ARTICLE IN PRESS

Journal of Hydrology: Regional Studies xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Transboundary aquifers of Africa: Review of the current state of knowledge and progress towards sustainable development and management

Geert-Jan Nijsten[a,*], Greg Christelis[b], Karen G. Villholth[c], Eberhard Braune[d], Cheikh Bécaye Gaye[e]

[a] International Groundwater Resources Assessment Centre (IGRAC), Westvest 7, 2611AX, Delft, The Netherlands
[b] CHR Water Consultants, PO Box 21850, Windhoek, 9000, Namibia
[c] International Water Management Institute (IWMI), Private Bag X813, Silverton, 0127, Pretoria, South Africa
[d] UNESCO Chair in Hydrogeology, University of the Western Cape, Bellville 7535, South Africa
[e] Department of Geology, Faculty of Sciences and Techniques, Université Cheikh Anta Diop, PO Box 5030, Senegal

A R T I C L E I N F O

Keywords:
Transboundary aquifers
Africa
Assessment
Governance
Indicators

A B S T R A C T

Study region: Transboundary aquifers (TBAs) of Africa.
Study focus: Review of work on TBAs in Africa, including an overview of assessments and management efforts that have taken place over the last half century.
New hydrological insights: Seventy-two TBAs have been mapped in Africa. They underlie 40% of the continent, where 33% of the population lives, often in arid or semi-arid regions. TBA inventories have progressed since 2000 and remain work in progress. Despite their importance only eleven TBAs have been subjected to more detailed studies. Cooperation has been formalised for seven TBAs. Most of these TBAs are in North Africa and the Sahel. The recent global Transboundary Waters Assessment Programme compiled information at the national level to describe TBAs in terms of key indicators related to the water resource, socio-economic, and legal and institutional conditions. Availability of data at national level is low, hampering regional assessment. Comparing indicators, from questionnaire surveys, with those from a global water-use model showed variable levels of agreement, calling for further research. Reports on agreements scoping TBA management, indicate that this may be dealt with within international river/lake agreements, but reported inconsistencies between TBA sharing countries also indicate that implementation is limited. Increasing awareness and support to joint TBA management is noticeable amongst international organisations. However, such cooperation requires long-term commitment to produce impacts at the local level.

Abbreviations: AMCOW, African Ministers' Council on Water; ANBO, African Network of Basin Organisations; FAO, Food and Agriculture Organization of the United Nations; GEF, Global Environment Facility; IAH, International Association of Hydrogeologists; IGRAC, International Groundwater Resources Assessment Centre; ISARM, Internationally Shared Aquifer Resource Management; IAEA, International Atomic Energy Agency; IWMI, International Water Management Institute; IWMR, integrated water resources management; Joint authority, Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System; NSAS, Nubian Sandstone Aquifer System; NWSAS, North Western Sahara Aquifer System; ORASECOM, Orange-Senqu River Commission; OSS, Sahara and Sahel Observatory (Observatoire du Sahara et du Sahel); REC, Regional Economic Community; SADC, Southern African Development Community; SAP, Strategic Action Plan; TBA, transboundary aquifer; TWAP-Groundwater, Transboundary Waters Assessment Programme; WMO, World Meteorological Organization of the United Nations; UNESCO, United Nations Educational, Scientific and Cultural Organization; UNESCO-IHP, United Nations Educational, Scientific and Cultural Organization – International Hydrological Programme; UNDP, United Nations Development Programme

* Corresponding author at: International Groundwater Resources Assessment Centre (IGRAC), Westvest 7, 2611AX, Delft, The Netherlands.
E-mail addresses: geert-jan.nijsten@un-igrac.org (G.-J. Nijsten), gregchristelis@gmail.com (G. Christelis), k.villholth@cgiar.org (K.G. Villholth), ebraune123uwc@gmail.com (E. Braune), cheikhbecayegaye@gmail.com (C.B. Gaye).

https://doi.org/10.1016/j.ejrh.2018.03.004
Received 23 October 2017; Received in revised form 12 February 2018; Accepted 20 March 2018
2214-5818/

Please cite this article as: NIJSTEN, G.-J., Journal of Hydrology: Regional Studies (2018), https://doi.org/10.1016/j.ejrh.2018.03.004

1. Introduction

Groundwater is an important source of supply for basic human needs and development. As a perennial source of water, it provides a buffer in times of drought that can be developed for local use at relatively low cost (Masiyandima and Giordano, 2007). In many parts of Africa, groundwater is the only reliable source of water. Up to 75% of the population of Africa uses groundwater as the main drinking water source (UNECA et al., 2000), and groundwater is important for rural livelihoods, livestock rearing and urban water supply (Villholth, 2013; Foster et al., 2008). As pressures on groundwater resources increase with economic development, population growth and climate change, it is increasingly important to understand the potential and management practices of transboundary aquifer resources. Cooperation for the development and management of transboundary aquifer (TBA) resources started in the 1970s in Northern Africa. Presently, seventy-two TBAs have been identified on mainland Africa (IGRAC and UNESCO-IHP, 2015a). The island states of Africa have no TBAs. Of the forty-seven mainland African countries, only Sierra Leone and Equatorial Guinea have no known TBAs. TBAs underlie 40% of the continent, and 33% of the population (381 million) live on TBAs.[1] By combining maps of aquifer storage and yield, produced by BGS et al. (2017), and the TBAs map, it appears that most of TBAs are in areas of high storage and higher yielding aquifers (Fig. 1). The groundwater stored within these TBAs is thus of importance for the development of Africa. Yet after nearly half a century of TBA activities in Africa only eleven TBAs have been studied in detail in an international context (Table A1 in Appendix A).

TBAs may be subject to conflicts of interests because of unequal resource partitioning and different management capacities within the social, economic and environmental contexts of sharing countries. Yet, TBA cooperation provides opportunity for cross-border dialogue and data sharing for better evaluation of the shared resource and more equitable and sustainable use of those resources (Braune and Christelis, 2014). Nonetheless, only seven aquifers are subject to specific agreements on joint research, monitoring or governance (Table A1 in Appendix A).

This paper aims to describe the current state of the TBA resources in Africa, and progress in their management and governance. Starting with a brief history of early international initiatives on TBAs, the study describes developments in mapping, assessment and monitoring of TBA's, and provides an overview of the progress in terms of management and governance of these potentially important shared resources. The paper concludes with a discussion, presenting priorities contributing to the sustainable management and development of transboundary groundwater resources in Africa.

2. Method

This research combines insights from literature on TBAs in Africa and experiences from ongoing studies, with results from the groundwater component of the Transboundary Waters Assessment Programme (TWAP-Groundwater). TWAP-Groundwater was a worldwide indicator-based assessment of 199 TBAs, also including 64 of the 72 TBAs in Africa (UNESCO-IHP and UNEP, 2016). Ten core and ten additional indicators were defined in thematic clusters based on groundwater quantity, groundwater quality, socio-economic, and governance-related factors. The indicators aim to capture the current state and projected trends of transboundary aquifers, allow global or regional comparisons, and make it possible to monitor the effectiveness of management interventions through repeated assessments (UNESCO-IHP et al., 2012). Indicator values were derived from the results of a questionnaire survey and from regional workshops, both involving experts from the TBA countries. In parallel, six of the core and three of the additional indicators (related to e.g. recharge, groundwater development stress and population) were calculated using the global water use model, WaterGAP. This enabled assessment of projections for 2030 and 2050 for particular indicators (Riedel and Döll, 2015).

UNESCO-IHP and UNEP (2016) presented overviews and conclusions at the global scale, but did not discuss specific regions in depth. Data from TWAP-Groundwater are available via an on-line data and information portal (IGRAC and UNESCO-IHP, 2016). The data for Africa are analysed, in combination with results from the literature survey to compile an overview of the state of transboundary groundwater resources in Africa in terms of groundwater resource quantity and quality, the socio-economic importance and their management and governance. Three case study reports are included to illustrate different levels of maturity in TBA research and cooperation.

3. Early history of TBA works in Africa

Due to their strategic importance in semi-arid and arid countries, North African states started studying their TBAs − especially the Nubian Sandstone Aquifer System (NSAS − AF63), and the North Western Sahara Aquifer System (NWSAS − AF69) − relatively early in the 1970's. Cooperation agreements were established in 1992 for NSAS (Quadri, 2017) and in 1997 for NWSAS (AbuZeid et al., 2015). Studies of the NWSAS and NSAS were led by the Sahara and Sahel Observatory (OSS) and the International Atomic Energy Agency (IAEA).

Africa wide TBA studies began around 2000 following concerns over the lack of systematic assessment and governance of transboundary groundwater by member states of UNESCO and WMO. The 'Regional Aquifer Systems in Arid Zones' conference held in Tripoli in 1999 established the concept of regional aquifers. This conference was instrumental in shaping the International Initiative on Shared Aquifers launched by UNESCO, FAO and IAH in 2000. This later became the UNESCO-led Internationally Shared Aquifer Resource Management (ISARM) programme (UNESCO et al., 2000; UNESCO-IHP, 2009). The African Ministers' Council on

[1] Calculations for 2015, based on data from (CIESIN and CIAT, 2005; FAO, 2014; IGRAC and UNESCO-IHP, 2015a; UNDESA, 2017).

