Transboundary aquifer mapping and management in Africa: a harmonised approach

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Introduction

According to the United Nations International Law Commission's (UNILC) Draft Articles on the Law of Transboundary Aquifers, a transboundary aquifer or a transboundary aquifer system (TBA) is defined as "an aquifer or aquifer system, parts of which are situated in different States" (Article 2c, Stephan 2009). While in principle the term 'transboundary' also refers to local jurisdictional boundaries (of e.g. a community, municipality, province, or region), or to river catchment delineation, the UNILC definition is adhered to here. While not spelled out in the short definition of a TBA, in practical identification and verification of a TBA, the spatial delimitation, hydrogeological similarity, recharge and discharge mechanisms and zones, and significant hydraulic connectivity between the national compartments of the TBA are important and should be established and agreed upon between aquifer-sharing states. The UNILC definition of TBAs does not imply that groundwater resources in border regions outside of TBAs do not exist or manifest similar properties as TBAs. However, the extent and significance of such resources are considered of limited transboundary importance or their transboundary extent have not been identified or acknowledged.

This report focuses on the internationally shared aquifers in Africa. While progress in understanding the importance and extent of these water resources and incipient management frameworks are evident from many reports, relatively little attention has been accorded these resources in the scientific literature. TBAs have been highlighted only since the beginning of the century, initially by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and specifically with the launch in 2000 of the International Shared Aquifer Resources Management Project (ISARM) by UNESCO's Intergovernmental Scientific Cooperative Programme in Hydrology and Water Resources (UNESCO-IHP; Puri and Aureli 2005; UNESCO 2010, 2008, 2004).

Prior to 2000, limited knowledge of TBAs was available, and this certainly was not commensurate with the level of knowledge and management tools and approaches bestowed internationally shared river systems. Hence, an immediate need was to identify, delineate, and map the TBAs at various scales, from local, to regional, to global. The first results of TBA mapping in Africa appeared in 2004 when ISARM published the first Africa-wide TBA map after the International Workshop on 'Managing Shared Aquifer Resources in Africa', held in Tripoli, Libya, in June 2002 (UNESCO 2004). Since then, several updated world maps of TBAs have been published, e.g. by the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP 2006) and the International Groundwater Resources Assessment Centre (IGRAC 2009, 2012a). Each evolution of maps comes with an increase in the number of aquifers identified and a progressively better delineation of the TBAs. Presently, more than 450 TBAs have been identified globally (IGRAC 2012a). This is far more than the number of international river basins at 263 (Cooley et al. 2009). While recognizing the mapping exercise as an on-going and iterative process, the various available maps lend themselves to confusion and inconsistencies (IGRAC 2012), and there is a need to coordinate and harmonise the present approaches. This is presently underway as IGRAC is currently the principal institution involved in global-level mapping of TBAs (N. Kukuric, IGRAC, personal communication, 2012). This report intends to support this process specifically for the African continent.

Focus on TBAs comes from the recognition of increasing stress on available water resources. Groundwater resources are already heavily relied on in Africa, with an estimated 75 % of the African population dependent on groundwater for basic water supply (UNECA et al. 2000). However, with population increase, climate change and need to combat growing food insecurity, demands for groundwater are set to increase in the future (MacDonald et al. 2012; Clifton et al. 2010). Transboundary groundwater resources in Africa represent and provide resources that at present are not sufficiently explored and utilised or they represent sources that are generally developed indiscriminately and commonly unilaterally (Scheumann and Herrfahrdt-Pähle 2008) with potential adverse impacts on the resources and international relations. Hence, cross-boundary knowledge development, coordination, cooperation and management is necessary to minimise conflict risk and environmental degradation and to expand shared benefits. Conflicts can occur because of groundwater-quality issues, reduced groundwater availability and/or socio-economic issues (e.g. inequity in user access across borders leading to human unrest or migration during drought). Unilateral uses, non-acceded monopole use by few users on one side of the border or adverse transboundary impact on groundwater resources or groundwater-dependent eco-systems from land-use changes is the consequence of failed TBA management. A cautionary example, while outside the region, of this is the Judean and Samarian aquifer systems shared by Israel and the Palestinian Territories. Israel uses 82 % of the abstracted groundwater due to its high agricultural and urban development, while the Palestinians claim the right to a larger share because they suffer from low water availability per capita as well as poor water quality (Eckstein and Eckstein 2003a). Similar, but less extreme examples can be found in Africa, e.g. in the case of the Pomfret-Vergelegen dolomite aquifer (or Khakhe/Bray dolomite aquifer) between South Africa and Botswana (AFS7 in Fig. 1 and Appendix) (Cobbing et al. 2008; Turton et al. 2006), the Limpopo River alluvial aquifer between South Africa, Zimbabwe and Mozambique (AFS 9) (Owen 2012; Cobbing et al. 2008), and the aquifer systems of the Lake Chad basin (AFWC14), shared by Chad, Cameroon, Niger, Nigeria, the Central African Republic, Sudan, Algeria, and Libya (Scheumann and Alker 2009).

As a significant proportion of Africa's water resources are contained in large international water bodies such as rivers, lakes and aquifers, the sensible management and sharing of these resources and their benefits are an issue of international importance, in terms of water security as well as for the long-term peaceful and equitable development of the continent. International river and lake basin organisations (R/LBOs) and associated international agreements on joint management of surface-water bodies have been established since the 1960s, initially in western Sub-Saharan Africa and later pan-Africa, with great financial and technical support from the international community (NEPAD et al. 2011; AMCOW and ANBO 2007). However, only recently has effort been put into defining the most appropriate institutional locus for TBA management in Africa as these underground resources generally do not coincide geographically with the extent of either lake or river basins.

Against this backdrop, this study provides an integrated review of the status and progress of TBA mapping and management in Africa, thereby filling a significant gap in the international scientific literature. Firstly, the report reviews and contributes to the efforts on creating an Africa-wide TBA map. This includes identifying additional TBAs not previously mapped, superimposing for the first time the map of TBAs on the R/LBs, proposing a harmonised nomenclature, and making an updated inventory on key TBA data. Secondly, the report discusses strategic legal and institutional frameworks applicable to TBA management and associated requirements to further progress effective TBA management in Africa. The overall objective of the report is to contribute to harmonised and integrated approaches to mapping and management of TBAs on the continent.

Current status of the TBA identification and mapping efforts in Africa

In 2004, ISARM published the first Africa-wide TBA map presenting 38 TBAs delineated by ellipses (UNESCO 2004; Table 1). Subsequently, WHYMAP was the first to present a world-wide TBA map (Struckmeier et al. 2006). In 2009, the inter-agency cooperation arising from ISARM (UNESCO-FAO-IAH-UNECE) with the support of IGRAC marked 40 major TBA systems in Africa (Puri and Aureli 2009). Concurrently, IGRAC published a global TBA map for the 5th Water World Water forum in Istanbul, Turkey (IGRAC 2009) identifying a total of 41 African TBAs. Unfortunately, there is no harmonisation in the labelling system used for TBAs of the three maps and associated databases. In 2012, IGRAC presented an updated version of the global TBA map at the 6th Water World forum in Marseille, France (IGRAC 2012a). This map shows 71 aquifers in Africa (Table 1), and the ID numbers (consisting of a pre-fix of

