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Guidelines to groundwater vulnerability mapping for Sub-Saharan Africa

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ABSTRACT

An approach to solving the challenges encountered in groundwater vulnerability assessment in Sub-Saharan African countries is discussed in this paper. The aim of this review is to highlight the gaps and difficulties encountered and provide guidelines for groundwater protection measures in sub-Saharan African countries, particularly countries without specific regulations and methodology of carrying out aquifer vulnerability assessments. Highlighted difficulties in groundwater vulnerability mapping in Sub-Saharan Africa include limited data, shortage of skilled professionals, inapplicability of most existing vulnerability methods and non-availability of funds. The numerical, travel time and parametric vulnerability approaches were recommended for use in sub-Saharan Africa based on the unique geomorphological features of the African continent. The goal of outlining the challenges and providing a guideline was to minimise the impact of groundwater pollution and to prioritise groundwater mapping in an aquifer protection assessment.

1. Introduction

Groundwater resources are the foundation of rural water supplies, sustaining livelihoods for the poorest of the poor communities in sub-Saharan African (SSA) countries (Turton et al., 2006). Groundwater is an important source for drinking, livestock and irrigation water in these countries. It is of vital importance to meeting the target of the Millennium Development Goals (MDGs) of all people having access to clean water, as most of rural Africa, and a considerable part of urban Africa, are supplied by groundwater (Altchenko et al., 2011; Lapworth et al., 2017). This goal cannot be achieved without a proper understanding of groundwater quality and quantity, location, accessibility, as well as its protection.

Groundwater qualities around the world and in SSA are increasingly being hampered negatively by anthropogenic sources and activities (Li et al., 2017). Contaminating sources such as human settlement developments (demographic dynamics, ignorance, improper watershed and waste management, advanced agricultural production and industrial activities) are the major threat that compromise groundwater quality and quantity (Baalousha, 2010; Li, 2016; Muhammad et al., 2015). Lapworth et al. (2017) reported that in many urban and peri-urban centres in Africa groundwater are being put under considerable pressure from pollution loading.

Adelana et al. (2008) concluded that groundwater is a crucial resource for future development in many SSA countries. Although generally not visible from the surface, groundwater is an accessible water supply to many SSA countries, the reason being that its development is simple and the quality of groundwater is generally good (MacDonald et al., 2012). Groundwater is also considered as the most resilient source of drinking water across much of Africa (Lapworth et al., 2107). The major constraints for obtaining and using of groundwater are the lack of precise data on aquifers such as depth, storativity and contamination status. This lack of information has hampered groundwater development and protection.

The importance of groundwater to SSA countries makes its protection critical. Groundwater vulnerability assessments are important components of groundwater protection and management. Such assessments are simple ways of evaluating the risk of contamination of an aquifer. Groundwater vulnerability assessments can generally not be made in the field, but are based on the evaluation of field data recorded prior to the assessment (Vrba and Zaporozec, 1994). Even though, groundwater vulnerability has been researched since the late 1960s and early 1970s (Albinet and Margat, 1970; Margat, 1968), the breakthrough came with the work of Aller et al. (1987) in the DRASTIC formulation.

Existing vulnerability methods have been reviewed by many researchers (Gogu and Dessargues, 2000; Goldscheider, 2002; Kumar et al., 2015; Liggett and Talwar, 2009; Oke, 2017; Vrba and Zaporozec, 1994). Based on availability of input data of the hydrogeological system, three basic vulnerability methods can be adopted: subjective overlay or index methods, statistical methods and physically based methods (Oke, 2017). The subjective or index-based method is the most

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important and commonly used method. It includes methods such as Parametric (DRASTIC, SINTACS, SEEPAGE, EPIK, HAZARD_PATHWAY-TARGET, GOD, AVI, PI), Non-Parametric (INDICATOR KRIGING) and Hybrid (ISIS). The subjective method is based on the rating of individual hydrogeological factors (Kumar et al., 2015, 2016).