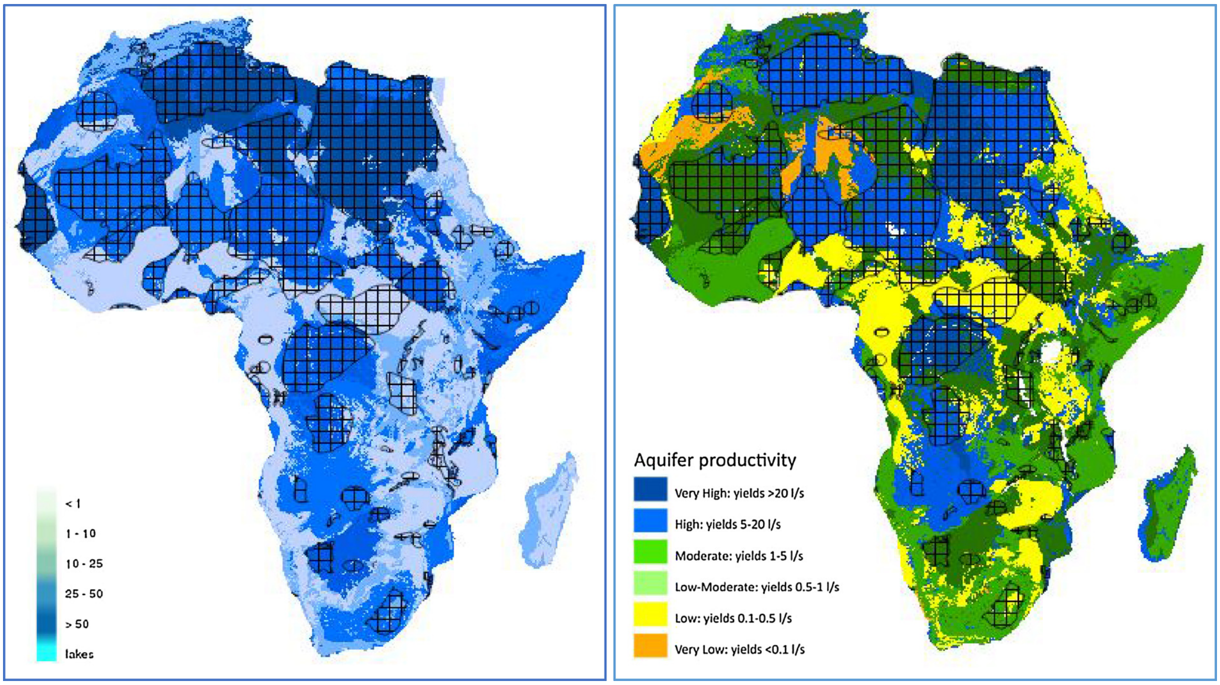

Fig. 1. Map of Transboundary Aquifers in Africa combined with aquifer storage [m] (left) and aquifer yields [l/s] (right). Sources: Transboundary aquifers: (IGRAC and UNESCO-IHP, 2015a), Aquifer storage and yield: (BGS et al., 2017).

Water (AMCOW), established in 2002, supported TBA management within the continent. In 2002, an ISARM workshop produced an inventory of 38 African TBAs with a map of their approximate locations (Appelgren, 2004). In 2005, IGRAC produced a map of 20 TBAs in the Southern African Development Community (SADC) region, with boundaries based on hydrogeological information, and developed a web-based system for storage and display of the TBA information for the SADC region (Vasak and Kukuric, 2006). World maps of TBAs have since been published, each update providing more detailed information for Africa (IGRAC, 2017). Since 2007, eleven (mostly ISARM) international conferences relevant to Africa have enhanced international networks to exchange information and share knowledge on TBAs (Fig. 2). Such conferences raised awareness on transboundary groundwater resources and triggered TBA-specific activities between neighbouring countries. ISARM, in line with integrated water resources management (IWRM) paradigms, recognised that TBA assessment should include hydrogeological characterisation, environmental and socio-economic aspects of the aquifer area as well as national legal and institutional contexts. To facilitate integrated assessments, guidelines for the multi-disciplinary assessment of TBAs have been compiled based on previous ISARM experience (IGRAC and UNESCO-IHP, 2015b). The ISARM programme also resulted in the indicator-based assessment of TBAs worldwide as part of TWAP-Groundwater (UNESCO-IHP and UNEP, 2016).

4. Mapping of TBAs

Since the first map of African TBAs in 2004 (Appelgren, 2004), additional TBAs have been identified. The 72 TBAs identified

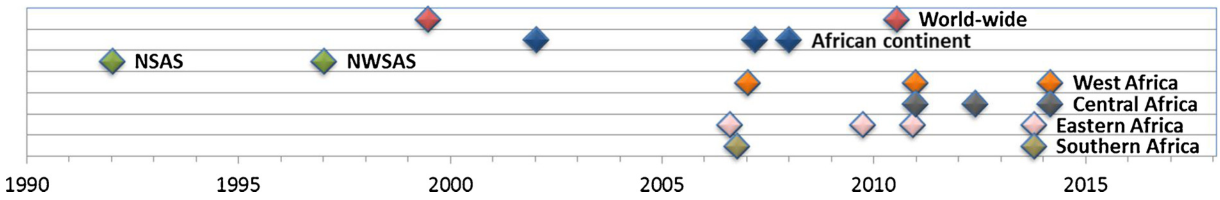

Fig. 2. Timeline of international conferences dedicated to TBAs. Conferences on individual aquifers are excluded. The cooperation agreements on the Nubian Sandstone Aquifer System (NSAS) and the North Western Sahara Aquifer System are shown as reference points for early activities on individual TBAs in Africa.

today (Fig. 3 and Table A1 in Appendix A) may increase with additional hydrogeological knowledge, as indicated by the increased numbers on consecutive TBA maps (Fig. 4).

Although local hydrogeologists may have had more detailed knowledge on TBAs in their country, the ovals on the 2006 map are indicative of the limited international awareness on TBAs at that time. For 64 of the 72 TBAs (89%) boundaries are based on hydrogeological knowledge. The other 8 TBAs are known by approximate location only. The TWAP-Groundwater project improved mapping of TBAs: Nine new TBAs were recognised in Africa; ten TBAs which were previously only known by approximate location were mapped more accurately; for fifteen TBAs significant boundary changes were made (change in surface area > 10%); for three TBAs minor changes were made (change < 10%); and five TBAs were removed as having no transboundary significance because of limited regional hydraulic continuity. From this it may be concluded, that if management of (potential) issues is the only reason for cooperation, it may be efficient to define zones of transboundary impact within the larger TBAs, as transboundary groundwater issues will normally manifest locally in the border areas. For aquifer states also seeking cooperation to jointly deal with non-transboundary issues, this will be less relevant. Continued hydrogeological research and assessment will further refine TBA boundaries and definitions, but guidelines on defining TBAs including consequences of different approaches, would be instrumental.

5. Assessment of TBAs

Throughout Africa, especially in drought-prone rural areas, some hydrogeological characterisation has been conducted, usually for groundwater resource assessment, development and less so for groundwater management. TBA assessment only benefits from this research, if countries are willing to share information. Accessibility of information is however often hampered by a lack of functioning databases and information management structures.

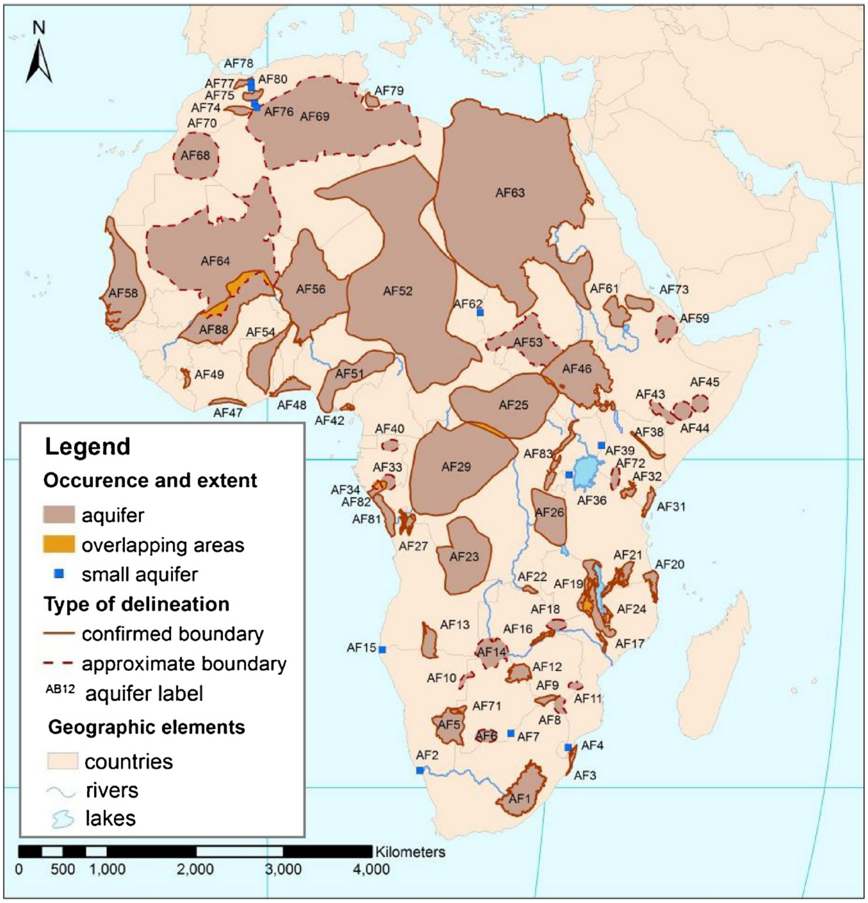

Fig. 3. Transboundary Aquifers of Africa, with TBA codes. After: (IGRAC and UNESCO-IHP, 2015a).

