on data gathering to enable improved understanding of the TBAs that could potentially become troublesome in the future due to, for example, change in demographics and climate.

Keywords Transboundary aquifer · Africa · Arid regions · Over abstraction · Groundwater management

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Introduction

A transboundary aquifer (TBA) is a groundwater unit shared by two or more nations. Cross-border impacts within the TBA need to be assessed in order to establish if international co-operation and management of the aquifer system would help towards equitable allocation of the shared resource. An often reported example is the West Bank Mountain Aquifer which is recharged in Palestine with groundwater flowing to spring discharges in neighbouring Israel (Mansour et al. 2012) and is a source of tension (World Bank 2009). In most cases, the management of TBAs and the allocation of resources between neighbouring political units is carried out unilaterally by each state and few are managed collaboratively. One of the few that is jointly managed is the Genevese Aquifer, which is shared by France and Switzerland. In Africa, however, TBAs remain under-exploited and largely unmanaged.

The concept of the TBA grew from the riparian ideal of shared surface-water resources. One of the older formalised shared water-resource schemes is that controlled by the Rhine Commission in Europe, which oversees the equitable allocation of surface water from the Rhine catchment to its various riparian states. TBAs have only recently become recognised in international law (UNESCO 2009) largely because resource managers and policy-makers have so far focused mainly on surface water. There remains an inadequate acknowledgement that water security, be it derived from surface or groundwater reserves, is not only about water but that it should also include climate change, food security, energy security and the international co-operation needed to deliver regional, state, and human security.

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Groundwater management within TBAs remains hindered by inadequate understanding of groundwater systems — ‘out of sight, out of mind’. The difficulties of conceptualising flow in a TBA are exacerbated in the semi-arid and arid regions of sub-Saharan Africa where, although many boreholes have been installed to meet high demand, hydrogeological data are sparse and understanding of aquifer systems remains poor. In these areas, the impact of water abstraction, or cross-boundary pollution due to transfer of groundwater within a shared aquifer from one state to a neighbouring state, will be minimal if the groundwater in storage is small and the recharge potential is modest. Cross-border aquifer management may be unwarranted if demand is low on both sides of the border, and where land is sparsely populated.

Eckstein and Eckstein (2003) defined six types of TBA:

- An unconfined aquifer that is linked hydraulically with a river, both of which flow along an international border (i.e. the river forms the border between two states)
- An unconfined aquifer intersected by an international border and linked hydraulically with a river that is also intersected by the same international border
- An unconfined aquifer that flows across an international border and that is hydraulically linked to a river that flows completely within the territory of one state
- An unconfined aquifer that is completely within the territory of one state but that is linked hydraulically to a river flowing across an international border
- A confined aquifer, unconnected hydraulically with any surface body of water, with a zone of recharge (possibly in an unconfined portion of the aquifer) that traverses an international boundary or that is located completely in another state
- A transboundary aquifer unrelated to any surface body of water and devoid of any recharge

Understanding of a TBA is underpinned by assessment of the hydrogeological system. Data to support such assessments are scarce in many parts of sub-Saharan Africa; even describing the basic geological setting of some TBAs may be difficult. Nevertheless, classification and zoning of the respective aquifers is an essential prerequisite to prioritise management need. Standardised data collection, comparison and harmonisation across borders are proving to be a key challenge. Classification of TBAs provides stakeholders with information necessary for decision-making and allows focus to be made on those TBAs where co-operation and joint international management would promote equitable division of the resource. TBAs can be classified as having the potential to be the cause of tension between neighbouring states, i.e. politically sensitive or politically troublesome, and those unlikely to become problematic even in the future, i.e. in no particularly urgent need of shared management. The stakeholders need to be armed with this classification to know which TBAs are likely to be troublesome and, therefore, in need of management and which are not currently in need of management intervention.

This paper classifies the TBAs identified by IGRAC (2012) and UNESCO (2009) in the Southern African Development Community (SADC) region of sub-Saharan Africa according to their need for and likely responsiveness to management. The paper questions the concept that hydrogeological maps alone are sufficient to remotely identify TBAs, and recommends that a thorough appraisal of groundwater availability and demand should be carried out as part of the designation process. This recommendation is illustrated by ranking the 14 TBAs in the SADC region identified by the Hydrogeological Map of SWECO Int. et al. (2010), between the classes of ‘troublesome’ and ‘unlikely to become troublesome’; the illustration demonstrates that a number of the TBAs in the drier parts of the region are not currently in need of management intervention.

TBAs in sub-Saharan Africa

The importance of groundwater to many rural communities in sub-Saharan Africa cannot be overstated. A cross-border impact on a groundwater resource such as degradation of supply by interception (quantity) or deterioration of water quality, will affect livelihoods and may become the cause of political disquiet. It is, however, also an opportunity to enhance cross-border collaboration regarding data gathering and data sharing, as well as full co-operation over the evaluation of the potential shared resource and its management.