Qian et al. (2012) suggested ways of validating vulnerability methods and attempted to modify the DRASTIC index vulnerability method. DRASTIC, which was initially developed by Aller et al. (1987) and reviewed by the US Environmental Protection Agency (USEPA) (1993) has been modified by adding different parameters to the original seven. OREADIC (Qian et al., 2012), AHP-DRASTIC (Thirumalaivasan et al., 2003), SINTACS (Civita and De Maio, 2000) are examples of these modifications. Others are land use, lineament, sewage, pesticides, impact of contaminants to the original DRASTIC methods to produce good results (Secunda et al., 1998; Shahid, 2000; Panagopoulos et al., 2006).

The physically based method is an objective method. It is also known as the processed-based method and it is widely used next to the subjective method. The physically based method relies on the physical processes that take place in the hydrogeological systems. They are used for groundwater assessment where similar contaminants are present. Statistical methods are mostly applied where there is need for assessment between spatial variables and the presence of contaminants (Kumar et al., 2015). This means they are mostly relevant for assessment of groundwater where similar contaminants are present. Process-based simulation methods are popular for assessing specific vulnerability (Bazimenyera and Zhonghua, 2008).

Each method has its weakness and strengths which lies in their suitability under a particular set of factors. The statistical method uses spatial variation (Babiker et al., 2005). Major constraints to process-based methods are computational difficulties, field calibration and proper assessment of contaminant movements in vadose zones (Saha and Alam, 2014). Unavailability of adequate data is another major shortcoming for using the process-based method. The major advantage of index-based techniques is that it can be applied with different levels of available data. This is the main reason for its wide acceptance and applicability and it is the most widely used method in SSA countries where hydrogeological data availability is a major constraint.

The results of vulnerability assessments are often presented in the form of vulnerability maps showing areas that are vulnerable to contaminant impacts. The reliability of these maps is influenced by the availability, quality and interpretation of the field data (Ravbar and Goldscheider, 2007). Vulnerability maps on a country-wide scale are not available for SSA countries, apart from a few exceptions, such as South Africa and the recent work of Ouedraogo et al. (2016). This lack of availability of vulnerability maps is mainly due to low funding of scientific research in SSA countries and low research outputs from these countries as compared to those of developed economies (Thornton et al., 2006). This paper therefore describes the challenges faced when performing groundwater vulnerability assessments in SSA countries, proposes guidelines to mapping of vulnerability assessments for SSA countries and reviews existing methodologies applied to SSA countries which can be reapplied to assess the groundwater vulnerability for the rest of the continents.

2. Disparity in the definition of groundwater vulnerability

The definition of *groundwater vulnerability* as it appears in the literature is perceived to be ambiguous and lacking clear definition (Daly et al., 2002; Frind et al., 2006; Sorichetta, 2010; Stigter et al., 2006). A simple description of groundwater vulnerability is that it is a relative, non-measurable and dimensionless property (Vrba and Zaporozec, 1994). Groundwater vulnerability has a different meaning to other terms that are often used when discussing groundwater and its risks to contamination. Terms such as *pollution risk* and *contamination risk* all have distinct meanings. The terms *groundwater vulnerability, groundwater susceptibility*, and *aquifer sensitivity* are frequently used interchangeably, but are different to *groundwater risk*. Groundwater risk is defined as a threat posed by a hazard to human health due to pollution of a specific natural aquifer discharge. *Groundwater risk* is different to *groundwater vulnerability* because groundwater risk is related to the presence and level of a particular contaminating substance in groundwater systems, while the assessment of groundwater vulnerability is predicting the degree to which the groundwater in an aquifer is sensitive to contamination (Focazio et al., 2002).

Frind et al. (2006), Popescu et al. (2008), Sorichetta (2010) and Vrba and Zaporozec (1994) describe widely used definitions of groundwater vulnerability. These descriptions include:

> "Groundwater vulnerability is the tendency of, or likelihood for, contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer" (National Research Council [NRC], 1993),

and:

> "Groundwater vulnerability is an intrinsic characteristic of the natural environment, which is independent of contaminant type and source, as well as specific land use and management practices" (United States Environmental Protection Agency [USEPA], 1993).