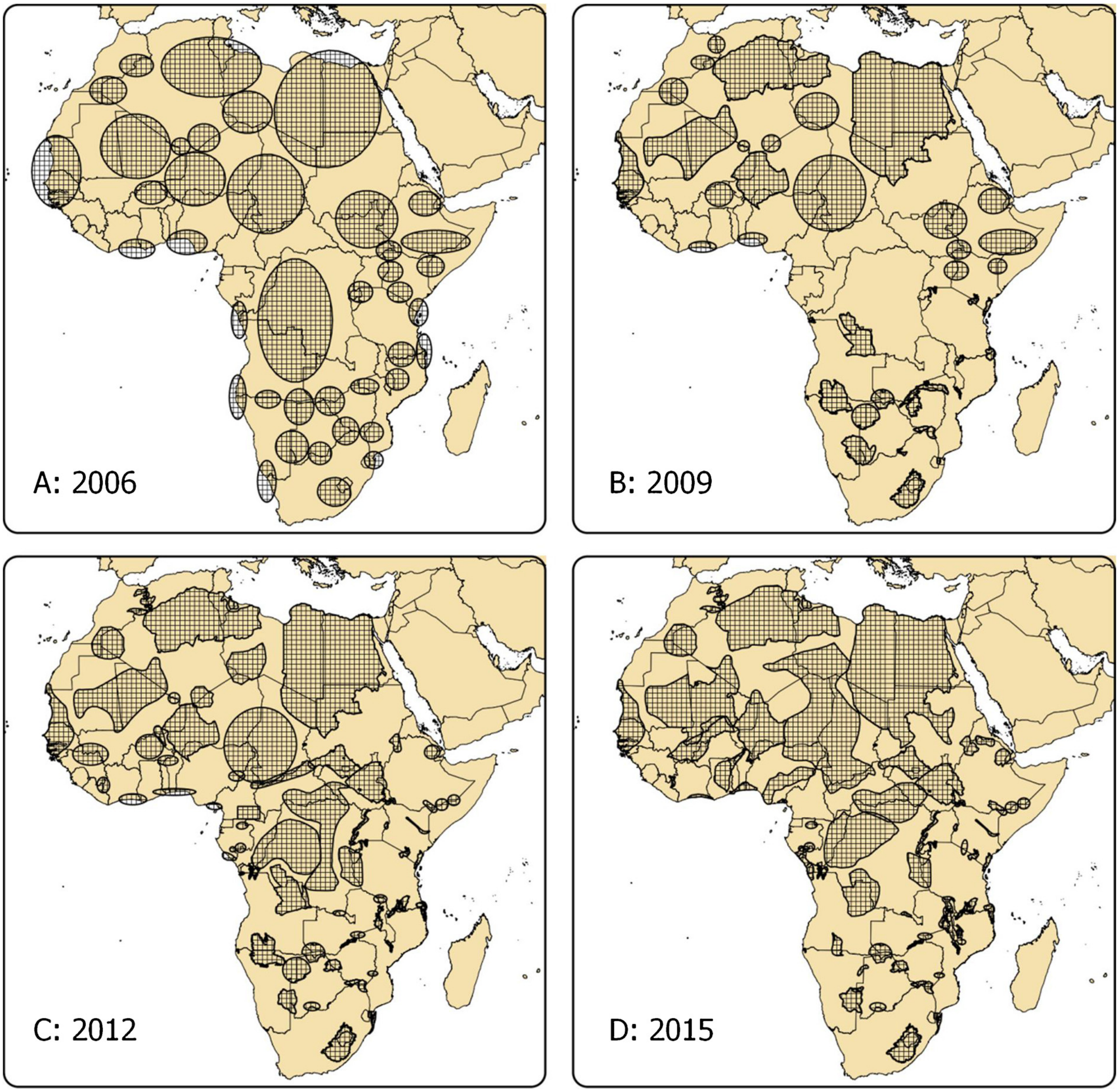

Fig. 4. Development in the mapping of transboundary aquifers in Africa over the last 2 decades. A: after Struckmeier et al. (2006), B: after IGRAC (2009), C: after IGRAC (2012), D: after IGRAC and UNESCO-IHP (2015a,b).

5.1. Aquifer-specific assessment

To date, eleven TBAs have been studied to a substantial degree in the Sahara/Sahel region and in Southern Africa (Table A1 in Appendix A). The International Atomic Energy Agency (IAEA) in cooperation with UNESCO, the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP), supported investigation of TBAs in Northern Africa. Isotope hydrology methods aided the characterization of TBAs such as the NWSAS (AF69), the NSAS (AF63) and the Iullemeden Aquifer System (AF56) and paved the way for cooperation frameworks (Brittain et al., 2015). Pioneering efforts were also made by the Sahel and Sahara Observatory (OSS), when they conducted the 'Aquifers of the Major Basins' program starting in 1992, with focus on the Iullemeden Aquifer aiming to identify transboundary risks, formulate management policies and adopt a legal and institutional framework (Conti, 2017). From 2012–2017, further investigations have been carried out in five TBA systems within the Sahel region (the Iullemeden Aquifer System − AF56, the Liptako-Gourma-Upper Volta System − AF54, the Senegalo-Mauritanian − AF58, the Lake Chad − AF52 and Taoudeni basins − AF64). The studies resulted in recommendations for governments to draw up plans to save water and protect it from pollution (IAEA, 2017). The findings will be integrated at regional level, and common priorities and recommendations to enhance the sustainable management and rational use of these shared aquifer systems, will be identified.

In more recent years, studies have also been initiated in the southern drought-prone parts of Africa, on the Stampriet Transboundary Aquifer System − AF5 (UNESCO-IHP and IGRAC, 2016) and the Ramotswa Transboundary Aquifer − AF7 (Altchenko et al., 2017). These studies aim to initiate coordinated monitoring and management of shared resources through joint research and assessment to build trust for further cooperation.

5.2. Results from TWAP-Groundwater comparative assessment for Africa

TWAP-Groundwater considered 64 of the 72 TBAs in Africa, mostly those larger than 5000 km^2 in area, shared by in total 45 countries (Table A1 in Appendix A) and consisting of 178 national segments.[2] The model calculations were limited to the 34 larger TBAs, involving 112 national segments. Table 1 shows the distribution of national segments per core indicator category compiled from IGRAC and UNESCO-IHP (2016). Using the limited data yield from the questionnaires, indicators could only be calculated for a small number of country segments (indicated by non-zero values in Table A1 in Appendix A).

5.2.1. Groundwater quantity indicators

For sixty-four national TBA segments estimates of *mean annual recharge rates* were provided (Table 1). These range from highs of > 300 mm/year in four TBA country segments in humid areas to lows between 2 and 20 mm/year for 20 TBA segments in drier regions. Twenty-four country segments have reported recharge rates < 2 mm/year, as in arid areas of the NSAS (AF63), the northern parts of the Lake Chad Basin aquifer (AF52), the Taoudeni Basin aquifer (AF64) and the Irhazer- Illuemeden Basin aquifer (AF56). In areas of major irrigation, the model indicated return flows from irrigation for the NSAS (AF63) of 44% of total groundwater recharge in Egypt and 38% in Sudan (Riedel and Döll, 2015; UNESCO-IHP and UNEP, 2016). Mean annual groundwater recharge is a crucial quantity in a country's water balance, because it indicates the amount of groundwater that is utilizable on a sustainable basis. In general, countries provided information on this parameter, but only 5 countries indicated that dedicated recharge studies had been undertaken.

Groundwater depletion rates (mm/year averaged over a TBA total area), are mainly low. High to very high depletion rates are reported for 10 of the 30 country segments that supplied data via the questionnaires. These include TBAs in North and West Africa in arid areas with high abstraction rates, and TBA segments in Zambia, Malawi and South Africa where long-term abstraction from low replenishment aquifers can have detrimental impacts.

5.2.2. Groundwater quality

Data on the *natural background groundwater quality*, defined as the percentage of aquifer area where natural groundwater quality satisfies local drinking water standards, were obtained for only 38 country segments (Table 1). The TBA country segment with reported very low quality water is in the NSAS in Egypt, where < 20% of the area contains water suitable for human consumption. Data on *groundwater pollution,* defined as polluted zones as a percentage of the total aquifer (segment) area, are available for only 21 country segments (12%). Nearly all of those (20) report low pollution levels (Table 1).

5.2.3. Socio-economic aspects

Population density, defined as the number of people living within a TBA area divided by the areal extent of the aquifer, varies from very high in 39 country segments to very low in 38 country segments. TBAs with very high population density are found in Nigeria, most of West Africa's coastal aquifers and along the Rift Valley.