Historically, the first inventory of shared aquifers in Africa was produced at a workshop in Tripoli (Libya) in 2002. Earlier, in 1997 the International Association of Hydrogeologists established the Transboundary Aquifer Resource Management Commission, followed in 2000 by the establishment of the Internationally Shared Aquifer Resources Management (ISARM) initiative (Puri and Aureli 2005). Studies commissioned as a result included the map “Groundwater Resources of the World: Transboundary Aquifer Systems” by Struckmeier and Richts (2008). Since the initiation of the ISARM-Africa project in 2000 more than 40 TBAs have been identified in Africa (IGRAC 2012; UNESCO 2009). However, no account was made of groundwater availability, flow potential or demand so that many of the identified TBAs are neither politically sensitive nor in need of management. Struckmeier and Richts (2008), however, recognise ‘major groundwater basins’, ‘areas with complex hydrogeological structure’ and ‘areas with local and shallow aquifers’. SWECO Int. et al. (2010) used the single criteria of a ‘continuous groundwater unit shared by more than one state’ to identify the 14 TBAs on the regional scale SADC Hydrogeological Map.

Cobbing et al. (2008) focused on the TBAs that border South Africa and concluded:

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> Based on this study of South African transboundary aquifers, it is proposed that the traditional understanding of transboundary groundwater issues as a potential source of conflict be modified. For most of the length of South Africa's border, potential dispute over transboundary groundwater is not a major concern. In general, transboundary aquifers such as the 'Coastal Sedimentary Basin' or the 'Karoo Sedimentary Aquifer' (Struckmeier et al. 2006) are potentially misleading in terms of the level of management required. Given the sparse data on southern African transboundary aquifers and the relatively low levels of technical co-operation between the riparian states, the region would be better served by using transboundary groundwater as a vehicle to improve technical cooperation, data sharing, training and research…

Cobbing et al. (2008) highlight the lack of technical co-operation between states, which is an important issue in SADC. SADC, however, now has an opportunity to provide an umbrella management institution to start to promote co-operation, and TBA monitoring is an important vehicle with which to promote such collaboration. Identification of the more troublesome TBAs will allow targeting of effort. A key outcome must be the promotion of better understanding of the impact of the water abstraction/recharge management processes and of the hydraulic conditions of aquifers common to contiguous borders. A parallel outcome, as Cobbing et al. (2008) underscore, is a widespread need for training and capacity building throughout sub-Saharan Africa.

There are 14 TBAs recognised in the SADC Hydrogeology Map (SWECO Int. et al. 2010; Table 1; Fig. 1). Cobbing et al. (2008) reported that most so-called TBAs that border South Africa are low-yielding aquifers with only small water demand from a low population density so that the risk of over-pumping or pollution is generally low. They concluded that potential dispute over transboundary groundwater is not a major concern but rather an opportunity to improve technical cooperation and data sharing between neighbour states, and for collaborative training and research. They also comment that 'the concept of transboundary groundwater must necessarily include aquifers where little cross-border flow occurs', i.e. that physical groundwater flow is only one issue, equitable sharing of the resource and its sensible management another, and potential over-pumping and pollution is a third key aspect, while attraction of international surface waters into a shared aquifer is a fourth.

The TBAs in sub-Saharan Africa, as along most of the South African borders, involve, almost without exception, low flow volumes with little potential for surface or groundwater-resource degradation across a political border. The most common form of TBA is recently deposited ribbon-like shallow alluvial sand bodies deposited along river courses that act also as political boundaries. In some cases the river loses to groundwater, in others it gains from groundwater baseflow, but the river, international or not, is a low elevation constant head boundary which will not readily allow unconfined groundwater cross-flow beneath it. Nevertheless, there remains a risk that a transboundary groundwater resource that is not managed in a co-operative and holistic way, may be over-exploited in one state to the detriment of a neighbouring state (Godfrey and van Dyk 2002; Jarvis et al. 2005). Similarly, there is a fear that pollutants may migrate across a border to contaminate a neighbour's aquifer (Puri 2001).

Transboundary water-resource management aims to prevent disputes that might otherwise arise from an unmanaged resource. However, Cobbing et al. (2008) argue that where transmissivities are low, the potential for groundwater movement is also low, and the technical resolution of the allocation of the resource may be difficult. Besides, uncertainty regarding water demand trends, impact of over-exploitation on riverine ecology, and the impact of groundwater-resource development in tributary catchments on downstream-shared aquifer resources collectively conspire to complicate the issue.

Classification of the TBAs within the SADC region

The geological and hydrogeological setting of each of the 14 TBAs recognised by SWECO Int. et al. (2010) are reviewed and summarised in Table 1. The data for each TBA were assembled in summary reports (Wellfield and BGS 2011) comprising:

- Geography: location, politics
- Climate: temperature, rainfall
- Morphology and drainage
- Geology: lithostratigraphy, depth of weathering, aquifer units
- Hydrogeology type and permeability: aquifer type, depth to water, borehole yields, specific capacity, transmissivity, groundwater dependent ecosystems
- Demand: demography, land use, industry
- Institutional and governance: understanding, data availability

These data were obtained from various sources including published and unpublished maps, technical papers and reports as well as dialogue with in-country technical experts. For some of the sites, a considerable knowledge base has been gathered while for others little information is available on the precise nature of the aquifers and their relationship to surface waters and other nearby or underlying aquifers (Wellfield and BGS 2011). In some cases, information and data are available for one side of the border but not for the other. Given the complex nature of a TBA, they are not easy to assess according to the volume of groundwater in storage, groundwater flow, abstraction regimes and pollution. It is nevertheless important to identify TBAs in which collaborative resource assessment and management would benefit neighbour states, and those in which management of the resource is likely to be a lower priority despite likely