The above definitions are just two of the many definitions proposed in groundwater vulnerability studies. In general, groundwater vulnerability assessments can be grouped into three different approaches:

1) Those that assume groundwater vulnerability to be related to the response of the system to impacts from natural processes and human activities (Bachmat and Collin, 1987; Sotornikova and Vrba, 1987; Villumsen et al., 1983).
2) Those that consider vulnerability to be an intrinsic (natural) property of the groundwater system without considering the properties of the contaminants impacting on the system (International Association of Hydrogeologists [IAH], 1994; Margat, 1968; Olmer and Rezac, 1974, SNIFFER, 2004).
3) Those that are used to synthesise complex hydrogeologic information into a useable form for planners, decision makers and policy-makers, geoscientists and the public (Liggett and Talwar, 2009).

With the available approaches to vulnerability assessments, the aims and objectives of a specific vulnerability assessment should be considered when selecting an approach and when determining which actions to take as part of the assessment. Although most vulnerability assessments focus on vulnerability to contamination, the groundwater resource is also vulnerable to other impacts, such as drought and climate change. When assessing the vulnerability of an aquifer to drought, for example, the above definitions of groundwater vulnerability would not necessarily be applicable. By considering a specific definition of groundwater vulnerability that is relevant to the particular vulnerability assessment, ambiguity can be avoided. Furthermore, the choice of vulnerability definition used during particular assessments is important because it is more dangerous than beneficial to use vulnerability categories that are unclear and not practically defined (Foster et al., 2013).

3. The vulnerability concept

Groundwater protection is complex and groundwater is affected by a wide range of natural processes and human activities, particularly those involving land usages. The vulnerability concept can sometimes be confusing and if not specifically stated, the wrong method of investigation may be applied in assessing the vulnerability of an aquifer. To have a common understanding of the available techniques of vulnerability assessment, scientists of different groundwater vulnerability forums have cooperated to outline the various methodologies of vulnerability assessment. These forums include the International Conference on Vulnerability of Soil and Groundwater to Pollutants (van Duijvenbooden and van Waegenigh, 1987), the Committee on Techniques for Assessing Groundwater Vulnerability (1993), the European Cooperation in Science and Technology (COST, 1995, 2003). At the conference on Groundwater Vulnerability – From Scientific Concept to Practical Application (Witkowski, 2016), significant changes in the general approach to groundwater vulnerability assessment and its practical application in the context of the identification of potential groundwater pollution hazards were highlighted. The different concepts emanated from these forums, are today used in vulnerability assessment studies.

The objective of vulnerability assessment is to distinguish between areas where the groundwater system is more vulnerable to contamination and areas with lower groundwater vulnerability. Vrba and Zaporozec (1994) emphasised that vulnerability of groundwater is a relative, non-measurable, dimensionless property. They distinguished between intrinsic (natural) vulnerability and specific vulnerability. COST (2003) suggested that vulnerability should be investigated based on the origin-pathway-target model of environmental management. Due to the importance of groundwater as a non-commercial product, a directive from the European Union on water protection (Water Framework Directive [WFD], 2000) instructs scientists to distinguish between groundwater resource protection and groundwater source protection.

In the assessment of groundwater vulnerability, an additional factor that should be considered is the scale of the assessment. Due to local variations in the conditions affecting vulnerability, vulnerability assessments on a local scale are likely to differ from those done on a regional scale.

3.1. The origin-pathway-target model in vulnerability assessment

The origin-pathway-target model of vulnerability assessment was modelled after the methodology used in environmental investigations to assess the risk that contaminants pose to potential receivers.

The term *origin* describes the location of a potential contaminant release. The term *target* refers to the groundwater body that could potentially be impacted on by the contaminants, while the *pathway* includes all the earth materials between the origin and the target. For groundwater vulnerability assessments, COST (2003) suggested taking the land surface as the origin, because contaminant releases often occur at surface. However, contaminant releases may also take place below the ground surface, for example via leakages in sewerage systems and underground petrochemical tanks. In groundwater vulnerability assessments, the target (receptor) is the groundwater that must be protected from contaminant impacts.

A distinction is often made between *resource protection* and *source protection*. For resource protection, the groundwater surface is considered the target, while for source protection the target is the water in the well or spring. For resource protection, the pathway consists of the material through which contaminants must travel vertically to reach the groundwater surface (Fig. 1). For source protection, the water in the well or spring is the target and the pathway includes mostly horizontal movement in the aquifer (Goldscheider et al., 2000).