Human dependence on groundwater for domestic, agricultural and industrial water use is defined as groundwater abstraction as a percentage of total water use. Useable data were obtained only for 27 country segments, of which data from 17 indicate a dependence on groundwater of more than 60%. High dependence on groundwater is, as expected, in the fossil TBAs across mainly arid north Africa, and the arid parts of Southern Africa. High dependence on groundwater from TBAs is also reported for the more humid rural parts of Malawi and Tanzania. Surprisingly, the model-calculated dependence for TBAs in Malawi and Tanzania is low, contradicting the information from the questionnaires, highlighting the need for further research. The model study indicates a high dependence on groundwater for agriculture (irrigation) on TBA groundwater in Libya and Algeria, the Mauritanian part of the Taoudeni Basin (AF64) and the Kalahari Karoo Basin/Stampriet Artesian Aquifer System (AF5) in Namibia. The questionnaire survey yielded no information for comparison (Riedel and Döll, 2015; UNESCO-IHP and UNEP, 2016).

Groundwater development stress is defined as annual groundwater abstraction divided by annual recharge. Country segments with groundwater withdrawals exceeding renewable groundwater resources are in the Sahara and Sahel zone where groundwater recharge to exploited aquifers is extremely low or non-existent. Country segment with groundwater development stress values of 50–100% are reported for Senegal, Malawi, South Africa and Swaziland (UNESCO-IHP and UNEP, 2016). Groundwater development stress

[2] The TWAP programme considered national or country segments of the transboundary aquifers as the primary reporting unit (UNESCO-IHP et al., 2012). A country segment is the part of the TBA located within one country.

Table 1
Distribution of African TBA country segments per indicator category for all TWAP-Groundwater core indicators. Based on the questionnaire outcomes (adapted from: (UNESCO-IHP and UNEP, 2016)). (For interpretation of the references to color in this Table legend, the reader is referred to the web version of this article.)

Groundwater Quantity	1.1 Recharge [mm / year]					
	Very high: >300	High: 100-300	Medium: 20-100	Low: 2-20	Very low: <2	No data
	4	6	10	20	24	123
	3.1 Long term groundwater depletion (mm/year)					
	Very low: <2	Low: 2 - 20	Medium: 20 -50	High: 50 - 100	Very high: >100	No data
	16	2	2	2	8	157
Groundwater Quality	1.3 Natural background quality (% of surface area with good quality)					
	Very high: >80	High: 60 - 80	Medium: 40 - 60	Low: 20 - 40	Very low: <20	No data
	20	10	3	4	1	149
	3.2 Groundwater pollution [%]					
	No pollution identified	Some pollution identified (not specified)	Low: 0 - 30	Medium: 30 - 65	High: >100	No data
	1	16	4	0	0	166
Socio-economic	4.1 Population density [cap/km2]					
	Very low: <5	Low: 5 - 10	Medium: 10 - 50	High: 50 – 100	Very high: >100	No data
	38	25	61	23	39	0
	1.2. Renewable groundwater resources per capita (m3/year/capita)					
	Very high: >10000	High: 5000 - 10000	Medium: 1000 - 5000	Low: 100 - 1000	Very low: <100	No data
	0	4	10	28	22	123
	2.1 Human dependency on groundwater (%)					
	Very low: <20	Low: 20 - 40	Medium: 40 - 60	High: 60 - 80	Very high: >80	No data
	4	1	2	5	12	163
	4.2 Groundwater Development Stress [%]					
	Very low: <2	Low: 2 - 20	Medium: 20 - 50	High: 50 – 100	Very high: >100	No data
	11	12	7	4	13	140
Legal & Institutional	5.1 Transboundary Legal Framework					
	1. Agreement with full scope for TBA management signed by all parties	2. Agreement with limited scope for TBA management signed by all parties	-	3. Agreement under preparation or available as an unsigned draft	4. No agreement exists, nor under preparation	No data
	14	9	0	7	53	104
	5.2 Transboundary Institutional Framework					
	1. Dedicated transboundary institution fully operational	2. Dedicated transboundary institution in place, not fully operational	3. National / Domestic institution fully operational	4. National / Domestic institution in place, but not fully operational	5. No institution exists for TBA management	No data
	9	7	13	45	8	105

Table 2
TBAs with at least one country segment under medium to very high groundwater development stress and a high dependence on groundwater (> 40%) in 2030 and/or 2050. Adapted from (Riedel and Döll, 2015; UNESCO-IHP and UNEP, 2016).

Aquifer name	Current conditions (reference 2010)	Future conditions (2030 and/or 2050)
SE Kalahari Karoo Basin/Stampriet Artesian Aquifer System (AF5)		X
Eastern Kalahari Karoo Basin (AF12)		X
Khakhea/Bray Dolomite (AF6)		X
Keta/Dahomey/Cotier basin aquifer (AF48)	X	X
Lake Chad Basin (AF52)	X	X
Irhazer-Illuemeden Basin (AF56)		X
Northwest Sahara Aquifer System (NWSAS – AF69)	X	X
Afar Rift valley/Afar Triangle aquifer (AF59)		X
Mereb (AF73)	X	X
Nubian Sandstone Aquifer System (NSAS – AF63)		X

estimated from model results is mostly very low to low, even in the semi-arid and arid zones of Africa, except for the Algerian segment of the Taoudeni (AF64) and the Libyan part of the Lake Chad Basin (AF52).

Riedel and Döll (2015) identified TBA hotspots where at least one country segment is experiencing medium to very high development stress and medium to very high human dependence on groundwater in 2010 and/or in the future (2020/2050). Ten of the nine-teen TBA hotspots identified are in Africa (Table 2). The need for improved management, including joint monitoring, is obviously more acute here.

5.2.4. Completeness and quality of the assessment

Data were provided for 43% of the national segments of TBAs, and as such the TWAP-Groundwater project managed to collect a lot of data previously only available in grey literature or at the national level. Data, however, are often incomplete so that not all indicators can be estimated (Table A1 in Appendix A). The chronic lack of available systematic data, both on static aquifer characteristics (such as aquifer thickness) and on time-dependent trends (such as groundwater abstraction), indicate that African countries require further hydrogeological characterisations as well as systematic monitoring of groundwater in TBAs. Because questionnaire responses were obtained separately from the individual countries, a complete and harmonized response per aquifer was seldom achieved, hampering assessment of aquifers as a whole.

The importance of groundwater in various TBAs and in Africa as a whole, as well as the state of the resource, is not obvious from the data collected. There are considerable differences between the outcomes of the questionnaire survey and the model results, which may question the validity of the indicators used in the analyses. It is not evident which method provides the most reliable results, and there is a clear need for ‘ground truthing’ using additional monitoring data and site-specific research. Harmonization of aquifer information across country boundaries is fundamental for joint management. The current lack of information can be taken as an indicator that joint aquifer management still has some way to go.

6. Monitoring TBAs

Long-term monitoring of groundwater levels, borehole abstractions and groundwater chemistry are essential inputs required for assessments and developing sustainable groundwater resources management policies. At national level, some states have systems in place for monitoring their groundwater resources. Unfortunately, most states display a near absence of active monitoring systems or monitoring archives with historic time series. The fragmentary nature of monitoring data and other information makes effective management of groundwater resources difficult, particularly at TBA level. Recent cooperation on the Stampriet TBA shared between Botswana, Namibia and South Africa, and the Ramotswa TBA shared by Botswana and South Africa, may result in the first joint groundwater monitoring programmes for Southern Africa (Altchenko et al., 2017; UNESCO-IHP and IGRAC, 2016). Deficiencies in monitoring of shared aquifers in Central African states are the result of poor institutional capacity due to the low importance given to groundwater resources and less donor attention. This has resulted in a lack of hydrogeological data. In Benin and Togo and other more humid regions, water resource programs have focused on surface water rather than groundwater. As a result, there are no long-term time series of groundwater monitoring data, nor a thorough conceptual understanding of aquifer characteristics such as structure, groundwater flow and chemical water quality. West African countries of the Sahel region have focused upon groundwater so that hydrogeological systems are well studied, and institutions responsible for the management and monitoring of aquifer systems, e.g. the Water Resources Management and Planning Directorate in Senegal and the Sahara and Sahel Observatory (OSS) in Mali, are well established. However, even in the arid Sahel region, not all TBA segments are covered. Within the Senegalo-Mauritanian Basin (AF58), there may be good information for the Senegalese segment, but little data are available from the Mauritania, Gambia and Guinea Bissau segments (UNESCO-IHP and UNEP, 2016). In general, the joint monitoring of transboundary groundwater is still largely absent and imbalance in efforts across borders exists. Within the Iullemeden Aquifer (AF56), shared by Mali, Niger and Nigeria, a Transboundary Diagnostic Analysis has been completed and a joint groundwater database and information system has been set up (OSS, 2011), but no joint monitoring has been initiated to date.

A major challenge in transboundary cooperation and joint monitoring is the harmonisation of systems, methods and data formats across aquifer boundaries. Such harmonisation was not apparent from the TWAP inventory. At all TBA management levels, i.e. at regional, river basin and TBA level, there needs to be increased focus on standardized data collection and harmonisation across borders. TBA states should be encouraged to commence joint monitoring of representative groundwater levels and water quality and promote data exchange as an early part of transboundary groundwater management and development. The database and portal developed by IGRAC and UNESCO-IHP (2016) can aid such cooperation.