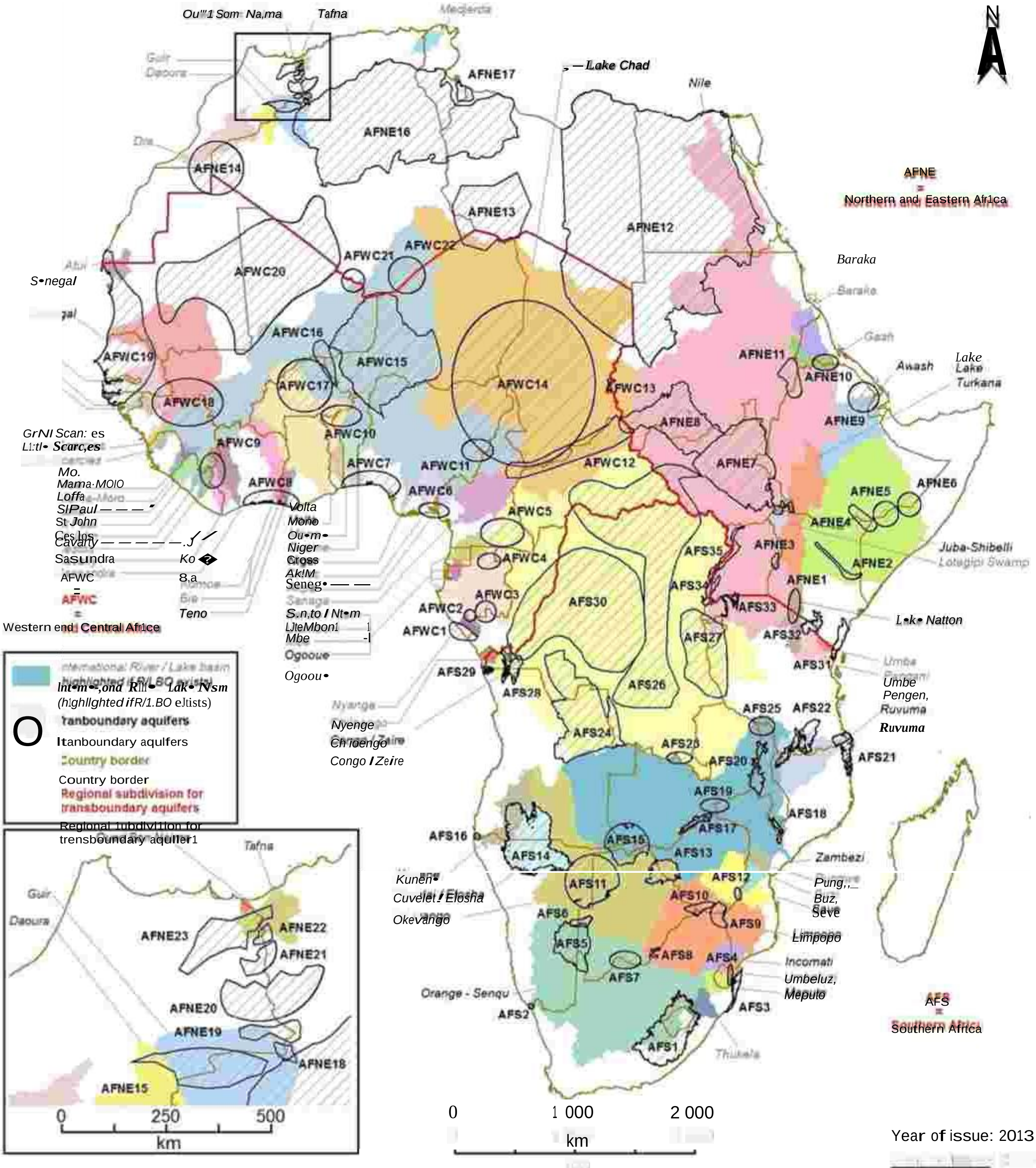


Fig. 1 Transboundary aquifers and international river/lake basins in Africa (see also Appendix)

letters signifying the region/continent and a number) given to the aquifers were changed compared to the 2009 map. In the 2012 map, the ID numbers are actually given starting with 1 in the south east of the continent and finishing with 71 in the north west of the continent; whereas in 2009, the ID numbers are more random, e.g. in the SADC region, increasing from north to south—with some discontinuity when new aquifers are identified—then for the rest of the continent the ID numbers increase from north to south also with some randomness.

Table 1 Evolution of the number of TBAs in Africa, inventoried and mapped by various efforts and subdivided into regions

African region[a]	UNESCO 2004	WHYMAP 2006	IGRAC 2009	IGRAC 2012a	This report 2012
North Africa	6	6	7	9	15
Western and Central Africa (except countries in SADC[b])	9	9	9	22	22
Eastern Africa (except countries in SADC)	5	5	5	6	8
Southern Africa (SADC countries)	18	20	20	34	35
Total	38	40	41	71	80

[a] According to United Nations sub-region definition (UN data 2013)

[b] SADC Southern African Development Community

Table 1 shows the evolution in the number of TBAs inventoried by ISARM, WHYMAP and IGRAC during the last decade. A significant increase in numbers is noticed in Southern Africa and Western/Central Africa, due primarily to activities of ISARM in both areas. As has been done in Southern Africa in collaboration with SADC, the work of ISARM is presently planned to improve the identification and delineation of the TBAs in Central/Western (First ISARM Central Africa and Second ISARM West Africa Workshop in Douala, Cameroon; 16–19 May 2011), and East Africa—the Sahara and Sahel Observatory (OSS) currently implements the "Mapping, Assessment and Management of Transboundary Water Resources in the IGAD sub-region (MAM/IGAD)" project (IGRAC 2012a).

Disparity and non-uniqueness in labelling systems as well as inconsistency in the numbering of newly identified TBAs in Africa relative to their location makes it relatively difficult to locate these aquifers and prompts the need for a more harmonised and systematic nomenclature and labelling system. The scheme proposed here divides Africa into three regions (Northern/Eastern Africa, Western/Central Africa and Southern Africa; Table 2; Fig. 1), each with its own unique ID and consecutive numbering scheme. The system facilitates the labelling of new aquifers and the localizing of existing aquifers. The subdivision acknowledges the importance and efforts of the regional economic communities (RECs) in Africa in terms of transboundary water resources management and regional integration (Granit 2010; Öjendal et al. 2010). Each zone has an abbreviation (AFNE, AFWC and AFS) used as a pre-fix for the TBA number. These prefixes have been inspired by IGRAC, which uses the AF prefix for the African TBAs. As a primary nomenclature, acknowledging that new numbers may break this pattern, TBA numbering is done in an east–west and south–north pattern starting with 1 in the south east part of the zone and finishing in the north west of the zone, adhering to the IGRAC-2012 version. Hence, the main difference in the new system is that TBA IDs include a regional location identifier as well as a continental signature.

The zone separation is based on existing RECs, their active involvement in transboundary water-resources management (Table 2), the riparian countries of major river basins (i.e. Niger and Nile) and similarity in climatic conditions. Equality in the number of identified TBAs in each zone is considered as well. For example, Eastern and Northern Africa form one area because of the non-negligible number of TBAs in the Nile River basin in Eastern Africa. Likewise, Western and Central Africa are coalesced into one region, despite climatic differences, in order to maintain a similar number of TBAs in each region. Each TBA is classified into one of these three zones based on the location of the majority of its surface area within the regions sharing it. Hence, for example the Disa aquifer (AFWC13, in Fig. 1 and Appendix) fully located in the Lake Chad basin belongs to the AFWC zone, and the Mourzouk-Djado basin (AFNE13) mainly located in Libya is classified in the AFNE zone. Figure 1 shows the map of the 80 TBAs currently identified in Africa using the new nomenclature, and the Appendix presents a table of the TBAs including different names used in the literature for individual aquifers as well as some hydrogeological data and information on the aquifers (aquifer rock type, mean annual rainfall, and recharge) when available from the literature. Using the proposed nomenclature, new TBAs can easily be added in each zone with subsequent consecutive numbers. The main advantage of the proposed scheme is that it logically and systematically facilitates the location of existing TBAs as well as the specification of unique IDs to new aquifers. It is likely that such regionalisation and use of a similar ID system for TBAs are possible and beneficial for other continents as well.

In the Appendix, one main name for each aquifer is highlighted to suggest a single common accepted name for the TBAs. The objective is to reduce confusion because different aquifer names exist in the literature for the same aquifer. Some reasons for different names stem from:

- Improvement in the identification and delineation of the aquifers as being transboundary in nature, e.g. the separation of one TBA into several TBAs (e.g. AFNE18 to AFNE23) or the union of two or more aquifers into one TBA (e.g. Northern Kalahari/Karoo basin, AFS11)
- Co-existence of names reflecting the transboundary aquifer and names referring to the local/national/town association of the aquifer (e.g. Nata Karoo sub-basin, AFS15)
- Discrepancy in TBA names across borders due to difference in spelling of, e.g. rivers giving names to aquifers

A few TBAs (mainly in the Central/Western region) only have an ID but do not have a name (marked with ? in the Appendix). This can be explained by the presently preliminary assessment of these resources. The Appendix gives

Table 2 The proposed regional sub-division for TBA nomenclature in Africa

Sub-division zone name (code name)	African continental countries	Regional economic communities (RECs) concerned[a]
Northern and Eastern Africa (AFNE)	Algeria, Djibouti, Egypt, Eritrea, Ethiopia, Kenya, Libya, Morocco, Somalia, South Sudan, Sudan, Tunisia, Uganda and Western Sahara	IGAD[b] (A) COMESA[c] (PA) CEN-SAD[d] (PA) EAC[e] (PA) AMU[f] (N)
Central and Western Africa (AFWC)	Republic of Benin, Burkina Faso, Cameroon, Central African Republic (CAR), Chad, Republic of the Congo, Republic of Côte d'Ivoire, Equatorial Guinea, Gabon, Republic of Gambia, Republic of Ghana, The Republic of Guinea, The Republic of Guinea Bissau, The Republic of Liberia, Republic of Mali, Mauritania, Republic of Niger, Federal Republic of Nigeria, Republic of Senegal, Republic of Sierra Leone and Togolese Republic	ECOWAS[g] (A) ECCAS[h] (PA) CEN-SAD (PA) AMU (N)
Southern Africa (AFS)	Angola, Botswana, Burundi, Democratic Republic of Congo (DRC), Lesotho, Madagascar, Malawi, Mozambique, Namibia, Rwanda, South Africa, Swaziland, United Republic of Tanzania, Zambia and Zimbabwe	SADC[i] (A) COMESA (PA) EAC (PA)

[a] A active; PA poorly active; N non-active in transboundary water resources management, according to NEPAD et al. 2011

[b] Intergovernmental Authority on Development: Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda

[c] Common Market for Eastern and Southern Africa: Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Libya, Malawi, Rwanda, South Sudan, Sudan Swaziland, Uganda, Zambia and Zimbabwe

[d] Community of Sahel-Saharan States: Republic of Benin, Burkina Faso, Central African Republic (CAR), Chad, Republic of Côte d'Ivoire, Djibouti, Eritrea, Republic of Gambia, Republic of Ghana, The Republic of Guinea, The Republic of Guinea Bissau, Kenya, The Republic of Liberia, Libya, Republic of Mali, Mauritania, Morocco, Republic of Niger, Federal Republic of Nigeria, Republic of Senegal, Republic of Sierra Leone, Somalia, Sudan, Togolese Republic and Tunisia

[e] East African Community: Burundi, Kenya, Republic of Tanzania, Rwanda, Uganda

[f] Arab Maghreb Union: Algeria, Libya, Mauritania, Morocco, Tunisia and Western Sahara