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Table 1 TBAs in the SADC region of sub-Saharan Africa. Transboundary aquifer number (*column 1*) originates from SWECO Int. et al. (2010)

Transboundary aquifer	Member State	Geology		Hydrogeology		Recharge		Aquifer summary
		Lithology	Depth	Aquifer type	Permeability	Potential recharge	River proximity	
Ruvuma Delta Coastal Sedimentary Basin Aquifer (3)	Tanzania	Alluvium/Sedimentary	Shallow–medium	Unconfined semi-confined	Primary	Medium to high/seasonal	Adjacent to distant	Tertiary to Quaternary age alluvial sands and gravels with fresh groundwater of Ruvuma Delta, overlying Cretaceous-age marlstones with brackish-to-saline water. High-permeability sediments mainly draw water from the Ruvuma River. Little TBA through-flow, flow mainly towards the coast, possible marine saline intrusion
	Mozambique	Alluvium/Sedimentary	Shallow–medium	Unconfined semi-confined	Primary	Medium to high/seasonal	Adjacent to distant	
Congo Delta Coastal Sedimentary Basin Aquifer (4)	DR Congo	Alluvium/Sedimentary	Shallow–medium	Unconfined semi-confined	Primary	High/seasonal	Adjacent to near	Pliocene to Recent age alluvial sands and gravels of the Congo Delta, overlying Cretaceous to Eocene marine sedimentary strata. High-permeability alluvium mainly draws water from the Congo River. Little TBA through-flow, flow mainly towards the coast, possible marine saline intrusion
	Angola	Alluvium/Sedimentary	Shallow–medium	Unconfined semi-confined	Primary	High/seasonal	Near to distant	
Congo/Zambezi Basins Benguela Ridge Watershed Aquifer (5)	DR Congo	Alluvium/weathered sandstone	Shallow–medium	Unconfined semi-confined	Primary/ secondary fractured	Moderate/ periodic	Headwaters along watershed	Tertiary-age Kalahari alluvial and marine sands and gravels, overlying Cretaceous-age sandstones and shales; high-yield porous sediments in Benguela Ridge watershed area between the Congo and Zambezi catchments. Some deep waters are saline. There is some potential for TBA flow especially related to large-scale abstraction for the processing of diamondiferous strata.
	Angola	Alluvium/weathered sandstone	Shallow–medium	Unconfined semi-confined	Primary/ secondary fractured	Moderate/ periodic	Headwaters along watershed	
Tunduru/Maniamba Basin Karoo Sandstone Aquifer (6)	Tanzania	Sedimentary basaltic	Shallow–medium	Unconfined semi-confined	Secondary fractured	Moderate/ periodic	Adjacent to near	The Karoo Sandstones that underlie basalts have moderate yields and are artesian in part. The aquifer has some primary porosity and fractured permeability. The Ruvuma River forms the international boundary between the Tunduru and Maniamba parts of this basin. The prospects for TBA flow are poor
	Mozambique	Sedimentary basaltic	Shallow–medium	Unconfined semi-confined	Secondary fractured	Moderate/ periodic	Adjacent to near	
Middle Zambezi Rift Upper Karoo Aquifer (11)	Zambia	Sedimentary basaltic	Shallow–medium	Semi-confined	Secondary fractured	Low to moderate/ periodic	Adjacent to near	Lower and Upper Karoo sandstones and siltstones underlie basalts within the down-faulted Zambezi Rift graben. The aquifer has some primary porosity and fractured permeability. The Zambezi River forms the international boundary between the upstream Zambian basin and the downstream Zimbabwe basin. The prospects for TBA flow are poor as the main source of groundwater, the river, forms the international boundary
	Zimbabwe	Sedimentary basaltic	Shallow–medium	Semi-confined	Secondary fractured	Low to moderate/ periodic	Adjacent to near	
Shire Valley Alluvial Aquifer (12)	Malawi	Alluvium	Shallow-medium	Unconfined semi-confined	Primary	High/seasonal	Adjacent to near	Tertiary to Quaternary and Recent alluvial sands and gravels overlie Cretaceous age sandstones within the southern continuation of the Nyasa Rift graben. High yields are obtained from the very porous Shire River alluvial sediments. Some large areas with salinised waters do occur
	Mozambique	Alluvium	Shallow–medium	Unconfined semi-confined	Primary	High/seasonal	Adjacent to near	
South West Kalahari/ Karoo Basin Aquifer (13)	Botswana	Continental sediments sandstones	Medium–deep	Confined	Secondary fractured	Low/periodic	Possible watershed	Thick Kalahari Beds sands, calcretes and clays confine productive Lower Karoo sandstones interbedded with mudstones, shales and coals. In Namibia, the Lower Karoo Stampriet Aquifer is a major source of water for domestic and agricultural use. Little development of this aquifer has been made in south-western Botswana or the adjacent part of South Africa. Large parts of these areas have been demarcated as national parks. Over-abstraction in Namibia may have caused a reduction in natural flow into areas of South Africa and Botswana within this aquifer
	Namibia	Continental sediments sandstones	Medium–deep	Confined	Secondary fractured	Low to moderate/ periodic	Possible watershed	
	South Africa	Continental sediments sandstones	Medium deep	Confined	Secondary fractured	Low/ periodic	Possible watershed	