7. Managing and governing TBAs

Africa is fortunate to have governance structures at both the continental level through AMCOW and at the regional level in the form of the eight Regional Economic Communities (RECs) of the African Union. In addition, the continent has several functioning river and lake basin organisations. Critical for groundwater in Africa is AMCOW's commitment to the continent-wide strategic groundwater initiative through the Africa Groundwater Commission established in 2007 (AMCOW, 2008). The major river/lake basins have been identified as units for water management. This is challenging for the management of those TBAs which underlie several river/lake basins, or those TBAs located in areas not covered by international river or lake basin organisations, such as the NWSAS (AF69) or NSAS (AF63).

7.1. Progress in TBA governance

The NSAS (AF63, shared between Egypt, Libya, Chad and Sudan) has an agreement with full scope for TBA management signed by all parties (Conti, 2017; Tujchneider and van der Gun, 2012). Although national institutions are in place, some are not fully operational. The Nile Basin Initiative (NBI), established in 1999, includes Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda with Eritrea as an observer. From 2008–2011, a collaborative study, mainstreaming groundwater considerations into the integrated management of the Nile River Basin, was undertaken to raise the profile of groundwater in the NBI and initiate joint actions on groundwater issues (Braune and Christelis, 2014). This could potentially be relevant for the TBAs in or intersecting the basin (approx.10 TBAs).

The NWSAS (AF69, shared between Algeria, Libya and Tunisia) has an agreement with full scope for TBA management signed by all parties (Conti, 2017; Tujchneider and van der Gun, 2012). An institutional arrangement for the assessment and consultative management of this TBA has been developed, consisting of a NWSAS Coordinating Unit, a NWSAS Steering Committee, the three countries with each their Institutions/Research Centres and an ad-hoc Scientific Committee. By mid-2008, the tri-partite institutional arrangement had been inaugurated and continues to function.

The Irhazer-Iullemeden Basin (AF56, shared between Algeria, Mali, Niger and Nigeria) has an agreement on joint policy implementation through a joint legal and institutional consultative mechanism adopted by the aquifer states (Tujchneider and van der Gun, 2012). It also contains a joint risk mitigation and data sharing policy. In the TWAP-Groundwater assessment, the national reporting on the status of the institutional arrangements varied between TBA countries. This indicates that the agreement is not yet fully operational within relevant national institutions and departments dealing with groundwater management.

SADC-region: The SADC region is an example of a Regional Economic Community (REC) which has relatively advanced TBA management. The SADC Protocol on Shared Watercourses (SADC, 1995 and SADC, 2000) was instrumental in getting groundwater added into the programme of activities of the African Network of Basin Organizations (ANBO) in 2008. Some of the river basin organisations in the SADC region are starting to play a role in transboundary groundwater management. The Orange-Senqu River Commission (ORASECOM) was the first river basin commission in SADC to establish a Groundwater Hydrology Committee (in 2007) to facilitate dialogue between the basin states on TBA management. The ORASECOM agreement (ORASECOM, 2000) specifically mentions "hydrogeological" data among the data that the countries are obligated to exchange. ORASECOM was one of the parties suggesting to pilot TBA management principles in SADC focussing on the Stampriet transboundary aquifer system. This became a case study in the UNESCO-IHP-executed project on 'Governance of Groundwater Resources Governance in Transboundary Aquifers' (UNESCO-IHP and IGRAC, 2016). In 2017, ORASECOM decided that the Stampriet TBA Multi Country Cooperation Mechanism be housed within the ORASECOM Groundwater Hydrology Committee, with the aim to coordinate further joint study and assessment of the TBA (ORASECOM, 2017).

7.2. TWAP-Groundwater comparative assessment for Africa

Seven TBA-specific agreements exist in Africa (Table A1 in Appendix A) as reported by Conti (2017) and ORASECOM (2017). In TWAP-Groundwater, national experts from other TBAs have also reported that agreements scoping TBA management exist (Table 1). These findings indicate that management of TBAs may be dealt with within existing framework agreements on international river/lake basins. As such river and lake basin organisations may play an increasingly important role in TBA management, although at present there is little evidence of concrete activities related to TBA assessment, monitoring or management. As long as most of the TBAs have no agreement in place, the domestic legal and institutional frameworks for sustainable water resources management continue to play a key role in the coordinated cross-border management.

8. Case studies

This section describes three case studies of transboundary aquifers, ranging from a very large, well-studied transboundary aquifer with a long history of cooperation (Nubian Sandstone Aquifer System), to a small TBA which is currently under investigation by the states sharing the resource (Ramotswa TBA), and a TBA which is potentially at risk of pollution and population pressure and which is in need of joint assessment, monitoring and management (Coastal Sedimentary Basin 1).

8.1. The Nubian Sandstone Aquifer System − the heavyweight of TBAs in Africa

The Nubian Sandstone Aquifer system (NSAS − AF63) forms one of the largest aquifers in the world underlying some 2,500,000 km^2 of Egypt, Libya, Chad and Sudan, dominated by desert and arid to semi-arid climate (CEDARE, 2001). To the countries that share this TBA it is important as a source for drinking water and irrigation. The aquifer is confined in places and semi-confined in others. Isotopic studies reveal that groundwater was recharged during several humid phases during the Pleistocene (Sturchio et al., 2004) and Holocene periods (Edmunds et al., 2004; Edmunds and Wright, 1979; Wallin et al., 2005) within the unconfined Nubian sediments of southwestern Egypt, although present day groundwater recharge may also occur. The estimated groundwater storage is about 500.000 km^3 with the recoverable amount estimated at around 3% (IAEA et al., 2013). Water quality varies, from excellent in the south to saline in the north of Libya (Alker, 2008). Exploitation of this enormous freshwater reserve has increased during the past forty years, with large abstractions by Egypt and Libya for irrigation and public water supply.The NSAS States cooperate through agreements made from 1992 to date. These agreements confirm increased cooperation, with the aquifer states being prepared to engage at increased levels and intensity of cooperation (Quadri, 2017). The agreement of the Joint Authority for the Study and Development (joint authority) of the NSAS, signed in 1992, was the first step in the process of cooperation. The only instrument on record regarding the joint authority is an "internal regulation" of the Authority, setting out the internal structure, functions, decision-making process, and funding of the Authority. The agreement carries no provisions regarding the management of the aquifer or groundwater stored in it. Two agreements made in 2000, mark an advance in the process of cooperation among the NSAS States. These agreements require that regular monitoring and updating and sharing of data and information from the NSAS are needed for the sustainable use of the aquifer's groundwater resources. Regarding monitoring and information exchange, the four NSAS countries agreed to share data collected and analysed through the "Programme for the Development of a Regional Strategy for the Utilization of the NSAS". A further step in the process of cooperation between the NSAS countries is the "Regional Action Programme for the Integrated NSAS Management", funded by GEF and implemented by UNDP, IAEA, and UNESCO-IHP (IAEA et al., 2013). This project supports the development of a regional strategy for the integrated NSAS management, aimed at the equitable long-term exploitation of the aquifer. The project fosters a better understanding of aquifer issues and responses, while laying the basis of a regional Strategic Action Plan (SAP). The SAP agreement, signed by the NSAS countries and the Joint Authority in 2013, binds the Parties to agree, at a later stage, on actions for the sustainable management of the aquifer.

8.2. The Ramotswa Transboundary Aquifer − an example of recent joint efforts

The Ramotswa TBA (AF7), shared between Botswana and South Africa, is a TBA hotspot in SADC, impacted by increased water insecurity due to population growth and urbanisation in Botswana and from economic water scarcity in South Africa (Cobbing et al., 2008; Davies et al., 2013). Groundwater scarcity on the Botswana side is exacerbated by nitrate and faecal pollution of the aquifer due to onsite sanitation (Beger, 2001; Staudt, 2003). The TBA, of small (300 km^2) extent, is part of a segmented karstic dolomite formation within central southern Africa that is locally intensively used in South Africa (Meyer, 2014). A joint project involving Botswana and South Africa, initiated in 2015 and funded by USAID, aims to better understand the aquifer characteristics and issues around its use, and to improve water security through conjunctive use. The TBA was surveyed using a targeted airborne electromagnetic survey to improve the 3-D visualisation of the transboundary part of the dolomite aquifer, which is compartmentalised by fracture zones and dolerite dikes (Altchenko et al., 2017). Results from joint research based on national monitoring data identified groundwater flow directions and water quality issues, indicating potential cross-border issues of nitrate pollution and significant surface water-groundwater interconnections (Altchenko et al., 2017). Geo-data and information generated by this project are shared between the TBA countries and made available to stakeholders through a web-based system (IGRAC and IWMI, 2017). Information forms the basis for development of a strategic action plan identifying joint priorities. The bilateral Joint Permanent Technical Committee functions as an interim forum and precursor for taking forward a formal institutional arrangement for the long-term joint management of the aquifer.