[g] Economic Community of West African States: Republic of Benin, Burkina Faso, Republic of Côte d'Ivoire, Republic of Gambia, Republic of Ghana, The Republic of Guinea, The Republic of Guinea Bissau, The Republic of Liberia, Republic of Mali, Republic of Niger, Federal Republic of Nigeria, Republic of Senegal, Republic of Sierra Leone and Togolese Republic

[h] Economic Community of Central African States: Cameroon, Central African Republic (CAR), Chad, Republic of the Congo, Equatorial Guinea and Gabon

[i] Southern African Development Community: Angola, Botswana, Democratic Republic of Congo (DRC), Lesotho, Madagascar, Malawi, Mozambique, Namibia, South Africa, Swaziland, United Republic of Tanzania, Zambia, and Zimbabwe

approximate figures for population (UNEP 2000) and area for each TBA (determined from various database sources) in order to highlight the importance of the TBAs in Africa. Results show that the TBAs represent approximately 42 % of continental Africa's land area and 30 % of the population, which can be compared to 45 % of area (Wolf et al. 1999) and 69 % of population (this study) for the 63 international river basins in Africa. There is a huge difference between the aquifers in terms of population living within individual TBAs, reaching approximately 63 million in the case of the Nubian Sandstone aquifer system (AFNE12) to less than a hundred inhabitants (Coastal Sedimentary basin 4, AFS16; and L'Air Cristalline aquifer, AFWC21). The same heterogeneity exists in terms of areal extent, which can be smaller than 1,500 km^2 (Jbel El Hamra aquifer, AFNE22 and Figuig aquifer, AFNE18) and larger than 2.6 mill. km^2 (Nubian Sandstone aquifer system, AFNE12). The latter is comparable to the size of the Lake Chad River basin (2.4 mill. km^2). TBAs are shared between two and up to eight states, the latter being the case for the Lake Chad basin (AFWC14). In addition, Table 3 gives approximate figures for the percentage of the country area lying within TBA basins.

Difficulties in TBAs identification and delineation typically arise from the common-place unilateral study of the aquifers, if any at present. A typical example is the South

West Kalahari/Karoo aquifer (AFS5) shared by South Africa, Botswana and Namibia. Namibia has investigated the aquifer since 1915, while limited information about this aquifer is available from the two other riparian countries, probably because of earlier lack of interest in this resource due to water-quality degradation toward South Africa and Botswana and limited human development in these areas (Alker 2008a). Few integrated international studies on TBAs have been done and the existing studies are mostly on the North Western Sahara aquifer system (AFNE16) and the Irhazer-Iullemeden basin (AFWC15), through studies coordinated by the Sahara and Sahel Observatory (OSS; i.e. the UNEP/OSS/GEF Iullemeden Aquifer Project and the UNEP/OSS/GEF Northwest Sahara Aquifer Project), as well as the Nubian Sandstone aquifer system (AFNE12).

As part of the on-going process of TBA identification and mapping, the map proposed in this report presents, based on a thorough literature review, 80 TBAs in Africa. The nine additional TBAs included compared to the IGRAC 2012 map derive from the following observations:

– The International Network of Water-Environment Centre for the Balkans (INWEB), which mapped the TBAs in the Mediterranean states, presents fifteen TBA systems in the Northern African region (INWEB

Table 3 Approximate percentage of country area located within TBAs in Africa

Country	Percentage (%) of country area within TBAs	Country	Percentage (%) of country area within TBAs	Country	Percentage (%) of country area within TBAs
Algeria	41	Gabon	16	Rwanda	24
Angola	24	Gambia	100	Senegal	84
Benin	30	Ghana	5	Sierra Leone	0
Botswana	23	Guinea	40	Somalia	5
Burkina Faso	55	Guinea Bissau	41	South Africa	12
Burundi	86	Kenya	9	South Sudan	81
Cameroon	36	Lesotho	100	Sudan	32
CAR	43	Liberia	11	Swaziland	12
Chad	73	Libya	72	Tanzania	13
DRC	65	Malawi	29	Togo	10
Republic of Congo	34	Mali	47	Tunisia	47
Cote d'Ivoire	15	Mauritania	42	Uganda	9
Djibouti	28	Morocco	15	Zambia	8
Egypt	89	Mozambique	5	Zimbabwe	11
Equatorial Guinea	0	Namibia	28	Western Sahara	12
Eritrea	13	Niger	51		
Ethiopia	10	Nigeria	33		

2012), while the IGRAC database shows only nine, principally due to smaller aquifers between Algeria and Morocco indicated, rather than delineated. The six additional aquifers shared between these countries are AFNE18–AFNE23

– The identified "Rift aquifer", shared by Kenya, Tanzania and Uganda, has been deleted on the IGRAC 2012 map compared to the 2009 version. However, regardless of poor water quality (Lake Natron and Lake Magadi are not freshwater) and low groundwater potential (Mwango et al. 2004; Kashaigili 2010), groundwater flow seems to exist from Lake Naivasha to Lake Magadi (Becht et al. 2006) as well as a hydrogeological link between Lake Natron and Lake Magadi (Hillaire-Marcel and Casanova 1987). AFNE1 has been added to Fig. 1 to reflect this.
– Abiye (2010) identified and discussed the TBAs in East Africa. He included a transboundary aquifer, here called the Mareb aquifer for lack of other published name, between Eritrea and Ethiopia, which is not present on the IGRAC 2012 map; thus, the AFNE10 has been added.
– Rahube (2003) worked on the recharge and groundwater resources of Lokalane-Ncojane basin (between Botswana and Namibia). This work shows that a TBA exists in the region of the Ncojane basin. Location of this aquifer does not seem to coincide with the delineation of the SW Kalahari/Karoo basin nearby (AFS5). Hence, AFS6 (Fig. 1) has been added as an individual TBA though additional work may be needed to verify its separate unity.

The updated map in Fig. 1 depicts the delineation of TBAs according to the best available knowledge. Hence, where boundaries are well known (and in most cases agreed by co-riparians), the TBAs are shown as polygons. In cases where the boundaries are not well known, the TBAs are given as circles or ellipses. Due to uncertainty in boundaries, overlap of some TBAs appears. Also, TBA polygon shape shows more details in TBA delineation in the AFS area and in Northern Africa, indicating relatively advanced delineation in these areas. The additional nine aquifers in Fig. 1 relative to IGRAC map will have to be reaffirmed and consolidated through their mapping and consultation processes.

Transboundary aquifer management: an emerging framework

The complexities and diversity in TBA physical and hydraulic configurations entail challenges for mapping that are distinct from surface-water courses. These challenges are increasingly explored in an attempt to develop typologies, indicators, and associated best-management strategies (UNESCO-IHP 2011; Scheumann and Alker 2009; UNECE 2007; Jarvis et al. 2005; Eckstein and Eckstein 2003b; Barberis 1991). Still, groundwater that transcends international borders is a critical missing link in attaining a truly integrated approach to transboundary water-resources management (TWM), which has hitherto been totally dominated by a surface-water focus, practically ignoring the intricate and almost ubiquitous interconnectedness between these systems.

Globally, experience with practical TBA management is limited (Eckstein 2011), and Africa is no exception (Eckstein 2011; Scheumann and Herrfahrdt-Pähle 2008). Having said this, there is currently a strong drive from the international donor community as well as some of the African countries themselves to leverage increased efforts and to include TBA management into holistic TWM (Aureli and Eckstein 2011; Stephan 2009). The approach is currently mostly pre-emptive in the sense that significant conflicts over shared aquifers are not apparent or are still not fully documented in terms of extent and underlying causes (Scheumann and Alker 2009). A critical prerequisite for better grasping the risk and implications of conflict is through increased understanding of the resource and the human interaction and impacts on it and associated dependent systems, which for the most part is missing, or emerging in Africa.

Groundwater in Africa has traditionally been associated with rural water supply and drought prevention through dispersed schemes and low abstraction rates (mostly Sub-Saharan Africa), or more intensive use associated with development for urban use and larger-scale irrigation (mostly Northern Africa). While this image is slowly changing, with increasing attention to and demand for groundwater development for urban and industrial use and irrigation, as well as climate change, at various scales in Sub-Saharan Africa, TBAs will no doubt in the future play a significant role in meeting increased water demands for multiple purposes. Hence, an increased focus on TBA management is fully warranted and has to transcend the traditional ways of viewing groundwater, namely as a small-scale extensive use source. TBAs, and groundwater in general in Africa, will have to serve multiple uses at various scales and levels of development and often simultaneously within the same geographic locations. Furthermore, reconciling such development with significant ecosystem dependence on groundwater at local and transboundary scale for the inherent value of these systems and for the sustained human reliance on them is a major challenge in Africa, where only recently an understanding of these groundwater-dependent ecosystems and required environmental flows and characteristics related to groundwater is emerging (Colvin et al. 2007).

On-going challenges associated with TBA management in Africa are related to:

1. Identifying, delimiting and understanding TBAs
2. Developing appropriate legal frameworks for their joint and sustainable management
3. Developing appropriate institutional setups
4. Ensuring that development and benefits from TBA are inclusive and equitable

In the following, each of these challenges is briefly discussed, along with present progress and requirements to proceed.