This origin-pathway-target model is also referred to as the *European approach* to vulnerability investigations (COST, 2003). The concept was developed with the aim of protecting both the groundwater resources and the groundwater sources (Daly et al., 2002). Different existing groundwater vulnerability assessment methodologies based on the European approach are EPIK (Doerfliger et al., 1999), the Irish approach (Daly and Drew, 1999), COP (Vías et al., 2006) and PI (Goldscheider et al., 2000).

It is important to state that it is erroneously believed that the more complex and detailed vulnerability assessment methods are, the more reliable the assessments become (Sililo et al., 2001). It is rather the selection of parameters considered during the assessment that determines the reliability of the assessment. Groundwater vulnerability in a specific area may be more sensitive to certain parameters than to others. Including redundant parameters in the assessment will not add to the reliability of the assessment. Foster et al. (2013) stated that "the more complex the vulnerability assessment procedure is, the more likely it is to obscure the obvious and make the subtle indistinguishable".

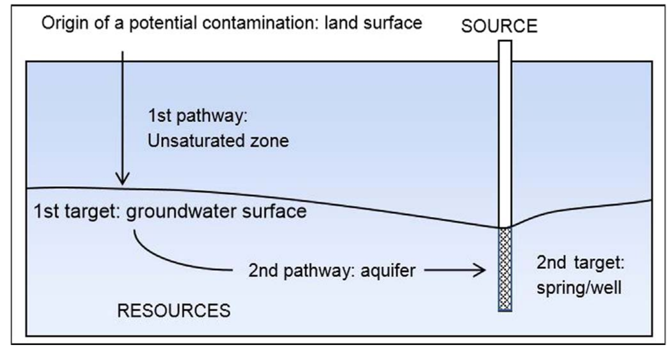

Fig. 1. Illustration of the origin-pathway-target model for groundwater vulnerability mapping and the concept of resource and source protection modified after Goldscheider et al. (2012)

3.2. Intrinsic versus specific vulnerability

The term *intrinsic vulnerability* is used to define the vulnerability of groundwater to contaminations generated by human activities (Daly et al., 2002). It takes into account the geological, hydrological and hydrogeological characteristics of an area, but is independent of the nature of the contaminants (Goldscheider, 2002). Intrinsic vulnerability strictly evaluates the properties of the earth materials through which contaminants must pass before reaching the aquifer system. The assessment of intrinsic vulnerability involves the investigation of the possibility of retardation, degradation or filtration of the contaminant as it travels through the system. To evaluate intrinsic vulnerability, three factors need to be taken into consideration (Daly et al., 2002):

1) The advective travel time through the system.
2) The quantity of contaminants that reach the target because not all contaminants that leave the surface catchment infiltrate into the aquifer, some leaves as surface run-off.
3) The physical attenuation of the contaminant as it travels through the system such as dispersion or dilution.

Commonly used intrinsic vulnerability assessment methods are *subjective methods* (also known as *overlay* or *index methods*). The most common subjective methods are described by Gogu et al. (2000) and include the methods of Albinet and Margat (1970), Carter et al. (1987), Goossens and Van Damme (1987), as well as GOD (Foster, 1987), DRASTIC (Aller et al., 1987), SINTACS (Civita, 1994), SEEPAGE (Moore, 1990), AVI (Van Stempvoort et al., 1993), ISIS (Civita and De Regibus, 1995), EPIK (Doerfliger et al., 1999) and the German Method (von Hoyer and Söfner, 1998).

The DRASTIC method was developed at the U.S. Environmental Protection Agency in Oklahoma in collaboration with the National Water Well Association in Dublin, Ohio, with the sole aim of evaluating the potential of groundwater pollution by considering the hydrogeological parameters (Aller et al., 1987). The method is based on the Delphi techniques of ranking important hydrogeological parameters of the aquifer, namely depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C). These seven parameters were ranked and a weight assigned according to their passive ability to degrade infiltrating

Table 1
Assigned weights for DRASTIC hydrogeological factors.