8.3. Coastal Sedimentary Basin 1 − an example of a high priority aquifer

The Coastal Sedimentary Basin1 (AF31) shared by Kenya (south coast) and Tanzania (north coast). It is a multi-layered sedimentary system with limestone horizons, and the groundwater is an important resource for the population. The sequence is characterized by a high primary porosity with secondary porosity resulting from karst dissolution as described in TBA information sheet AF31 in IGRAC and UNESCO-IHP (2016). The population density in the TBA is high (195 persons/km^2) with a population of 2.9 million people within an aquifer area of 15 000 km^2. The main aquifer recharge mechanism is percolation of rainfall with natural discharge of groundwater to river base flow and the sea. The average depth to the water table is shallow from ground surface to 10 m below ground level. Up to 50% of the natural water quality does not meet drinking quality standards due to elevated levels of salinity. In some areas, high levels of pollution occur due to mining, agriculture and urban development (UNESCO-IHP and UNEP, 2016). The shallow groundwater levels are important in maintaining groundwater dependent ecosystems across the TBA.

The observed polluted zones, combined with the issues of salinization, and its location along the African east coast with high population pressure, makes this TBA a hotspot for future groundwater stress. Joint assessment and monitoring initiatives must be undertaken to develop effective management strategies and action plans to curb potential threats.

9. Discussion, conclusion and forward look

Many TBAs exist in Africa relative to other continents (IGRAC and UNESCO-IHP, 2015a), and those are underlying about 40% of the surface area of the continent. This provides rationale for focus on their management as a critical component of water resources management to improve water security and international cooperation. TBAs are diverse in size, climate, hydrogeology, human pressure and present levels of management, and therefore require in-depth studies.

Two historic phases of TBA management are discerned. The first occurred in North Africa from the 1970's, driven by the need to further develop and manage the large sedimentary aquifers predominantly in arid regions. The second phase began in the early 2000s, with the ISARM programme systematically identifying and mapping TBAs Africa-wide and initiating widespread cross-border discussions, defining issues and developing optimum ways to manage TBAs.

Some mainstreaming and best practise in TBA management are emerging from these studies. Achieving mature approaches requires time, and each TBA requires different levels of study and cooperation due to the uniqueness of each TBA. International support has facilitated management approaches, related to technical assessments and development of legal and institutional frameworks. International support tends to push for short term solutions, while critical trust-building processes have proven to take time to develop. Aquifer impacts from corrective TBA management, in terms of reversal of negative trends, are slow in manifesting, requiring long-term planning horizons and long-term monitoring that cannot be achieved by short-term projects. Similarly, inertia towards formalizing expanded legal frameworks and identifying the best bases for overseeing institutions, for example in existing river basin organisations, takes time and careful negotiation. These processes must be nurtured by international development support, but not driven in a desire to see rapid results, as this could lead to non-sustainable outcomes. AMCOW's increased commitment to groundwater, along with the Regional Economic Committees, could play an over-arching role in supporting coordination, lesson-harnessing and sharing for the benefit of Africa as a whole.

Mapping of TBAs has progressed steadily through international initiatives. Even though TBAs contain important resources for the development of Africa, only 11 of the currently known 72 TBAs have been studied in detail since TBA activities started nearly 50 years ago. These TBAs are mostly located in the semi-arid and arid regions of Africa, indicating that assessment of TBAs seems to be primarily driven by (potential) water scarcity issues. International organisations prove to be key in initiating TBA work. TWAP-Groundwater has shown that assessment of TBAs can hardly build on data and information from national studies as in many cases this information is either lacking, not accessible in a structured manner, or requires harmonisation between countries sharing a TBA. Because of this it is not possible, even with an indicator based assessment which requires little data, to assess the importance and state of these important groundwater resources of Africa. Global water use models may be able to fill the data gaps, but comparing indicators, determined using questionnaire surveys with results from a global water use model showed variable levels of agreement, calling for further in-depth research on both methods.

The argument that transboundary groundwater issues manifest locally in the border area, in zones of transboundary impact, at a scale smaller than the whole aquifer, and potentially only require involvement of a subset of aquifer states and stakeholders must be further explored. Similarly, nested and scale-dependent approaches to TBA management, with various degrees and levels of formal or informal arrangements, need further consideration, in particular for large TBAs, of which there are many in Africa. Such nesting or zoning, based on sound hydrogeological and scientific methods, will justify the allocation of limited resources for groundwater-related activities, while making them more efficient and effective. This approach also has the potential to focus cooperation at the bilateral level, which according to Puri and Aureli (2005) is more effective than multi-lateral cooperation.

TBA work in Africa has leveraged cooperation on groundwater more broadly between aquifer-sharing countries and at regional levels, creating incipient frameworks for broader collaboration on aquifer management. The transboundary nature of the shared resources, which receives augmented international attention, potentially increase national emphasis on groundwater resource management, which could improve the overall management of groundwater in Africa.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector. This research made use of publicly available data from TWAP Groundwater (UNESCO-IHP and UNEP, 2016), available via the TWAP-Groundwater data portal (IGRAC and UNESCO-IHP, 2016). TWAP was funded by the GEF and implemented by UNEP, with the groundwater component being executed by UNESCO- IHP. The authors express gratitude to the institutions and the great number of national experts and regional coordinators who contributed to TWAP-Groundwater. USAID, the CGIAR Research Programme on Water Land and Ecosystems are acknowledged for their financial support to work on the Ramotswa Aquifer.

Appendix A

Table A1

Transboundary aquifers of Africa: key figures, data availability from TWAP-Groundwater indicator assessment (number of countries for which indicators are available. Compiled from (IGRAC and UNESCO-IHP, 2016)) and known TBA-specific assessment, monitoring or existence of governance frameworks.

Code	Name	Area (1)	Pop. (2)	Pop. dens. (3)	No.of CS	TWAP										TBA specific		
						Quan.		Qual.		Soc.-Econ.				L&I				
						1.1	3.1	1.3	3.2	4.1	1.2	2.1	4.2	5.1	5.2	A	M	G
AF1	Karoo Sedimentary Aquifer/ Orange-Senqu River Basin Aquifers	140	4600	3	2	2	0	1	0	2	2	2	2	2	2			X
AF2	Coastal Sedimentary Basin V	0,75	0,2	1	2	Not included in TWAP-Groundwater												
AF3	Coastal Sedimentary Basin VI/Coastal Plain Sedimentary Basin Aquifer	8,5	290	3	2	0	0	0	0	2	0	0	0	1	1			
AF4	Rhyolite-Breccia Aquifer	4,1	400	3	3	1	1	1	0	3	1	1	1	1	1			
AF5	Stampriet Aquifer System	87	35	1	3	1	1	1	1	3	1	1	1	1	1	X	X	X
AF6	Khakhea/Bray Dolomite	25	30	2	2	1	0	0	0	2	1	0	1	1	1			
AF7	Zeerust/Lobatse/Ramotswa Dolomite Basin Aquifer	0,3	19	3	2	1	0	0	0	2	1	0	0	1	1	X	(X)	(X)
AF8	Limpopo Basin	17	460	3	3	1	0	0	0	3	1	0	0	1	1			
AF9	Tuli Karoo Sub-Basin	12	120	3	3	1	1	0	0	3	1	0	1	1	1			
AF10	Northern Kalahari/Karoo Basin/Eiseb Graben Aquifer	11	6,2	1	2	1	1	1	0	2	1	1	1	1	1			
AF11	Save Alluvial	9,9	380	3	2	0	0	0	0	2	0	0	0	2	2			
AF12	Eastern Kalahari Karoo Basin	34	250	2	2	0	0	0	0	2	0	0	0	1	1			
AF13	Cuvelai and Etosha Basin/ Ohangwena Aquifer System	41	260	2	2	1	1	1	0	2	1	1	1	1	1	(X)		(X)
AF14	Nata Karoo Sub-basin/ Caprivi deep-seated Aquifer	79	280	2	5	2	2	2	1	5	2	1	2	2	2			
AF15	Coastal Sedimentary Basin IV	1,2	0,62	1	2	Not included in TWAP-Groundwater												
AF16	Medium Zambesi Aquifer	9,4	200	3	2	1	1	1	1	2	1	0	1	2	2			
AF17	Shire Valley Alluvial Aquifer	5,5	580	4	2	1	1	1	1	2	1	1	1	2	2	(X)		
AF18	Arangua Alluvial	19	270	3	2	1	1	1	1	2	1	0	1	2	2			
AF19	Sand and Gravel Aquifer	22	3800	4	3	2	2	2	2	3	2	1	2	2	2			
AF20	Coastal Sedimentary Basin III	23	1200	3	2	1	0	1	0	2	1	1	1	2	2			
AF21	Karoo Sandstone Aquifer	36	470	3	2	1	0	1	0	2	1	0	0	2	2			
AF22	Kalahari/Katangian Basin/ Lualaba	7	420	3	2	1	0	0	0	2	1	0	0	1	1			
AF23	Congo Intra-cratonic Basin	330	4800	3	2	0	0	0	0	2	0	0	0	1	1			
AF24	Weathered basement	11	130	4	4	2	2	3	2	4	2	1	2	3	3			
AF25	Karoo-Carbonate	540	5700	3	3	0	0	0	0	3	0	0	0	1	1			
AF26	Tanganyika	170	9100	3	3	1	0	1	0	3	1	0	0	1	1			
AF27	Dolomitic Basin	19	1100	3	3	1	0	0	0	3	1	0	0	1	1			
AF29	Cuvette	790	25000	3	3	Not included in TWAP-Groundwater												
AF31	Coastal Sedimentary Basin I/ Karoo Sedimentary Aquifer	15	2900	4	2	1	0	1	1	2	1	0	0	1	1			
AF32	Kilimanjaro Aquifer	13	2000	4	2	1	0	1	1	2	1	0	0	2	2			
AF33	AF33	21	110	2	2	No data provided by any of 2 countries												
AF34	AF34	6,5	40	2	2	No data provided by any of 2 countries												
AF36	Kagera Aquifer	5,2	580	4	3	1	0	2	1	3	1	0	1	3	3			
AF38	Merti Aquifer	12	230	3	2	1	0	0	0	2	1	0	1	2	2	X		
AF39	Mount Elgon Aquifer	4,9	1300	4	2	1	0	1	0	2	1	0	0	1	1			
AF40	AF40	18	54	2	2	No data provided by any of 2 countries												
AF42	Rio DelRey	5,8	2200	4	2	No data provided by any of 2 countries												
AF43	Dawa	31	400	3	3	2	1	2	0	3	2	1	1	2	2			
AF44	Jubba	31	340	3	2	No data provided by any of 2 countries												
AF45	Shabelle	28	300	3	2	0	0	0	0	2	0	0	0	1	1			
AF46	Sudd Basin	330	5500	3	5	2	1	2	2	5	2	2	2	2	2			
AF47	Tano Basin	14	4800	4	2	2	2	1	1	2	2	1	2	1	1			
AF48	Keta/Dahomey/Cotier Basin Aquifer	33	22000	4	3	2	2	3	2	4	2	2	2	3	3			
AF49	Cestos – Danané Aquifer	8,4	710	3	3	1	0	1	0	3	1	0	1	1	1			
AF51	Aquifer Vallee de la Benoue	200	34000	4	2	No data provided by any of 2 countries												
AF52	Lake Chad Basin	2000	45000	3	7	2	0	1	2	7	2	0	2	2	3	X		X