Identifying, delimiting and understanding TBAs

Transboundary aquifers are inherently not different from other aquifers. Their distinguishing character pertains to the fact that they cross international borders implying complexities in their optimal management. Many of these aquifers, however, to have more than local management interest, are relatively large and may have regional deep subsurface flow characteristics (Tóth 1963), lending themselves to the need for understanding the implications of far-reaching often slow lateral inter-basin flow processes (e.g. Gleeson and Manning 2008) besides any interactions with surface-water bodies.

The unit of management, equivalent to the river basin in traditional river-basin management, is critical to ascertain and map. Initial efforts by IGRAC and ISARM developed strategies for these processes, involving converging national and emerging regional and continental geological maps (Vasak and Kukuric 2006; Puri and Aureli 2005). Increasingly, modern hydrogeological technologies like tracer and isotope studies (Wang et al. 2010), air-borne geophysics (Siemon et al. 2005) and satellite-based remote sensing (Saradeth et al. 2010; Marsala et al. 2009) are used to complement more traditional hydrogeological studies, though a more transboundary focus is warranted. Joint cross-boundary interpretation and harmonisation of maps along with characterisation of the border region from hydrogeophysical as well as socio-economical perspectives helps develop an overall conceptual model of the aquifer or aquifer system (Jarvis 2006). The need for pursuing a multi-disciplinary, consultative and dynamic process in delineating and characterising a TBA in order to address complexities, uncertainties and changes in states, processes and stress factors at TBA-system scale, as well as those that capture the social, economic and governance factors associated with human impacts on the TBAs is increasingly acknowledged (UNESCO-IHP 2011; Jarvis 2006). Emphasis on consensus and transparency regarding a preliminary delineation and a conceptual model may be more conducive for further joint assessment of a TBA, and hence reducing uncertainties, than excessive emphasis on a detailed but less open and shared assessment by one or a sub-set of stakeholders. Data on TBAs in Africa reside with national institutions, transboundary R/LBOs, and newly developed data sharing mechanisms related to specific TBAs (see next section) as well as international organisations like IGRAC.

Developing appropriate legal frameworks for joint and sustainable management of TBAs

Legal frameworks for TWM continually evolve, reflecting a growing understanding of best practices and pertinent principles and issues (Giordano et al. 2013; Conca et al. 2006). The topic of groundwater illustrates this very well. Prior to 1950, practically no attention was paid to groundwater in TWM agreements (Giordano et al. 2013). Increasingly, groundwater attains significance in treaties, with explicit mentioning and dedicated agreements with specific groundwater provisions (Eckstein 2011; Burchi and Mechlem 2005). However, despite significant efforts to harmonise the UN Convention on the Law of the Non-Navigational Uses of International Watercourses (UNWCC; United Nations 1997) and the UNILC Draft Articles on TBAs (the UNILC Draft Articles take the UNWCC as a starting point in an effort to harmonise international rules on water resources and the UNWCC was based on articles drafted by the UNILC), there is still a significant stride to be achieved in obtaining a fully integrated and holistic approach to the various water systems in international law. This is due to the early exclusive focus on the visible water resources (international rivers and later also lakes), lack of understanding of groundwater functioning among legislators, legal scholars and policy makers (Eckstein and Eckstein 2003b), and the tardiness of adjusting existing international law despite growing recognition of the needs to do so (Cooley et al. 2009).

Notwithstanding the fact that the United Nations Economic Commission for Europe's Convention on the Protection and Use of Transboundary Watercourses and International Lakes (The UNECE Water Convention; UNECE 1992) is soon to be open for universal accession (GWP 2013), there are presently basically two options to adopt groundwater into international agreements based on international law, albeit neither is currently in force: either by adopting the 1997 UNWCC (presently ratified by 10 parties to the Convention out of 35 required for it to enter into force; International Water Law Project 2013), which defines groundwater as a physical extension of the surface-water body within the watercourse spatial domain, or by using the 19 Draft Articles on the Law of Transboundary Aquifers (still not adopted by the UN General Assembly, UNGA). The discrepancies and insufficiencies in terms of addressing groundwater universally with the UNWCC relates to the fact that an aquifer does not comply with the notion of 'normally flowing into a common terminus' as the river system does, and its boundaries do not necessarily conform with the river basin. In addition, some aquifers may not be associated with a traditional water course as, e.g. fossil or 'confined' groundwater (Eckstein and Eckstein 2003b). Confined groundwater here refers to water contained in aquifers that does not relate to surface water (McCaffrey 2011: Eckstein and Eckstein 2003b; UNGA 2003), which potentially causes confusion on applicability as it is inconsistent with conventional hydrogeology terminology. To partly compensate for these legal deficiencies, the UN International Law Commission (UNILC) has developed—in consultation and collaboration with technical and hydrogeological partners, like UNESCO, IAH, FAO, UNECE (UNGA 2003)—and proposed for adoption to the UNGA a set of 19 Draft Articles on the Law of Transboundary Aquifers (Stephan 2009; United Nations 2008). These draft articles, the final form of which (convention or guidance document) is still pending a decision by the UNGA at its 68th session in 2013 (Eckstein 2011) in order to potentially have legally binding character, focus on the transboundary aquifers and hence fill a significant gap in international water law. They are quite comprehensive and include direct mentioning of aquifer relationships with surface-water courses and ecosystems and, hence, are presently the most comprehensive, albeit debated (Dellapenna 2011; McCaffrey 2011), set of international legislation available for TBAs. In the interim, the UNGA promotes bilateral or regional agreements between countries sharing aquifer systems (UNGA 2012). The Guarani aquifer in South America is the first legal agreement based on the Draft Articles (Villar and Ribeiro 2011).

In Africa, legal agreements on groundwater are evolving, like in most parts of the world (Aureli and Eckstein 2011; Stephan 2009). Examples exist in the multilateral agreements to explicitly share data, jointly perform diagnostic analysis on TBAs, and to develop joint consultation mechanisms as a precursor for more formalised joint-management frameworks and institutions. Cases in point are the Nubian Sandstone Aquifer system (AFNE12) (agreement from 2000), North Western Sahara Aquifer system (AFNE16) (agreement from 2002) (GEF 2012; Eckstein 2011; Stephan 2009; Burchi and Mechlem 2005), and Irhazer-Iullemeden (AFWC15) (agreement from 2009) (Eckstein 2011), while Orange-Senqu River basin, and Lake Victoria basin have a high degree of focus on groundwater in their shared R/LBs (Braune and Xu 2011). The first three pertain explicitly to the aquifers, while the latter two hinge on existing river/lake basin organisations (R/LBOs) and their formalised agreements. Collaboration and present initiatives, not surprisingly, tend to reflect the importance and value of groundwater in more arid water-deficient areas with few or limited surface-water resources. They also reflect priorities of international donors and institutions, presently putting TWM high on the development agenda (GWP 2013; GEF 2012; UN-WATER 2008) and growing national awareness in critical areas or basins. Creating or revising legal frameworks for international cooperation on specific shared water courses is a tedious process, especially if the water-resource issues are contentious (e.g. the Nile River case, Cascão 2010). While initial efforts to bring partners together around improving the knowledge base may be relatively easy and facilitate trust building for potentially developing further agreements (Linton and Brooks 2011; Aureli and Eckstein 2011; Scheumann and Herrfahrdt-Pähle 2008), there is also a risk of losing momentum as the legal and political processes stall as seems to be the case for the Iullemeden aquifer system (International Water Law Project 2012), indicating the need for sustained support from international donors. It also points to the need of addressing critical TBAs at a point when mutual interest is expressed but while significant disputes have not evolved.

RECs, as part of their strategy for regional integration and development, and poverty alleviation, promote international natural resource, and specifically water, management as a means to foster sustainable development (Öjendal et al. 2010). SADC is taking a frontrunner position in this respect, with a dedicated Regional Strategic Action Plan (RSAP) for integrated water-resources management (SADC 2011), explicitly addressing TBA management, through transboundary diagnostic analysis and strategic action plans, as part of an ongoing groundwater-management programme in the region. This programme is overseen by a sub-committee on hydrogeology, which has also developed a guideline for groundwater development in the region (SADC-WSCU 2001). Furthermore, SADC has adopted the Protocol on Shared Watercourses in 1995 (with a revision in 2000; SADC 1995), which hinges on the UNWCC mentioned earlier (Braune and Xu 2011). The Protocol seeks 'to promote and facilitate the establishment of shared watercourse agreements and shared watercourse institutions for the management of shared watercourses' (SADC 2000). SADC is presently contemplating how to adopt the Draft Articles on the Law of TBAs (Braune and Xu 2011; UNESCO-IHP 2009). Furthermore, work is in progress in SADC to identify 'troublesome' TBAs in order to accord prioritised support (Davies et al. 2012) and on piloting harmonised and up- and out-scalable solutions to TBA management (SADC 2011; Christelis et al. 2010). Several TBA-relevant outputs of the SADC groundwater management programme have come out, including a region-wide seamless map of groundwater drought risk (Villholth et al. 2013).