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Zeerust-Ramotswa-Lobatse Dolomite Basin Aquifer (14)	Botswana	Karst limestone	Shallow–medium	Unconfined semi-confined	Secondary karst	High/periodic	Adjacent to distant	The Precambrian Transvaal Cherty Dolomite forms an arcuate karstic aquifer between Zeerust, Ramotswa, Lobatse and Mafokeng. Natural cross border flow and degradation are unlikely as groundwater occurs in a series of isolated basins. There is a minor risk of localised cross-border pollution
	South Africa	Karst limestone	Shallow–medium	Unconfined semi-confined	Secondary karst	High/periodic	Adjacent to distant	
Tuli Karoo Basin Aquifer (16)	Botswana	Alluvium: Karoo sandstones and basalts	Shallow–deep	Unconfined to confined	Primary/ secondary fractured	High to moderate/ periodic	Alluvium along rivers; adjacent to near	The high porosity, high yield, unconfined sand and gravel alluvium sand river aquifers occur along the Shashe, Limpopo and Umzingwane rivers and have been much developed as a sources of irrigation water, to such an extent that dry-season flow along the Limpopo has all but ceased. The underlying Upper Karoo basalts and sandstones with some primary porosity and fractured permeability, form confined to semi-confined aquifers. Although moderate yields have been obtained from these aquifers, brackish to saline waters are occasionally produced. If exploitation of the resource were to increase, its apportionment and management could become significant, but for the moment, the potential for cross-border degradation is small
	South Africa	Alluvium: Karoo sandstones and basalts	Shallow–deep	Unconfined to confined	Primary/ secondary fractured	High to moderate/ periodic	Alluvium along rivers; adjacent to near	
	Zimbabwe	Alluvium: Karoo sandstones and basalts	Shallow–deep	Unconfined to confined	Primary/ secondary fractured	High to moderate/ periodic	Alluvium along rivers; adjacent to near	
Cuvelai Delta and Ethosha Pan Alluvial and Kalahari Sediments Aquifer (20)	Angola	Alluvium	Shallow	Unconfined	Primary	High/periodic	Adjacent - Cuvelai delta	Cuvelai deltaic alluvial sediments underlie the area in Angola. In northern Namibia the deltaic sediments are underlain by Kalahari sediments with calcretes, underlain by Karoo sandstones at depth. Groundwaters of variable quality, fresh to saline in complex multi-layered aquifer. The viability of this aquifer system in Namibia is dependent upon seasonal cross-border flow
	Namibia	Alluvium, calcretes and sandstones	Shallow–medium	Unconfined semi-confined	Primary to secondary karst	High/periodic	Adjacent to near	
Coastal Tertiary to Recent Sedimentary Basin Aquifer (21)	Mozambique	Alluvium/sedimentary	Shallow–medium	Unconfined semi-confined	Primary	High/seasonal	Adjacent to distant	Tertiary to Quaternary-age alluvial deltaic sands and gravels and dune sands overlying Cretaceous-age sedimentary strata. High-permeability sediments obtain water from local rivers and rainfall. Little TBA through-flow, flow mainly towards the coast, possible marine saline intrusion
	South Africa	Alluvium/sedimentary	Shallow–medium	Unconfined semi-confined	Primary	High/seasonal	Adjacent to distant	
Lower Congo Precambrian Dolomite Aquifer (22)	DR Congo	Karst limestone	Shallow–medium	Unconfined semi-confined	Secondary karst	High/seasonal	Adjacent to distant	The Congo River flows across the outcrop of the Precambrian age Schisto-Calcaire Dolomites via a series of cataracts. This karst weathered dolomite aquifer receives recharge from the river within DR Congo. Away from the river in Angola the dominant direction of flow is towards the river
	Angola	Karst limestone	Shallow–medium	Unconfined semi-confined	Secondary karst	High/seasonal	Near to distant	
Sands and gravels of weathered Precambrian Basement Complex Aquifer (23)	Malawi	Alluvium/weathered basement	Shallow–medium	Unconfined semi-confined	Primary/ secondary fractured	Moderate/ periodic	Headwaters along watershed	Quaternary palaeo-fluvial sands and gravels deposited in dendritic dambo channels developed on the 'African Surface', an ancient late Cretaceous–early Miocene peneplain. These with the underlying weathered crystalline basement form a complex low to medium permeability aquifer within the plateau watershed area between eastern Zambia and western Malawi. The low regional hydraulic gradients, <0.005 m/km, reflect the flat surface topography. There is some potential for cross-border flow to take place
	Zambia	Alluvium/weathered basement	Shallow–medium	Unconfined semi-confined	Primary/ secondary fractured	Moderate/ periodic	Headwaters along watershed	

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Table 1 (continued)

Transboundary aquifer	Member State	Geology		Hydrogeology		Recharge		Aquifer summary
		Lithology	Depth	Aquifer type	Permeability	Potential recharge	River proximity	
Eastern Kalahari Karoo Basin Aquifer (24)	Botswana	Karoo sandstones and basalts	Medium–deep	Confined	Some primary/ mainly secondary fractured	Moderate/ periodic	Headwaters along watershed	Upper Karoo sandstones partially covered by basaltic volcanics with some primary porosity and fractured permeability, form confined to semi-confined aquifers. The aquifer is located on the plateau-like watershed between Zambezi to the north and Nata River to the west. Here, the Karoo aquifer is shared across the border with potential for cross border flow, degradation and even for one side of the border to pollute the other
	Zimbabwe	Karoo sandstones and basalts	Medium–deep	Confined	Some primary/ mainly secondary fractured	Moderate/ periodic	Headwaters along watershed	

future temporal changes which may include demographic, land use, climate variability and institutional change.