(*continued on next page*)

Table A1 (*continued*)

Code	Name	Area (1)	Pop. (2)	Pop. dens. (3)	No.of CS	TWAP										TBA specific		
						Quan.		Qual.		Soc.-Econ.				L&I				
						1.1	3.1	1.3	3.2	4.1	1.2	2.1	4.2	5.1	5.2	A	M	G
AF53	Baggara Basin	210	4000	3	4	2	0	0	0	4	2	1	2	2	2			
AF54	Volta Basin	130	6300	3	5	2	0	0	0	5	2	1	1	2	1	X		
AF56	Irhazer-Iullemeden Basin	510	21000	3	5	2	0	1	0	5	2	0	1	3	1	X		X
AF58	Senegalo-Mauretanian Basin	290	16000	3	5	3	1	1	1	5	3	0	2	1	3	X		
AF59	Afar Rift valley/Afar Triangle Aquifer	51	870	3	3	2	1	2	0	3	2	0	2	2	2			
AF61	Gedaref	51	1800	3	3	1	0	0	0	3	1	0	1	1	0			
AF62	Disa	1,3	34	3	2	Not included in TWAP-Groundwater												
AF63	Nubian Sandstone Aquifer System (NSAS)*	2500	94000	3	5	5	0	0	0	5	5	0	5	5	5	X	X	X
AF64	Taoudeni/Tanezrouft Basin	1100	5100	2	3	3	3	3	0	3	3	0	3	3	3	X		X
AF68	Système Aquifère de Tindouf	180	240	2	4	Not included in TWAP-Groundwater												
AF69	Northwest Sahara Aquifer System (NWSAS)*	1000	7100	2	3	3	3	0	0	3	3	3	3	3	3	X	X	X
AF70	Système Aquifère d'Errachidia*	17	120	2	2	0	0	0	0	2	0	0	0	0	2			
AF71	Ncojane Basin	8,8	5,1	1	2	No data provided by any of 2 countries												
AF72	Rift Aquifer	19	510	3	2	No data provided by any of 2 countries												
AF73	Mereb	34	3800	4	2	1	1	0	0	2	1	0	0	1	1			
AF74	Angad	3,7	96	3	2	Not included in TWAP-Groundwater												
AF75	Ain Beni Mathar*	15	67	2	2	2	2	0	0	2	2	0	0	2	2			
AF76	Chott Tigri-Lahouita	2,9	13	2	2	Not included in TWAP-Groundwater												
AF77	Figuig	1,2	3,7	2	2	Not included in TWAP-Groundwater												
AF78	Jbel El Hamra	0,44	21	3	2	Not included in TWAP-Groundwater												
AF79	Système Aquifère de la Djeffara*	13	520	3	2	2	2	0	0	2	2	2	2	0	2			
AF80	Triffa*	9,1	840	3	2	2	0	0	0	2	2	0	2	2	2			
AF81	Aquifere Cotier	41	2600	3	4	No data provided by any of 4 countries												
AF82	AF82	17	88	2	2	No data provided by any of 2 countries												
AF83	Aquifere du Rift	40	7900	4	5	0	0	1	0	5	0	0	0	1	1			
AF88	Aquifer extension Sud-Est de Taoudeni	300	13000	3	3	2	0	0	0	3	2	0	1	2	2	X		

(1) Surface area in 1000 km^2 (calculated based on: (IGRAC and UNESCO-IHP, 2016)); **(2)**: Population in 1000 persons/km^2 (calculated based on: (IGRAC and UNESCO-IHP, 2016) and (CIESIN and CIAT, 2005)); **(3):** Population density: 1. Very low (< 1 p/km^2); 2. Low (1–10 p/km^2); 3: Medium (10–100 p/km^2); 4: High (> 100 p/km^2); **No. of CS**: No of countries sharing TBA; **TWAP:** no. of country segments with indicators; **Quan:** Groundwater quantity indicators: **1.1**: Mean annual groundwater recharge; **3.1**: Groundwater depletion; **Qual:** Groundwater quality indicators: **1.3**: Groundwater natural background quality; **3.2**: Groundwater pollution; **Soc.-Econ**: Socio-economic indicators: **4.1**: Population density; **1.2**: Renewable groundwater per capita; **2.1**: Human dependence on groundwater; **4.2**: Groundwater development stress; **L&I:** Legal and institutional indicators: **5.1**: Transboundary legal framework; **5.2**: Transboundary institutional framework; **TBA Specific: A**: X: TBA specific assessment/research undertaken in an international context. (X): in preparation; **M**: X: Monitoring of groundwater in place in an international context. (X): in preparation; **G**: X: Governance framework existing: Agreement and/or some form of formalized TBA specific cooperation in place. Source: Conti (2017), ORASECOM (2017); (X): in preparation. *: TBAs for which TWAP-Groundwater data and indicators are not available at country segment level, but only at TBA-level.

Note: There are currently 72 known TBAs in Africa, despite the highest TBA code being AF88. Over time TBAs have been merged, redefined or were taken of the map, resulting in some obsolete TBA codes (e.g. AF28 no longer exists). The TWAP included 64 of the TBAs in Africa.

References

AMCOW (African Ministers' Council on Water), 2008. Roadmap for the Africa Groundwater Commission.

AbuZeid, K., Elrawady, M., CEDARE, 2015. North Western Sahara Aquifer System (NWSAS). 2012 State of the Water Report, Monitoring & Evaluation for Water in North Africa (MEWINA) Project, Water Resources Management Program. CEDARE.

Alker, M., 2008. The nubian sandstone aquifer system: a case study for the research project: transboundary groundwater management in Africa. In: Scheumann, W., Herrfahrdt-Pähl, E. (Eds.), Conceptualizing Cooperation on Africa's Transboundary Groundwater Resources. German Development Institute, Bonn, pp. 231–273.

Altchenko, Y., Genco, A., Pierce, K., Woolf, R., Nijsten, G., Ansems, N., Magombeyi, M., Ebrehim, G., Lautze, J., Villholth, K.G., Lefore, N., Modisha, R., Baqa, S., McGill, B., Kenabatho, P., 2017. Resilience in the Limpopo Basin: The Potential Role of the Transboundary Ramotswa Aquifer. Hydrogeology Report IWMI, Pretoria, South Africa.

Appelgren, B., 2004. Managing shared aquifer resources in Africa. ISARM Africa. IHP-VI, Series on Groundwater No.8. UNESCO, Paris p. 216. ISBN: 9292200283.

BGS, DFID, NERC, ESRC, 2017. Africa Groundwater Atlas. Online, URL: https://www.bgs.ac.uk/africagroundwateratlas/ (Accessed 25/07/2017).

Beger, K., 2001. Environmental Hydrogeology of Lobatse (South East District; Republic of Botswana). Department of Geological Survey Botswana and BGR, Lobatse.

Braune, E., Christelis, G., 2014. Regional Report for Southern and Eastern Africa – TWAP Groundwater (unpublished).

Brittain, J., Grossi, A., Cayol, J., Malavasi, A., 2015. The international atomic energy agency: linking nuclear science and diplomacy. Sci. Dipl. 4.