Developing appropriate institutional setups

Establishing efficient and effective organisations for the management of TBAs is essential, and important lessons may be learned from experiences of R/LBOs in addressing

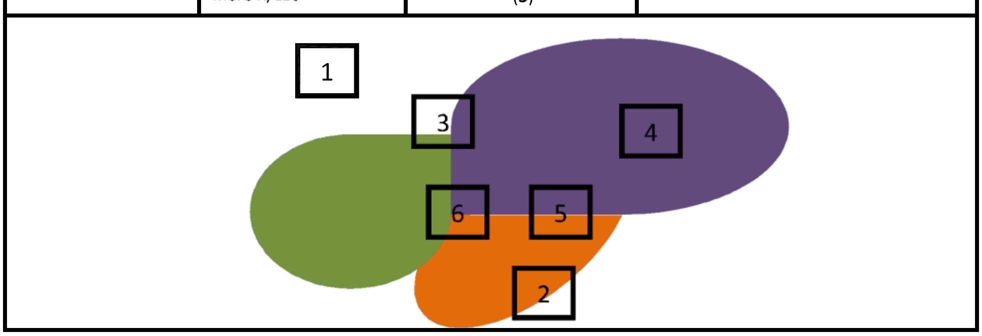
TWM (Schmeier 2010). In fact, the African Ministers' Council on Water (AMCOW) recommended in 2007 the R/LBOs as the nucleus for TBA management in Africa (Braune and Xu 2011). The immediate argument for this is their present integral role as custodians for shared river and lake-basin resources and the added advantage and options for further integration of the management of all hydrological resources in the same entity. Counterarguments include firstly that R/LBAs are not equipped, in terms of human capacity, financing, and authority, at present to take the responsibility of TBA management (Villholth and Vaessen 2013; Linton and Brooks 2011; NEPAD et al. 2011) and secondly that the geographical sphere of TBAs do not align with the spatial mandate of the R/LBOs (Schmeier 2010; Fig. 2). For some TBAs, international R/LBOs do not exist at all (18 cases according to Fig. 2, considering information on R/LBOs from AMCOW and ANBO 2007); hence, necessitating alternative management models. This can be because no R/LBO has yet been formalised for the area in question or because the TBA is located in an arid region with little perennial surface-water bodies, as in the case of some TBAs in Northern and Southern Africa. Figure 2, in conjunction with the listing of geographical types in the Appendix for the TBAs, may support first-hand geographical identification of possible international institutional management setups for individual TBAs; hence, creating a link between the mapping and the management framework put forward. However, it should be recognised that uncertainty prevails regarding the exact geographical boundaries of some TBAs.

Alternative solutions argue for the option of more localised management models suited to the particular scope and critical areas of the TBA and for the possibility to build particularly strong capacity on groundwater management in these areas (Scheumann and. Herrfahrdt-Pähle 2008; United Nations 2008). Yet, others argue for a strong involvement of the national authorities as the sovereignty aspect becomes critical in the management of cross-boundary water resources (Öjendal et al. 2010). Particularly for aquifers, this relates to extended issues of governance, with respect to, e.g. land use and geological, mineral, energy and sub-surface storage resources (Jarvis 2011). It becomes clear that an aquifer is more than the groundwater resource contained within it. So far, however, there persists ambiguity as to what the actual object of management is, whether the groundwater resource per se, or the broader resource along with its container, i.e. the geological formation. This is due to the use of the words 'groundwater' and 'aquifer' as synonyms in international law (Sanchez 2011). While beyond the scope of this report, the term used and the interpretation may, however, have far-reaching future implications (Jarvis 2011).

Whichever institutional setup is chosen for particular TBAs will depend on the trade-off between these advantages and disadvantages and the geographic, hydrogeological, socio-economic, and political context. R/LBOs and RECs

Fig. 2 Conceptual configuration of TBA location in relation to international river and lake basins (R/LBs); polygons represent river/lake basins, squares represent TBAs

Geographical type	Intersection of TBA with R/LB	Number of cases in Africa (number of cases with intersection with R/LBO)	Example of TBA with no R/LBO
1	None	3	Ain Beni Mathar (AFNE 20)
2	TBA partly inside a single R/LB	20 **(13)**	Coastal Sedimentary Basin 1 (AFS 31)
3	TBA partly inside two or more R/LBs	12 **(7)**	Tano Basin (AFWC 8)
4	TBA fully inside a single R/LB	23 **(22)**	Figuig (AFNE18)
5	TBA fully inside two R/LBs	18 **(17)**	Errachidia Basin (AFNE 15)
6	TBA fully inside three or more R/LBs	4 **(3)**	AFWC9



[a] TBA has no name according to IGRAC (2012)

will undoubtedly play an increasing role in TBA management in Africa as part of a harmonised and integrated approach, and the process of equipping these institutions for this mandate will have to be aligned with general efforts to build the capacity of these institutions. However, some hybrid multi-level solutions will most probably emerge, as national institutions with established capacity in hydrogeology will need to be drafted upon, e.g. as part of R/LBO sub-committees on hydrogeology (Orange-Senqu is an example, Braune and Xu 2011) to move informed management ahead, as well as to pledge national interests. Furthermore, increased cooperation between R/LBOs will be required to address those TBAs that transcend more than one river basin (types 3, 5, and 6 in Fig. 2). Finally, formalising management of TBAs at the international level may compromise more informal local level and traditional management approaches to groundwater that still have merit (Linton and Brooks 2011). This is an area of research that needs further attention.

Ensuring inclusive and equitable development and benefits from TBAs

In Africa in particular, poverty alleviation, food and water security, and climate resilience rank high on the national development agendas. Hence, ensuring the equitable and shared benefits of the water resources, and in this case TBAs, is essential in a long-term perspective as development and management frameworks emerge and mature (Puri and Aureli 2005). As often brought forward, groundwater holds many promises of democratic development and management as well as climate-proofed solutions due to its dispersed availability and large and protected storage characteristics. Hence, taking advantage of these properties, while protecting the resource and devolving the benefits to all spheres of society, is a key challenge. There may be a risk of focus on centralised and large-scale development benefitting certain sectors and sections of society if TBA development and management are conceived principally in an international context (Zeitoun and Jägerskog 2011). International development organisation may also inadvertently favour stronger parties, thereby entrenching existing power structures (Öjendal et al. 2010).

The nexus between TBAs and poverty alleviation has been recognised (Puri and Aureli 2005; Braune and Xu 2011), but requires significant further exploration. Some pointers can be derived from Zeitoun and Jägerskog (2011), who firstly hold that equitability in TWM (intra- and internationally) is key to effective cooperation and poverty alleviation and secondly point to strategies and policies to counteract capture of benefits by hegemons (i.e. the stronger riparian states) and stronger stakeholders. These strategies and policies ensure, possibly by third-party intervention, capacity building among the least developed aquifer states (in order to level the 'players' or 'playing field') and, hence, to reduce asymmetry between countries, which is seen as a major compounding factor to slow progress on TWM and TBA management in Africa (Braune and Xu 2011). It also involves ensuring bottom-up approaches to identifying development demand, to ensure priority no-regret small-scale development (water supply, irrigation, drought proofing, etc.) in early phases of joint development and management, and to demonstrate visible impacts on the ground, as well as to prioritise stakeholder involvement in local management and protection of the resource (NEPAD et al. 2011; Alker 2008b). Furthermore, as groundwater lends itself to decentralised development, policies to enhance its management may support and facilitate decentralised development solutions, supporting rural development and offsetting prevailing urbanisation trends, which tend to overwhelm many African countries at present.

Conclusion

The report has evidenced significant advances in Africa with respect to mapping, legal frameworks, institutional development, and multilateral agreements pertaining to TBAs, reflecting the growing importance of these resources for development in the continent. Notwithstanding, TBA management is only recently addressed as part of TWM and it is critical to implement frameworks that can pre-empt disputes over shared groundwater or associated dependent eco-systems and human development. While a harmonised approach is advocated, it is also acknowledged that flexible and hybrid institutional models that build on the present customary approach of making the R/LBOs responsible may be necessary. This is already evident and clearly required in Northern Africa where surface-water resources are secondary to groundwater.

Identification and mapping of TBAs is an ongoing and iterative process and the report suggests a regionalised approach to the mapping, which should facilitate the mapping of new aquifers and their inclusion into management efforts and strategies of relevant RECs. Furthermore, mapping TBAs conspicuously superimposed on R/LBs, and classifying TBAs according to intersection with these, facilitate early identification of geographically based best options for integrated management of surface and groundwater resources.

There is a need to address asymmetries in capacity, making the development and management of TBAs equitable across and within countries and making it pro-poor in a strategic and prioritised fashion. Pilot efforts need to strike a balance between bottom-up approaches and top-down efforts.

Conclusion of bilateral and regional agreements on TBAs and further development of international law on TBAs seem to concur in a parallel process, mutually reinforcing each other. While a truly integrated and comprehensive international legal framework for the holistic system of hydrological resources is the ideal and potential of the future, significant recent advances in covering transboundary groundwater in international law opens the opportunity to attain such instruments. For this, continued concerted inter-disciplinary collaboration between hydrogeologists and lawmakers is required.