Ultimately, the sustainability of abstraction must be judged on recognition of potential or real impacts on abstraction sustainability and on groundwater-dependent ecosystems for which prior dialogue between states is essential. Ecological impact is difficult to visualise, but a graphic example is a freshwater coastal aquifer in state X where date palms support livelihoods, but which is derogated by groundwater abstraction inland in state Y, which supports intensive groundwater-fed irrigation. Demand in state X is small whereas in state Y it is large. However, the reduction in the groundwater level in coastal state X created by excessive pumping in state Y causes sea-water intrusion to occur, which kills the date palms and destroys local livelihoods.

The TBAs in the SADC region of sub-Saharan Africa are classified according to hydrogeological conditions and other related factors. Aquifer type, aquifer potential, groundwater demand and environmental issues such as sustainability and connectivity with surface waters are important, but socio-economic factors and institutional elements, including the will to co-operate, also need to be considered. The five adopted categories are:

A. *Groundwater flow and vulnerability/susceptibility* including: natural flow, induced flow and aquifer vulnerability—collectively the physical and chemical attributes of the shared aquifer which control its ability to be troublesome and in need of international management
B. *Groundwater knowledge and understanding* including: groundwater quantity, groundwater quality and aquifer vulnerability—collectively the degree of understanding of the hydraulic performance of the aquifer; the more known about an aquifer the better it can be managed and the less troublesome it is
C. *Governance capability* including: groundwater management, knowledge and monitoring—collectively the ability to manage; the greater the ability the less troublesome it is
D. *Socio-economic/water-demand capability* including: demographics, land use and industrial capacity—collectively the anthropogenic stresses applied to the aquifer; the lower the stresses the less troublesome it is
E. *Environmental issues* including: hydrology, sustainability and climate—collectively the natural constraints on the aquifer; the lower the constraints the less troublesome it is

The information presented in Table 1, which is the source data for category A in the aforementioned list, mirrors similar tables that were prepared for categories B to F. Each category was divided into six critical subcategories (Table 2), for example in Table 1 they are: geology (lithology and its depth); hydrogeology (aquifer type and permeability); and recharge (potential recharge and proximity to surface water). These can all be reduced by a process of ranking and scoring such that the potential

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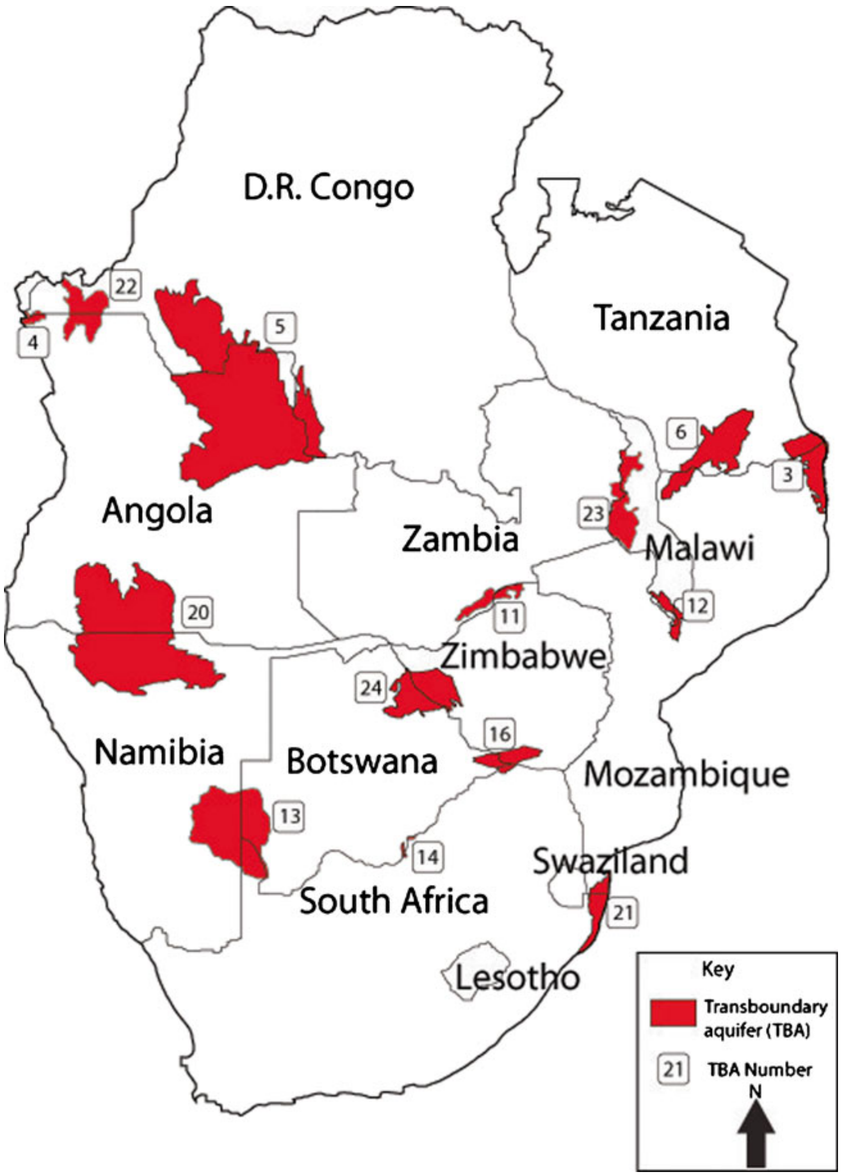