CEDARE (Centre for Environment and Development for the Arab Region and Europe), 2001. Regional strategy for the Utilization of the Nubian Sandstone Aquifer System. Volume II − Hydrogeology.

CIESIN, CIAT, 2005. Gridded Population of the World, Version 3 (GPWv3): Centroids. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). Data for year 2015. Online, URL: http://sedac.ciesin.columbia.edu/data/set/gpw-v3-centroids. (Accessed 30/05/2017) https://doi.org/10.7927/H4TT4NWQ.

Cobbing, J.E., Hobbs, P.J., Meyer, R., Davies, J., 2008. A critical overview of transboundary aquifers shared by South Africa. Hydrogeol. J. 16, 1207–1214. http://dx.doi.org/10.1007/s10040-008-0285-2.

Conti, K.I., 2017. Norms in Multilevel Groundwater Governance and Sustainable Development. PhD Dissertation. Universiteit van Amsterdam, Amsterdam.

Davies, J., Robins, N.S., Farr, J., Sorensen, J., Beetlestone, P., Cobbing, J.E., 2013. Identifying transboundary aquifers in need of international resource management in the Southern African Development Community region. Hydrogeol. J. 21, 321–330. http://dx.doi.org/10.1007/s10040-012-0903-x.

Edmunds, W.M., Wright, E.P., 1979. Groundwater recharge and palaeoclimate in the Sirte and Kufra basins. Libya J. Hydrol. 40, 215–241. http://dx.doi.org/10.1016/0022-1694(79)90032-5.

Edmunds, W.M., Dodo, A., Djoret, D., Gaye, C.H., Goni, I.B., Travi, Y., Zouari, K., Zuppi, G.-M., Gasse, F., 2004. Groundwater as an archive of climatic and environmental change: Europe to Africa. In: Battarbee, R.W., Gasse, F., Stickley, C.E. (Eds.), Past Climate Variability Through Europe and Africa. Springer, Netherlands, Dordrecht, pp. 279–306. http://dx.doi.org/10.1007/978-1-4020-2121-3_14.

FAO, 2014. Global Administrative Unit Layers (GAUL). Edition 2015. Online, URL: http://www.fao.org/geonetwork/srv/en/metadata.show?id=12691 (Accessed 03/07/2017).

Foster, S., Tuinhof, A., Garduno, H., 2008. Groundwater in sub-Saharan Africa: a strategic overview of developmental issues. In: Adelana, S., MacDonald, A. (Eds.), Applied Groundwater Studies in Africa IAH Selected Papers on Hydrogeology. Taylor & Francis. http://dx.doi.org/10.1201/9780203889497.ch2.

IAEA, UNDP, GEF, 2013. Regional strategic action programme for the Nubian Aquifer System.

IGRAC, IWMI, 2017. Ramotswa Information Management System (RIMS). Webbased data and information system for Ramotswa Transboundary Aquifer between Botswana and South Africa. Online, URL: http://ramotswa.un-igrac.org (Accessed 17/05/2017).

IGRAC, UNESCO-IHP, 2015a. Transboundary aquifers of the world [map]. 15 Scale 1: 50 000 000, edition 2015. IGRAC, Delft, Netherlands.

IGRAC, UNESCO-IHP, 2015b. Guidelines for multidisciplinary assessment of transboundary aquifers. Draft Version. IGRAC Delft.

IGRAC, UNESCO-IHP, 2016. IGRAC GGIS: TWAP Groundwater data and information portal. Data from UNESCO-IHP, UNEP, 2016. Transboundary Aquifers and Groundwater Systems of Small Island Developing States: Status and Trends. Transboundary Waters Assessment Programme TWAP. Online, URL: http://twapviewer.un-igrac.org (Accessed 15/05/2017).

IGRAC, 2009. Transboundary aquifers of the world [map]. Scale 1: 50 000 000, edition 2009. IGRAC, Utrecht, Netherlands.

IGRAC, 2012. Transboundary aquifers of the world [map]. Scale 1: 50 000 000, edition 2012. IGRAC, Delft, Netherlands.

IGRAC, 2017. Global Groundwater Information System (GGIS); Transboundary Aquifers of the World. Online, URL: http://tbamap.un-igrac.org (Accessed 15/05/2017).

Masiyandima, M., Giordano, M.F., 2007. Sub-Saharan Africa: opportunistic exploitation. In: Giordano, M.F., Villholth, K.G. (Eds.), The Agricultural Groundwater Revolution: Opportunities and Threats to Development. Cabi in association with IWMI, pp. 79–99. http://dx.doi.org/10.1079/9781845931728.0000.

Meyer, R., 2014. Hydrogeology of groundwater region 10: the karst belt. WRC Report No. TT 553/14. Water Research Commission, Gezina.

ORASECOM, 2000. Agreement Between the Governments of the Republic of Botswana, the Kingdom of Lesotho, the Republic of Namibia, and the Republic of South Africa on the Establishment of the Orange-Senqu River Commission.

ORASECOM, 2017. ORASECOM Resolution on Nesting the Stampriet Transboundary Aquifer System (STAS) Multi-Country Cooperation Mechanism (MCCM) in ORASECOM.

OSS, 2011. Iullemeden Aquifer System (Mali-Niger-Nigeria) Transboundary Diagnostic Analysis. OSS, Tunis.

Puri, S., Aureli, A., 2005. Transboundary aquifers: a global program to assess, evaluate, and develop policy. Ground Water 43, 661–668. http://dx.doi.org/10.1111/j.1745-6584.2005.00100.x.

Quadri, E., 2017. The nubian sandstone aquifer system −A case of cooperation in the making. In: World Water Congress XVI, International Water Resources Association (IWRA). Cancun, Mexico.

Riedel, C., Döll, P., 2015. Global-scale modeling and quantification of indicators for assessing transboundary aquifers. In: GEF Transboundary Waters Assessment Programme (TWAP). Frankfurt,.

SADC, 1995. Protocol on shared watercourses in the Southern African Development Community (SADC), signed at Johannesburg, 28 August 1995.

SADC, 2000. Revised Protocol on Shared Watercourses in the Southern African Development Community.

Staudt, M., 2003. Environmental hydrogeology of Ramotswa (South East District, Republic of Botswana). Department of Geological Survey Botswana and BGR, Lobatse.

Struckmeier, W.F., Gilbrich, W.H., van der Gun, J., Maurer, T., Puri, S., Richts, A., Winter, P., Zaepke, M., 2006. Groundwater resources of the world. Transboundary aquifer systems. Scale 1:50 000 000.

Sturchio, N.C., Du, X., Purtschert, R., Lehmann, B.E., Sultan, M., Patterson, L.J., Lu, Z.-T., Müller, P., Bigler, T., Bailey, K., O'Connor, T.P., Young, L., Lorenzo, R., Becker, R., El Alfy, Z., El Kaliouby, B., Dawood, Y., Abdallah, A.M.A., 2004. One million year old groundwater in the Sahara revealed by krypton-81 and chlorine-36. Geophys. Res. Lett. 31 (5). http://dx.doi.org/10.1029/2003GL019234. n/a-n/a.

Tujchneider, O., van der Gun, J. (Eds.), 2012. Analysis Report of the Groundwater Working Group − IW Science. The United Nations University.

UNDESA, 2017. World population prospects: The 2017 Revision Data 2015. Online, URL: https://esa.un.org/unpd/wpp/ (Accessed 04/07/2017).

UNECA (Economic Commission for Africa), Organization of African Unity, African Development Bank, 2000. Safeguarding life and development in Africa. A vision for water resources management in the 21st century. In: Africa Caucus Presentations. Second World Water Forum. The Hague, the Netherlands. Addis Ababa. p. 45.

UNESCO, IAH, FAO, 2000. Launching of an international initiative on shared aquifers. In: 14th Session of the Intergovernmental Council. Paris.

UNESCO-IHP, IGRAC, 2016. Stampriet Transboundary Aquifer System Assessment. Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) − phase 1. Paris.

UNESCO-IHP, UNEP, 2016. Transboundary aquifers and groundwater systems of small island developing states: status and trends. Transboundary Waters Assessment Programme TWAP. UNEP, Nairobi.

UNESCO-IHP, IGRAC, WWAP, 2012. GEF Transboundary Waters Assessment Programme (TWAP) Methodology and Execution Arrangements: Transboundary Aquifers and SIDS Groundwater Systems. Paris.

UNESCO-IHP, 2009. Atlas of transboundary aquifers. Global Maps, Regional Cooperation and Local Inventories ISARM Programme. UNESCO-IHP, Paris.

Vasak, S., Kukuric, N., 2006. Groundwater Resources and Transboundary Aquifers of Southern Africa. IGRAC, Utrecht, Netherlands.

Villholth, K.G., 2013. Groundwater irrigation for smallholders in Sub-Saharan Africa – a synthesis of current knowledge to guide sustainable outcomes. Water Int. 38 (4), 369–391. http://dx.doi.org/10.1080/02508060.2013.821644.

Wallin, B., Gaye, C., Gourcy, L., Aggarwal, P., 2005. Isotope methods for management of shared aquifers in Northern Africa. Ground Water 43, 744–749. http://dx.doi.org/10.1111/j.1745-6584.2005.00073.x.