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Appendix

Table 4 Inventory of transboundary aquifers in Africa

Proposed ID	Reference number WHYMAP 2006	IGRAC 2009	IGRAC 2012	INWEB	Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Population[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
AFNE1	417	37	NA	NA	Rift aquifer	Kenya Tanzania Uganda	Rift Valley (Lake Natron, Lake Navaisha/Turkana) Nile (Nyando, Simiyu)	6	279,000	21,150	Volcanic	450–1,100	Very low to medium	Betch et al. 2006
AFNE2	420	40	NA	NA	Merti aquifer (Wabishebele and Genale aquifer)	Kenya Somalia	Shebelli and Juba (Lak Dera)	4	129,000	13,500	Semi-consolidated sedimentary (clays, sands, sandstones, limestones)	350–750	Low to medium	Mumma et al. 2011; Mwango et al. 2002; Krhoda 1989
AFNE3	419	39	39	NA	Mount Elgon	Kenya Uganda	Nile (Victoria Nile, Nyando) Rift Valley (Lake Turkana)	5	806,550	5,400	Volcanic	1,000–1,300	Very low to medium	
AFNE4	418	38 or 49	43	NA	Dawa (part of Ogaden-Juba aquifer)	Ethiopia Kenya Somalia	Shebelli and Juba (Dawa)	4	223,150	24,000	Volcanic rocks, alluvials and Precambrian basement	300–650	Very low to low	Abiye 2010
AFNE5	418	38 or 50	44	NA	Juba aquifer (part of Ogaden-Juba aquifer)	Ethiopia Kenya Somalia	Shebelli and Juba (Juba)	4	197,600	34,600	Aquifers in Precambrian and intrusive rocks	270–450	Very low to low	Abiye 2010
AFNE6	418	38 or 51	45	NA	Shabelle aquifer (part of Ogaden-Juba aquifer)	Ethiopia Somalia	Shebelli and Juba (Shebelli, Fafen)	2	334,000	31,000	Sedimentary and minor volcanic aquifers	280–400	Very low to low	Abiye 2010
AFNE7	415	35 or 45	46	NA	Sudd basin (part of Upper Nile)	Ethiopia Kenya South Sudan Sudan	Nile (Kwahr M'boloko, Sue, White Nile, Kidepo, Akoba, Khawr Marchar, Khawr Adar, Khawr Biban, Khawr, Baro Wenz, Khawr Kuteira, Kwahr Tendik) Rift Valley (Lotagipi Swamp, Lake Turkana)	6	2,926,500	331,600	Aquifers in Precambrian and volcanic rocks with patches of alluvials along valleys and deep sedimentary aquifers	450–1,100	Medium	Abiye 2010
AFNE8	415	35 or 46	53	NA	Baggara basin (part of Upper Nile)	CAR South Sudan Sudan	Nile (Bandah, Al Ghallah, Buharyrat Abyad, White Nile, Sue, Sopo, Bahr al Arab, Al Ku) Lake Chad (Oulou, Bahr Azum)	5	2,433,500	239,300	Umm Ruwaba formation which is unconformable overlain the Nubian Formation.	300–900	Low to medium	
AFNE9	416	36	59	NA	Awash Valley aquifer (African Rift Valley aquifer)	Djibouti Eritrea Ethiopia	Rift Valley (Afrera Ye Chew Hayk, Awash, Harewa/Arje) North East Coast (Alal, Erythrean Coast)	2	627,400	50,700	Volcanic	110–350	Very low to low	
AFNE10	NA	NA	NA	NA	Mareb aquifer (Name proposed)	Eritrea Ethiopia	Gash (Mereb Wenz) Baraka (Nahr Al Qash	3	1,827,900	22,800	Precambrian and intrusive rocks	450–550	Very low to medium	Abiye 2010
AFNE11	NA	48	61	NA	Gedaref	Eritrea Ethiopia Sudan	Nile basin (Nahr Atbarah, Nahr ad Dindar, Tekeze Wenz)	4	732,000	38,700	Aquifers in	400–950	Very low to medium	Abiye 2010

Precambrian and
volcanic rocks with
patches of alluvials
along

Table 4 (continued)

Proposed ID	Reference number				Main name	Countries	Major river basin	Geographical	Population[a]	Area	Aquifer type	Average	Annual recharge	Sources other
	WHYMAP 2006	IGRAC		INWEB	(other names found)	sharing	(sub-river basin)	type (Fig. 2)		(km^2)[b]		rainfall (mm/a)[c]	(WHYMAP)[d]	than IGRAC or INWEB or UNESCO[e]
		2009	2012											
											valleys and deep sedimentary aquifers			
AFNE12	405	25	63	1	Nubian Sandstone aquifer system (NSAS)	Chad Egypt Libya Sudan	Lake Chad (Borkou) North Interior (Libyan Desert, Northern Kordofan,Egyptian Western Desert) Nile (Nile Delta, El Allaqi, Sooty Valley, Nile) Mediterranean Coast (Sirte Coast, Libyan North East Coast, Egyptian North West Coast) North East Coast (Bitter Lake, Egyptian East Coast)	3	67,320 000	2,608,000	Nubian (including Paleozoic and Mezosoic) and Post Nubian (including the Tertiary continental deposits in Libya and the Tertiary carbonate rocks in Egypt)	1–550 (mainly <30)	Mainly very low (from very low to very high)	Alker 2008c
AFNE13	404	24	67	7	Mourzouk-Djado basin (Murzuk aquifer)	Algeria Libya Nigeria	North Interior (Libyian Desert, Sahara) Lake Chad (Borkou)	2	108,000	286,200	Sedimentary (calcareous rocks and sand)	<20	Mainly very low (from very low to medium)	
AFNE14	401	21	68	4	Tindouf aquifer	Algeria Mauritania Morocco	North Interior (Saharan Atlas) North West Coast (Saquia el Hamra, Dra)	2	107,000	160,000	Alternating series of calcareous rocks and sand	30–200	Very low to medium	
AFNE15	402	22	70	2	Errachidia basin	Algeria Morocco	North Interior (Daoura, Guir)	5	156,300	18,500	Sandstone, calcareous, dolomite	80–200	Very low to low	
AFNE16	403	23	69	3	North Western Sahara aquifer system (NWSAS)	Algeria Libya Tunisia	Mediterranean Coast (Bay al Kebir, Zam Zam, Sawf al Jin, Jeffara, Tunisian East Coast) North Interior (Lybian Desert, Sahara, Chott Honda, Algerian Atlas, Guir)	2	4,000,000	1,190,000	Sand, sandstone, sandy clay, calcareous, dolomite	10–300 (mainly <50)	Very low to low	Schmidt 2008; OSS 2008b; Al-Gamal 2011
AFNE17	NA	NA	NA	15	Djaffar Djeffara	Libya Tunisia	Mediterranean Coast (Jeffara)	1	262,400	15,800	NI	130–250	Low	
AFNE18	NA	41	71	10	Figuig (part of Atlas Mountains Trans boundary aquifers)	Algeria Morocco	North Interior (Guir)	4	32,300	1,500	Phreatic aquifer, porous	100–170	Very low to low	
AFNE19	NA	41	71	12	Chott Tigri-Lahouita (part of Atlas Mountains Transboundary aquifers)	Algeria aq	North Interior (Guir, ers)	2 Morocco	26,800	4,700	Porous, karst,	180–250	Very low to low Algerian Atlas)	
AFNE20	NA	41	71	11	Ain Beni Mathar (part of Atlas Mountains Transboundary	uif Algeria Morocco							North Interior (Chott	

Table 4 (continued)

Chergui) Mediterranean Coast (Moulouya)		dolomite limestone and sandstone	260-350	e and dolomite	Very low to medium
	1	23,100 20,000 Karstic, dolomite limeston			

Table 4 (continued)

AFNE21	NA	41	71	5	Angad (Angad-Maghnia) (part of Atlas Mountains Transboundary aquifers)	Algeria Morocco	Mediterranean Coast (Moulouya) North Interior (Chott Chergui)	1	25,600	3,500	Porous, Plio-Quaternary	350–450	Very low to medium

Table 4 (continued)

Proposed ID	Reference number				Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Popu ation[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
	WHYMAP 2006	IGRAC 2009	IGRAC 2012	INWEB										
AFNE22	NA	41	71	14	Jbel El Hamra (part of Atlas Mountains Transboundary aquifers)	Algeria Morocco	Mediterranean Coast (Tafna, Moulouya)	2	40,100	1,250	Karstic	440–500	Very low to low	
AFNE23	NA	41	71	13	Triffa (part of Atlas Mountains Transboundary aquifers)	Algeria Morocco	Mediterranean Coast (Tafna, Moulouya)	2	920,000	13,100	Porous, Villafranchian and Quaternary	370–450	Medium	
AFS1	440	18	1	NA	Karoo Sedimentary aquifer	Lesotho South Africa	Orange basin (Orange, Caledon, Vaal); Indian Ocean Coast (Thukela, Mgeni, Mzimkulu, Groot kei, Groot Vis)	3	5,568,000	166,000	Consolidated sedimentary rocks	350–1,200	Very low to medium	
AFS2	439	17	2	NA	Coastal Sedimentary basin 5 (Gariep aquifer) (Orange River Coastal)	Namibia South Africa	Orange basin (Orange River); South Atlantic Coast (Groen)	2	7,900	1,700	Quaternary and consolidated sedimentary rocks	45–55	Very low to medium	
AFS3	438	NA	3	NA	Coastal Sedimentary Basin 6 (Incomati/ Maputo/Mbeluzi basin)	Mozambique South Africa	Indian Ocean Coast (Mfolzi/Mkuze, Maputo)	2	548,000	11,700	Quaternary and consolidated sedimentary rocks	700 - 1,200	Medium to high	Wellfield and BGS 2011
AFS4	438	19	4	NA	Rhyolite-Breccia aquifer (Umbaluzi basin; Maputo Primary aquifer; Incomati/Maputo/ Umbaluzi basin)	Mozambique South Africa Swaziland	Indian Ocean Coast (Black Umbeluzi, Maputo, Incomati)	5	206,000	5,500	Volcanic/Quaternary	600–850	Very low to medium	
AFS5	434	13	5	NA	South West Kalahari/ Karoo basin (SE Kalahari/Karoo basin; Stampriet/ Orange River; encompasses Nossop basin)	Botswana Namibia South Africa	Orange basin (Nosob, Auob)	4	15,500	85,000	Kalahari groups aquifer and Karoo supergroup aquifers (the Auob and Nossob sandstone of the Ecca subgroup in the Karoo and Kalahari sequences)	200–350	Very low to medium	Alker 2008a; ORASECOM 2009; Wellfield and BGS 2011
AFS6	NA	NA	NA	NA	Ncojane aquifer	Botswana Namibia	South Interior/ Okavango (Okwa) Orange basin (Nosob, Molopo)	5	2,300	10,300	Consolidated sedimentary rocks (Karoo and Kalahari groups)	300–350	Very low to medium	Rahube 2003
AFS7	NA	NA	6	NA	Khakhea/Bray Dolomite (Tosca/ Pomfret -	South Africa	Orange basin	4	57,000 V e r	30,000	Dolomite gelegen Dolomite)	300–450	Very low to medium	Turton et al. 2006