Fig. 1 Transboundary aquifers (TBAs) identified by IGRAC (2012) and as previously mapped and modified by SWECO Int. et al. (2010)

troublesomeness of each sub-category for each component national part of each TBA can be identified as a defensible although semi-quantifiable set of scores: low (1), medium (2) and high (3) TBA troublesome potential. A 'troublesome potential score' of 1 is awarded in a situation which is not in any way a cause for concern, whereas a score of 3 reflects potential troublesomeness of the TBA. Using the six sub-categories, the troublesome potential scores are added together to provide a score for each category out of a possible 18 (Table 3).

Table 2 Categories and their respective six sub-categories

Category	Sub-category					
	1. Lithology	2. Lithology depth	3. Aquifer type	4. Permeability	5. Potential recharge	6. River proximity
A. Groundwater flow and vulnerability	Lithology	Lithology depth	Aquifer type	Aquifer permeability	Recharge potential	Connectivity with surface water
B. Groundwater knowledge and understanding	Groundwater quantity data	Groundwater quantity understanding	Groundwater quality data	Groundwater quality understanding	Groundwater vulnerability data	Groundwater vulnerability understanding
C. Governance capability	Management of groundwater	Management other	Groundwater knowledge	Knowledge, other	Monitoring groundwater	Monitoring, other
D. Socio-economic and water demand	Demographics	Water source reliability	Land use, irrigation	Land use, livestock	Industry	Mining
E. Environmental issues	Surface and groundwater interaction	International river	Groundwater sustainability	Ecological sustainability	Drought risk	Flood risk

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Table 3 Transboundary aquifer (TBA) ranking for the SADC region of sub-Saharan Africa

Transboundary aquifer	TBA No.	Country	Category					Total ranking score	Ranking class
			A	B	C	D	E		
Ravuma Delta Coastal Sedimentary Basin Aquifer	3	Tanzania	8	6	6	11	15	304	b
		Mozambique	6	10	7	11	15	258	
Congo Delta Coastal Sedimentary Basin Aquifer	4	DR Congo	6	6	6	9	13	204	b
		Angola	8	6	6	10	13	280	
Congo/Zambezi Basins Benguela Ridge Watershed Aquifer	5	DR Congo	6	6	6	9	9	90	c
		Angola	6	6	6	9	9	90	
Tunduru/Maniamba Basin Karoo Sandstone Aquifer	6	Tanzania	6	9	6	9	13	222	b
		Mozambique	6	9	7	8	13	222	
Middle Zambezi Rift Upper Karoo Aquifer	11	Zambia	6	16	14	9	11	300	b
		Zimbabwe	6	16	12	6	11	270	
Shire Valley Alluvial Aquifer	12	Malawi	8	12	10	10	14	368	b
		Mozambique	6	9	7	10	14	240	
South West Kalahari/Karoo Basin Aquifer	13	Botswana	8	18	12	8	9	376	b
		Namibia	10	18	16	12	10	560	
		South Africa	8	18	12	6	9	360	
Zeerust-Ramotswa-Lobatse Dolomite Basin Aquifer	14	Botswana	10	18	15	13	9	550	b
		South Africa	8	18	13	9	9	392	
Tuli Karoo Basin Aquifer	16	Botswana	8	18	16	10	12	448	a
		South Africa	8	18	18	14	12	496	
		Zimbabwe	8	16	10	12	12	400	
Cuvelai Delta and Ethosha Pan Alluvial and Kalahari Sedimentary Aquifer	20	Angola	10	6	8	8	13	350	b
		Namibia	10	16	16	12	13	570	
Coastal Tertiary to Recent Sedimentary Basin Aquifer	21	Mozambique	6	8	7	8	10	198	c
		South Africa	6	14	9	9	10	252	
Lower Congo Precambrian Dolomite Aquifer	22	DR Congo	6	6	6	7	12	186	c
		Angola	8	6	6	7	12	248	
Sands and gravels of weathered Precambrian Basement Complex Aquifer	23	Malawi	8	14	10	10	11	360	b
		Zambia	8	14	11	10	11	368	
Eastern Kalahari Karoo Basin Aquifer	24	Botswana	10	18	13	10	9	500	a
		Zimbabwe	10	18	12	12	9	510	

a troublesome; *b* potentially troublesome; *c* unlikely to become troublesome

In order to rank the activity of the 14 TBAs, the category scores can be amalgamated either numerically or graphically. Review of sub-category score amalgamation procedures accepted in hydrogeology, for example the DRASTIC vulnerability procedure (Aller et al. 1987), revealed a preference for numerical amalgamation with score weighting. Consequently an algorithm was devised to bring the five category scores into a single score for each line of each table that best reflected the overall collective TBA ability to be troublesome. The problem is how to derive a perceived best or realistic single weighting for each individual category score set. The selection of an appropriate algorithm to conjoin the scores from the five data categories involved a process of trial and error to achieve a meaningful best possible ranking of the likely troublesomeness of each TBA according to best available prior knowledge.