Rating	Depth of water (m) D × (5)	Net recharge (mm/y) R × (4)	Aquifer media A × (3)	Soil media S × (2)	Topo-graphy T × (1)	Impact of vadose zone I × (5)	Hydraulic conductivity (GPD/ft^2) C × (3)
10	0.0–1.5		Karst limestone	Thin or absent, gravel	0–2	Karst limestone	< 2 000
9	1.5–4.5	> 250	Basalt	Sandstone and volcanic	2–3	Basalt	
8		180–250	Sand and gravel	peat	3–4	Sand and gravel	1 000–2 000
7	4.5–9		Massive sandstone and limestone	Shrinking and/or aggregate clay/alluvium	4–5	Gravel, sand	
6		100–180	Bedded sandstone, limestone	Sandy loam, schist, sand, karst volcanic	5–6	Limestone, gravel, sand, clay	700–1 000
5	9–15		Glacial	Loam	6–10	Sandy silt	
4			Weathered Metamorphic/ Igneous	Silty loam	10–12	Metamorphic gravel and sandstone	300–700
3	15–23	50–100	Metamorphic/ Igneous	Clay loam	12–16	Shale, silt and clay	
2	23–31		Massive shale	Muck acid, granitoid	16–18	Silty clay	100–300
1	> 31	0.0–50		Non-shrink and non-aggregated clay	> 18	Confining layer, granite	1–100

contaminants. The assigned weight is from 1 (least important) to 5 (most important). The weights and ratings of the seven parameters considered in the DRASTIC method are presented in Table 1.

The DRASTIC index produced from summation of the seven hydrogeological parameters is shown in Equation below:

$$\text{DRASTIC Index} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$$

Where D, R, A, S, T, I and C are the seven parameters of the method and the subscripts R and W are the corresponding ratings and weights, respectively. The DRASTIC method assumes the following points while evaluating the vulnerability of aquifer to pollution:

a) The contaminant is released from the earth surface.
b) The contaminant moves with the velocity of water.
c) The contaminant flushes into the groundwater through precipitation.
d) The area under investigation should be large.

A number of authors suggested that DRASTIC equivalent results can be obtained by using fewer parameters (Babiker et al., 2005; Kumar et al., 2015; Merchant, 1994; Qian et al., 2012). Others still opined that DRASTIC must be modified to suit the specific hydrogeological conditions to be assessed (Kumar et al., 2015, 2016; Qian et al., 2012).

The SINTACS method considered the same hydrogeological parameters and formulation of vulnerability index as in the DRASTIC method but using different nomenclature (Civita, 1994; Ricchetti and Polemio, 2001). Depth to water (S), Net infiltration (I), Unsaturated zone (N), Soil media (T), Aquifer media (A), Hydraulic conductivity (C) and Slope (S) are the seven parameters (Civita, 1994). The difference lies in the way the parameters were assigned weights and relative ratings. Also, the model considered more than one weight assignment to consider the land use factor and calculated vulnerability indices for different zones (Kumar et al., 2015).

GOD was proposed by Foster (1987) and its acronyms were coined from the first word of its parameters, namely the type of groundwater occurrence (G) (e.g. none, confined, unconfined), the overlying lithology (O) (e.g. loam, gravel, sandstone, limestone), and the depth of the groundwater table (D) (Kumar et al., 2015; Shirazi et al., 2012). GOD is rated between 0 and 1. The overall values for vulnerability assessment is derived by multiplying the three factors, and consequently the ranges, between 0.0 (negligible) and 1.0 (extreme). GOD has lesser parameters in comparison to methods such as DRASTIC, and its modification such as SINTACS, ISIS, SEEPAGE and OREADIC. This makes GOD easy and quick to use. Its main advantage is that it can be applied to any type of aquifer, except in the karst areas, because it does not consider the special nature of epikarst and vertical shaft of karst can cause a problem when using this method. Another shortcoming includes the overrating of the factor D, for example depth of 100 m to water table is assigned moderate vulnerability (0.4; Kumar et al., 2015; Oke, 2017).