Table 4 (continued)

Botswana						(Molopo)								
AFS8	435	14	7	NA	Ramotswa Dolomite basin	Botswana South Africa	Limpopo basin (Marico, KroKodil);	5	135,500	3,200	Malmani subgroup of the Transvaal	500–550	Very low to medium	Catuneanu and Eriksson 1999;
AFS9	437	16	8	NA	(encompasses Pafuri Alluvial aquifer)	South Africa Zimbabwe	(Olifants, Limpopo)				basement rocks			
					(Ramatlabana/ Molopo; encompasses Dinokana-Lobtse Dolomite aquifer)		Orange basin (Molopo)				supergroup (series of isolated basins)			Beger 2001; Staudt 2003; Wellfield and BGS 2011
					impopo basin	Mozambique	Limpopo basin	4	313,800	20,000	Volcanic and	400–700	Very low to low	

Table 4 (continued)

Proposed ID	Reference number				Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Population[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
	WHYMAP 2006	IGRAC 2009	IGRAC 2012	INWEB										
AFS10	436	15	9	NA	Tuli Karoo Sub-Basin (Gaborone To Shashe River; encompasses Motloutse Sand River aquifer)	Botswana South Africa Zimbabwe	Limpopo basin (Limpopo, Sashe, Motloutse)	4	70,600	14,330	Volcanic and basement rocks (plus alluvial along river)	300–450	Very low to low	Wellfield and BGS 2011
AFS11	430	9	10	NA	Northern Kalahari/Karoo basin (encompasses Okavango aquifer and Eiseb Graben)	Angola Botswana Namibia Zambia	South Interior/Okavango (Okavango, Okwa, Omuramba Omatako)	4	35,900	144,400	Consolidated sedimentary rocks	380–550	Very low to high	Stadtler et al. 2005
AFS12	NA	NA	11	NA	Save Alluvial aquifer	Mozambique Zimbabwe	Indian Ocean Coast (Save, Runde, Buzi)	5	32,600	4,500	Alluvial	400–600	Very low to medium	Burgeap 1962
AFS13	NA	24	12	NA	Eastern Kalahari/Karoo basin (encompasses Panda/Nyamandlovu aquifer)	Botswana Zimbabwe	South Interior/Okavango (Botletli, Okavango)	4	54,300	39,600	Upper Karoo Sandstone	400–600	Very low to medium	Wellfield and BGS 2011
AFS14	429	20	13	NA	Cuvelai and Etosha basin (encompasses Ohangwena II aquifer)	Angola Namibia	South West Coast (Kunene) South Interior/Cuvelai-Etosha (Omuramba Ovambo/Cuvelai-Etosha)	5	1,032,400	202,000	Consolidated sedimentary rocks	300–900	Low to medium	Wellfield and BGS 2011
AFS15	431	10	14	NA	Nata Karoo Sub-Basin (Lower Caprivi aquifer)	Botswana Namibia Zimbabwe	South Interior (Okavango) Zambezi basin (Cuando, Zambezi, Luanda)	5	195,000	91,000	Ecca sequence	500–750	Very low to medium	
AFS16	428	8	15	NA	Coastal Sedimentary Basin 4 (Cunene River Coastal)	Angola Namibia	South West Coast (Kunene)	2	20	2,200	Quaternary and consolidated sedimentary rocks	100–150	Very low to medium	
AFS17	432	11	16	NA	Medium Zambezi aquifer (Middle Zambezi Rift Upper Karoo aquifer; encompasses Ponguwe basin)	Mozambique Zambia Zimbabwe	Zambezi basin (Zambezi, Lake Kariba, Nabuguyu, Kafue)	4	50,800	10,700	Quaternary and consolidated sedimentary rock (lower and upper Karoo Sandstones)	720–780	Very low to medium	Wellfield and BGS 2011
AFS18	433	12	17	NA	Shire Valley aquifer	Malawi Mozambique	Zambezi basin (Shire)	4	527,000	6,200	Tertiary/Quaternary	780–900	Medium to very high	Wellfield and BGS 2011
AFS19	NA	NA	18	NA	Arangua Alluvial	Mozambique Zambia	Zambezi basin (Mucanha, Zambezi, Lusemfwa)	4	12,500	21,200	Alluvial	700–1,100	Very low to medium	
AFS20	NA	23	19	NA	Sand and Gravel aquifer	Malawi Zambia	Zambezi basin (Rukuru, Owangawa, Luangwa, Namitete, Lilongwe, Capoche, Kaombe)	4	2,233,000	25,300	Unconsolidated intergranular aquifer and weathered basement complex	800–1,200	Very low to very high	Wellfield and BGS 2011

Table 4 (continued)

AFS21	427	7	20	NA	Coastal Sedimentary Basin 3 (encompasses Rovunma Coastal aquifer or Ruvuma basin)	Mozambique Tanzania	East Central Coast (Lukuledi, Ruvuma, Montepuez/ Megaruma)	2	794,000	23,000	Quaternary and consolidated sedimentary rocks	930–1,200	High	Wellfield and BGS 2011

Table 4 (continued)

Proposed ID	Reference number WHYMAP 2006	IGRAC 2009	IGRAC 2012	INWEB	Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Popu ation[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
AFS22	426	6	21	NA	Karoo-Sandstone aquifer (Rovunma basin; Tunduru/ Maniamba basin)	Mozambique Tanzania	East Central Coast (Rufiji, Mantadu, Mbwenkuru, Ruvuma) Zambezi basin (Eastern catchment Lake Nyasa)	3	214,500	40,000	Consolidated sedimentary rocks (Karoo sandstone that underlies basalts)	900–1,700	Medium to very high	Wellfield and BGS 2011
AFS23	NA	NA	22	NA	Kalahari/Katangian basin (Lualaba)	DRC Zambia	Congo River basin (Lake Mweru, Lulaba) Zambezi basin (Lufwanyama, Lunga)	5	1,006,000	15,600	Katangian sequence (semi-consolidated Aeolian sandstones and gravels deposited) and Kalahari sequence (consolidated sedimentary rocks)	1,200–1,300	High to very high	Braune and Xu 2011
AFS24	422	5	23	NA	Congo Intra-Cratonic (Congo/ Zambesi basin; Benguela Ridge Watershed aquifer)	Angola DRC	South West Coast (Cuanza) Congo River basin (Kwango, Kasai, Lulua)	2	1,920,000	317,200	Consolidated sedimentary rocks and alluvial	1,200–1,650	High	Wellfield and BGS 2011
AFS25	NA	NA	24	NA	Weathered basement	Malawi Tanzania Zambia	Zambezi basin (Luangwa, Rukuru, Lake Nyasa) Congo River (Lake Mweru)	5	852,000	25,842	NI	900–2,000	Medium to very high	
AFS26	NA	NA	25	NA	Karoo Carbonate	CAR Congo South Sudan	Congo River (Oubangui, Ouaka, Kotto, Mbomou, Chinko, Ouatra, Mbomou, Congo, Uele, Aruwimi, Lulaba, Lomani, Sankuru, Lulua) Nile basin (Sue, Sopo, Kwahr M'boloko)	5	9,400,000	941,100	Limestone and sandstone	1,000–1,800	High to very high	
AFS27	NA	NA	26	NA	Tanganyika aquifer	Burundi DRC Tanzania Rwanda	Nile basin (Kagera) Congo River Southern basins, Lugaba, Lukuga) (Malagarasi, Lake Tanganyika, Lake Tanganyika Northern and	5	11,940,000	222,300	Fractured basalt and granite	800–1,800	Very low to very high	Coster 1960
AFS28	NA	22	27	NA	Dolomitic aquifer (Lower Congo Precambrian Dolomite aquifer)	Angola DRC	Congo River basin (Congo, Inkisi) South West Coast (Mebrigede)	2	750,600	21,300	Karst weathered dolomite	1,100–1,450	High to very high	Wellfield and BGS 2011
AFS29	421	4	28	NA	Coastal Sedimentary Basin 2 (Congo River Coastal)	Angola DRC	Congo River basin (Coast North/South of Congo)	2	34,000	2,250	Quaternary and consolidated sedimentary rocks	800–1,000	Very low to high	Wellfield and BGS 2011
AFS30	NA	NA	29	NA	Cuvette Centale	Congo DRC	Congo basin (Congo, Oubangui, Sangha, Likouala aux herbes, Maringa, Kouyou, Alima, Lefini, Inkisi, Nsele, Bombo, Lukenie, Kwango, Kwa, Kasai, Lulua, Sankuru, Lomani,	2	14,000 000	814,800	Alluvial sandstones	1,400–2,100	High to very high	Moukolo 1992