The objective of the algorithm design was to minimise the weighting to produce a simple, but robust, method. The algorithm has been based on two premises: that the key influence on TBA troublesomeness must be hydrogeology, and that the respective emphases of the remaining four categories are uncertain although likely to be similar, from one to another. The respective hydrogeological components of cross-border impact are:

- The ability of an aquifer to transmit water across an international border
- The ability of an aquifer to interact with surface water with international riparian ownership
- The ability of an aquifer to transmit an impact, which could be an environmental impact, across a border

While greatest emphasis should be given in the algorithm to these hydrogeological elements, it is difficult to weight the five component categories defensibly: is knowledge and understanding more important than governance or socio-economic elements or are environmental considerations paramount? Furthermore, increased knowledge and understanding may reflect higher abstraction and competition for resource thus providing an element of double accounting. These four categories are, therefore, each given an equal weighting of one. Originally it was believed that the sum of these four categories, i.e. categories B to E, added to a weighted score for category A (basic components of hydrogeology), would provide a best meaningful overall ranking index. However, results did not reflect perceived troublesome potential for some of the better understood TBAs and it was only when the category A score was multiplied by the sum of the scores from categories B to E that a sensible ranked order emerged. This new algorithm (category A score multiplied

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by sum of scores from categories B to E) also overcame the need to provide a weight for the category A score—a weight which could only be an arbitrary and unjustifiable number within an ill-defined range.

Using the scores and the algorithm, the TBAs were ranked; three classes of TBA were identified (Table 3) that are defined as:

1. Troublesome (a): in which some form of international collaboration in monitoring, management and apportionment are needed now in order to avoid confrontation in the future should demographics, land use or climate change
2. Potentially troublesome (b): in which there is potential for transboundary degradation of some form or another, although it does not currently require international collaboration, i.e. the potential for degradation is small and is unlikely to impact communities either side of the border
3. Unlikely to become troublesome (c): in which there is no apparent potential for cross border degradation or any impact from either human activities or natural phenomenon

Uncertainties arise over classification of the numerous data-scarce TBAs in the SADC region of sub-Saharan Africa. Where full classification is not robust the TBA is upgraded to the next more troublesome class in order to ensure that investigation is pursued to provide a more robust categorisation in the future; available information for each TBA is detailed in Wellfield and BGS (2011).

Two aquifers emerge as the most likely troublesome of the 14 TBAs in the SADC region—TBA 16, the Tuli Karoo Basin shared by Botswana, South Africa and Zimbabwe, and TBA 24, the Eastern Kalahari Karoo Basin Aquifer shared by Botswana and Zimbabwe. There are three TBAs that are unlikely to become troublesome: TBA 5, the Congo/Zambesi Basins Benguela Ridge Watershed Aquifer shared by DR Congo and Angola; TBA 21, the Coastal Tertiary to Recent Sedimentary Basin Aquifer shared by Mozambique and South Africa; and TBA 22, the Lower Congo Precambrian Dolomite Aquifer shared by DR Congo and Angola. The remaining nine TBAs are classed as potentially troublesome of which the most troublesome ones are: TBA 13, the South West Kalahari/Karoo Basin Aquifer shared by Botswana, Namibia and South Africa; TBA 14, the Zeerust-Ramotswa-Lobatse Dolomite Basin Aquifer shared by Botswana and South Africa; and TBA 20, the Cuevelai Delta and Ethosha Pan Alluvial and Kalahari Sediments TBA shared by Angola and Namibia.

The geographic setting of the two more troublesome TBAs is significant. Both have a semi-arid climate, with low surface runoff and high moisture deficits. The Tuli Karoo Basin lies at the confluence of the Shashe and Limpopo rivers, while the Eastern Kalahari Karoo Basin is situated between the Nata and Zambezi rivers. In both, cross-border flow can occur in the Karoo strata towards centres of abstraction, which may induce cross-border flow.

Conclusion

Fourteen TBAs are identified on the SADC Hydrogeological Map (SWECO Int. et al. 2010). These were selected because the aquifer unit crossed an international border or because an aquifer unit is in hydraulic contact with an international surface-water course. Consideration was not given to water availability or scarcity, demand, or whether the transboundary element of flow was groundwater or surface water. The need to rank the 14 TBAs in order of their likely troublesomeness stems from the need to focus investigatory resources on those TBAs in need of co-operative cross-border management. A key issue was establishing a methodology that embraced all the diverse influences on a TBA yet provided an overall justifiable and defensible index for the basis of ranking.

Assessment of the degree to which the 14 so-called 'troublesome' TBAs are indeed troublesome has been carried out using five data sets (categories), of which the first, groundwater flow and vulnerability, is perceived as the over-arching influence on the activity level of each TBA. The other data sets are: groundwater knowledge and understanding; governance capability; socio-economic/ water demand; and environmental. Each category has been scored for each country that shares each TBA according to the likelihood of it becoming troublesome due to cross-border derogation. A maximum of 18 points could be awarded in each category. These are amalgamated by multiplying the sum of scores for categories B + C + D + E by the hydrogeological score (category A), to give a total ranking score for each member state at each TBA (Table 3). Whilst it is acknowledged that this algorithm is not the only approach that could be made, trial and error application of other algorithms did not provide a set of scores that better fitted the overall hydrogeological setting of each TBA. The assessment is a semi-quantitative assessment but nevertheless, an assessment that is defensible.

The assessment concludes that there are only two currently troublesome TBAs in the region that would benefit from collaborative inter-state management. These are the Tuli Karoo Basin Aquifer, shared between Botswana, South Africa and Zimbabwe, and the Eastern Kalahari Karoo Basin Aquifer, shared between Botswana and Zimbabwe. Of the remainder, nine are classed as potentially troublesome (of which six as less potentially troublesome), and three as unlikely to become troublesome.

It is recognised that the classification of the TBAs will need revision as knowledge and understanding through monitoring and measurement progress. It is likely also that the classification scoring system will need modification as understanding increases. In the meantime, the real value of the classification is that it can be used as the basis on which to prioritise co-operative data gathering and assessment activities to underpin collaborative management of the available resources. Those in the top two ranking classes, troublesome and potentially troublesome, are priority targets for monitoring, while those TBAs that

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are less potentially troublesome and unlikely to become troublesome can receive attention at a later stage as resources become available.

The potential benefits of monitoring the troublesome and potentially troublesome TBAs derive from the concept of inter-state sharing and dialogue. Not only will knowledge of the aquifer systems be enhanced but so too will the technical capabilities of neighbouring states that are required to discuss the management of their shared aquifer units. This is critically important in those areas of SADC that are less well endowed with water resources, but where demand is nevertheless significant. It is only through monitoring and measurement that sufficient knowledge and understanding can be attained for neighbouring states to manage jointly the resources they have. Although some TBAs currently appear to offer no threat to their stakeholders, changing climate may require them to be reclassified once climate-change-scenario predictions become more robust. In the meantime this classification of TBAs in the SADC Region of sub-Saharan Africa is the best currently achievable.

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References

Aller L, Bennett T, Lehr JH, Petty RJ, Hackett G (1987) DRASTIC: a standardised system for evaluating groundwater pollution potential using hydrogeologic settings. US EPA report 600/2-87-035, US EPA, Washington, DC

Cobbing JE, Hobbs PJ, Meyer R, Davies J (2008) A critical overview of transboundary aquifers shared by South Africa. Hydrogeol J 16:1207–1214

Eckstein G, Eckstein Y (2003) A hydrogeological approach to transboundary ground water resources and international law. Am Univ Int Law Rev 19:201–258

Godfrey L, van Dyk G (2002) Reserve determination for the Pomfret-Vergelegen dolomitic aquifer, North West Province, part of catchments D41C, D, E and F. CSIR report ENV-P-C 2002-031, CSIR, Pretoria, South Africa

IGRAC (2012) Transboundary aquifers of the world, 1: 50 000 000, update 2012. IGRAC, Delft, The Netherlands

Jarvis T, Giordano M, Puri S, Matsumoto K, Wolf A (2005) International borders, groundwater flow, and hydroschizophrenia. Ground Water 43:764–770

Mansour MM, Peach DW, Hughes AG, Robins NS (2012) Tension over equitable allocation of water: estimating renewable groundwater resources beneath the West Bank and Israel. In: Rose EPF, Mather JD (eds) Military aspects of hydrogeology. Geol Soc Lond Spec Publ 362: 355–361

Puri S (ed) (2001) Internationally shared (transboundary) aquifer resources management: their significance and sustainable management. IHP-VI Series on Groundwater 1, UNESCO, Paris

Puri S, Aureli A (2005) Transboundary aquifers: a global program to assess, evaluate and develop policy. Ground Water 43:661–668

Struckmeier WF, Richts A (eds) (2008) WHYMAP and the world map of transboundary aquifer systems at the scale of 1:50 000 000. (revised), DIE, Hannover, Germany

Struckmeier WF, Gilbrich WH, Gun Jvd, Maurer T, Puri S, Richts A, Winter P, Zaepke M (2006) WHYMAP and the world map of transboundary aquifer systems 1: 50 000 000. Special edition for the Fourth World Water Forum, Mexico City, March 2006. BGR, Hannover and UNESCO, Paris

SWECO International, Water Geosciences Consulting, Council for Geosciences and Water Resources Consultants (2010) Explanatory Brochure for the Southern African Development Community (SADC) hydrogeological map and atlas. Technical Assistance to the Southern Africa Development Community (SADC) - SADC Hydrogeological Mapping Project, SWECO, Stockholm

UNESCO (2009) Transboundary aquifers, managing a vital resource: the UNILC draft articles on the law of transboundary aquifers. UNESCO, Paris

Wellfield, BGS (2011) Groundwater and Drought Management Project: regional groundwater monitoring network. Transboundary aquifers report, July 2011. www.sadcgwarchive.net. Accessed July 2012

World Bank (2009) West Bank and Gaza: assessment of restrictions on Palestinian water sector development. World Bank Middle East and North Africa Region Sustainable Development Sector Note, April 2009. http://www.irc.nl/url/32408. Accessed June 2012

 DOI 10.1007/s10040-012-0903-x