Table 4 (continued)

Proposed ID	Reference number				Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Population[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
	WHYMAP 2006	IGRAC 2009	IGRAC 2012	INWEB										
							Momboya, Salomga, Lomela, Tshuapa) Central West Coast (Niari)							
AFS31	425	3	31	NA	Coastal Sedimentary Basin 1 (Umba Coastal)	Kenya Tanzania	East Central Coast (Galana, Tana, Kenyan South Coast, Umba)	2	2,150,000	16,800	Quaternary and consolidated sedimentary rocks	850–1,250	Medium to high	
AFS32	424	2	32	NA	Kilimanjero aquifer	Kenya Tanzania	East Central Coast (Galana, Pangani) Rift Valley (Lake Natron)	3	1,396,000	14,600	Volcanic alluvium (sand, gravel, clay with calcareous deposits with lava and pyroclastic volcanic rocks)	600–1,600	Very low to medium	Grossmann 2008
AFS33	423	1	36	NA	Kagera aquifer	Rwanda Tanzania Uganda	Nile basin (Kagera)	4	493,500	5,800	Alluvial unconsolidated sand and gravels	930–1,800	Very low to medium	
AFS34	NA	43	35	NA	Mgahinga	DRC Rwanda Uganda	Nile basin (Semliki, Kagera) Congo River basin (Lulaba, Tanganyika Northern basin)	5	1,451,000	4,400	Volcanic	1,250–1,650	Very low to medium	
AFS35	NA	44	37	NA	Western Rift Valley Sediment	DRC Uganda	Nile basin (White Nile, Semliki, Lake Albert, Victoria Nile)	4	1,151,000	29,500	Volcanic	800–1,250	Very low to high	
AFWC1	NA	NA	30	NA	NN	Congo Gabon	Central West Coast (Mbia, Nyanga)	2	13,300	23,000	NI	1,400–1,750	Medium to very high	
AFWC2	NA	NA	33	NA	NN	Congo Gabon	Central West Coast (Ngounie/Ogooue, Nyanga)	3	48,500	7,100	NI	1,650–1,950	High to very high	
AFWC3	NA	NA	34	NA	NN	Congo Gabon	Central West Coast (Ogooue, Nyanga)	2	41,000	23,500	NI	1,750–1,950	High to very high	
AFWC4	NA	NA	40	NA	NN	Congo Gabon	Central West Coast (Ogooue:Ivindo and lalara)	4	1,700	19,600	NI	1,600–1,750	High to very high	
AFWC5	NA	NA	41	NA	NN	Cameroon CAR Gabon	Central West Coast (Nyong, Ivindo/Ogooue) Congo River basin (Boumba, Kadei)	3	178,000	66,400	NI	1,550–1,650	High to very high	
AFWC6	NA	NA	42	NA	Rio Delrey	Cameroon Nigeria	Central West Coast (Cross, Andokat/Akpa, Mungo)	3	3,300,000	24,000	Upper Miocene to Quaternary	2,500–3,130	Very high	
AFWC7	414	34	48	NA	Keta basin (Keita)	Benin Nigeria Togo	West Coast (Volta, Mono, Kouffo, Oueme, Yewa, Ogun, Oshun, Osse)	3	16,896 000	55,400	Quaternary (sand, silt, clay)	950–2,450	High to very high	
AFWC8	413	33	47	NA	Tano basin	Cote d’Ivoire Ghana	West Coast (Davo, Bandama, Agneby, Komoe, Bia, Tano)	3	4,740,000	43,000	Quaternary Terminal Continental and Maestrichtien aquifer	1,300–1,930	High to very high	
AFWC9	NA	NA	49	NA	NN	Cote d’Ivoire Guinea Liberia	West Coast (Saint Paul, Saint John, Cavalla, Cesta,	6	2,370,000	47,300	NI	1,400–2,050	High to very high	

Table 4 (continued)

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Table 4 (continued)

Proposed ID	Reference number: WHYMAP 2006	IGRAC 2009	IGRAC 2012	INWEB	Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Population[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
AFWC11	NA	NA	51	NA	Garoua - Chari	Cameroon Nigeria	Niger River (Benue, Faro)	4	1,870,000	38,400	Sandstone - clay	950–1,400	High to very high	
AFWC12	NA	NA	50	NA	NN	Cameroon CAR Chad Sudan	Lake Chad (Logone, Ouham, Chari, Barh Keita, Oulou, Bahr Azum)	4	716,000	155,400	Sedimentary (Quaternary and Tertiary)	700–1,600	High to very high	
AFWC13	NA	47	62	NA	Disa	Chad Sudan	Lake Chad (Bahr Azum)	4	74,300	1,500	Sandstone	500–550	Very low to medium	
AFWC14	412	32	52	NA	Lake Chad (encompasses Grand Yaéré Plains aquifer and Bilma-Agadem aquifer)	CAR Cameroon Chad Niger Nigeria	Lake Chad (Borkou, Dilia, Komadugu Yobe, Koramas, Hadedja, Jamaare, Komadugu Gana, Chitati, Lake Chad, Dagana, Fitri, Chari, Bahr Keita, Ouham, Logone, Yedseram) Niger River (Gongola, Benue, Faro, Mayo kebi)	5	22,419,100	1,300,500	Sedimentary aquifer with three main aquifers: the Upper Quaternary, the lower Pliocene and the Terminal Continental (TC; Oligocene–Miocene)	40–1,400	Very low to high	Alker 2008c
AFWC15	411	31	56	6	Irhazer-Iullemeden	Algeria Mali Niger Nigeria	Lake Chad (Dilia, Kormaras) Niger River (Tilemsi, Niger, Dallol Bosso, Dallol Maouri, Tarka, Sotoko, N'Kaba, Bunsuru, Zamfara, Gulbinka)	5	12,888,600	545,400	Group of sedimentary deposits containing two main aquifers: Intercalary Continental (IC) and Terminal Continental (TC)	80–900	Very low to very high	OSS 2008a
AFWC16	NA	NA	60	NA	NN	Burkina Faso Mali Niger	Niger basin (Gorouol, Niger, Faga)	4	333,000	36,500	NI	250–600	Very low to medium	
AFWC17	410	30	57	NA	Liptako-Gourma aquifer (encompasses Gondo Plain)	Burkina Faso Niger	West Coast/Volta (Sourou, Nakambe, Mouhoun, Oti) Niger River (Gorouol, Faga, Niger)	5	7,758,300	159,500	Fractured metamorphic	400–900	Very low to high	
AFWC18	NA	NA	55	NA	NN	Guinea Mai Senegal	Niger basin (Tinkisso, Mafou, Niger, Sankarani, Baoule) Senegal basin (Bakoy, Bafing, Faleme) West Coast (Gambia, Corubal)	6	4,250,000	185,500	Birrimien (schist and sandstone)	850–1,650	Very low to very high	
AFWC19	406	26	58	NA	Senegalo-Mauritanian	Gambia, Guinea-	North West Coast (Central Mauritania,	3	11,930,000	331,450	Maastrichtien (multilayer	20–1,850	Very low to very high	

Table 4 (continued)

basin	Bissau Mauritania Senegal	Adrar Sotuf) Senegal River (Senegal, Katchi, Ferlo) West Coast (Saloum, Gambia, Casamance, Corubal)		several aquiferous system from Cretaceous Superior to the Quaternary)

Table 4 (continued)

Proposed ID	Reference number				Main name (other names found)	Countries sharing	Major river basin (sub-river basin)	Geographical type (Fig. 2)	Population[a]	Area (km^2)[b]	Aquifer type	Average rainfall (mm/a)[c]	Annual recharge (WHYMAP)[d]	Sources other than IGRAC or INWEB or UNESCO[e]
	WHYMAP 2006	IGRAC		INWEB										
		2009	2012											
AFWC20	407	27	64	8	Taoudeni basin (Taoudeni-Tanezrouft)	Algeria Mali Mauritania	North Interior (Sahara) Niger River (Niger) Senegal River (Karakoro)	3	82,400	936,000	Multilayers (Infracambrian, Cambro-Ordovician, Devonian-Carboniferous)	10–350	Very low to low	Huneau et al. 2011
AFWC21	408	28	66	NA	L'air Cristalline aquifer	Algeria Mali	North Interior (Sahara) Niger River (Dallol Bosso, Tilemsi)	2	84	28,400	NI	60–100	Very low to medium	
AFWC22	409	29	65	9	Tin Seririne	Algeria Nigeria	Niger River (Dallol Bosso)	4	520	73,700	NI	20–50	Very low to low	

NA not applicable; NI no information; NN no name referenced; CAR Central African Republic; DRC Democratic Republic of the Congo

[a] Population calculated from population geographical information system (GIS) layer (UNEP/GRID 2004)

[b] Straight calculation from ArcGIS

[c] Annual average rainfall (mm) from annual total precipitation (FAO – Geonetwork): average annual precipitation from 1961–1990

[d] Annual recharge (mm) from WHYMAP: Very low = 0–2 mm/a; Low = 2–20 mm/a; Medium = 20–100 mm/a; High = 100–300 mm/a; Very high = >300 mm/a

[e] Amani (2011); IGRAC database (2012b); INWEB database (2012); Puri and Aureli (2009); Vasak (2008); Vasak and Kukuric (2006); UNEP (2010); UNESCO (2010)

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