Specific vulnerability is the term used to describe the vulnerability of groundwater to a particular contaminant or group of contaminants. It takes into account the properties of the contaminants and their relationship to the various aspects of the intrinsic vulnerability (Goldscheider, 2002). Some methods in COST (2003) relate to land use practices to specific vulnerability (Goldscheider et al., 2000; Ravbar, 2007), while other methods are based on the assumption that specific vulnerability is independent of the land use practices (Vrba and Zaporozec, 1994). As stated by Stigter et al. (2006), specific vulnerability integrates the contamination risk placed upon aquifers by human activities. Two commonly used methods for the assessment of specific vulnerability are the Slovene Approach (Ravbar, 2007; Ravbar and Goldscheider, 2007) and the several modifications of DRASTIC method (Alam, 2014; Babiker et al., 2005; Muhammad et al., 2015; Saha, and Alam, 2014; Secunda, 2008; Sener and Davraz, 2013; Shahid, 2000; Wang et al., 2007), with the addition of land use, pesticides, lineament and GIS.

4. Challenges of mapping groundwater vulnerability in Sub-Saharan African countries

At present, limited research has been done on groundwater vulnerability assessments in SSA countries. This is due to many factors that affect groundwater research in these countries. The major challenges identified are discussed below.

4.1. Lack of comprehensive hydrogeological data

The major impediment to vulnerability assessments in SSA countries is the lack of hydrogeological data. Due to this lack of data, hydrogeologists in these countries generally do not have access to comprehensive hydrogeological maps of their respective countries on a country-wide scale. Such hydrogeological maps could include maps showing the distribution of groundwater levels, aquifer types, hydrochemistry, soil types and hydraulic conductivity. This type of data is the foundation of groundwater vulnerability assessments. Table 2 lists a few studies carried out on the hydrogeology of Sub-Saharan African countries, as highlighted in Working Paper 6 of the African Climate Policy Centre (ACPC) of the United Nations Economic Commission for Africa (Altchenko et al., 2011). Table 2 also lists the available

Table 2
Selected regional hydrogeological studies and maps available in SSA countries.

Study	Region	Scale	Data
Howard et al. (1992)	Uganda	Country	Groundwater potential
Wright (1992)	Africa	Continent	Groundwater potential
Chilton and Foster (1995)	Africa	Continent	Groundwater potential
Biemi (1996)	Ivory Coast	Country and sub-continent	Water crises and constraints, groundwater availability
Taylor and Howard (2000)	Uganda	Country	Groundwater potential, flow types; groundwater balance
Tindimugaya (2000)	Uganda	Country	Groundwater potential, groundwater balance
Macdonald et al. (2001)	Ethiopia	Country	Groundwater availability
Taylor et al. (2004)	Uganda	Country	Groundwater potential, flow types
Mantin and Van de Giesen (2005)	Volta Basin	Basin	Groundwater potential
Woodford et al. (2006)	South Africa	Country	Groundwater balance
Tindimugaya (2008)	Uganda	Country	Groundwater potential, sustainability, storage capacity, flow types
WHYMAP (2008)	Africa	Continent	Groundwater resources
BGS (2011)	Africa	Continent	Basin yield, storage capacity, flow types, saturated thickness
Forkuour et al. (2011)	Northern Ghana	Sub-country	Groundwater potential, accessibility
SADC (2011)	SADC	Sub-continent	Groundwater drought vulnerability
Gumma and Pavelic	Ghana	Country	Groundwater potential

hydrogeological data which can be adapted to produce local scale vulnerability maps for the regions being studied.

4.2. Limitations of established vulnerability assessment methods

Many of the proposed vulnerability assessment methods that are based on the European Approach were designed for assessing groundwater vulnerability in the karst landforms of European countries. These methods include EPIK, COP, PaPRIKa and COP + K but are not generally valid for other aquifer systems, such as fractured rock aquifers. Groundwater in SSA countries occurs in different types of aquifer systems (Fig. 2), including weathered crystalline basement aquifers, aquifers in recent coastal limestones, aquifers in intermontane valley-fill material, consolidated/unconsolidated sedimentary aquifers and major alluvial formations (Foster et al., 2012; Gaye and Tindimugaya, 2012). Since these aquifer systems are significantly different to karst aquifers, vulnerability assessment methods based on the assumption of karstic conditions are inapplicable when assessing groundwater vulnerability in SSA countries when not dealing specifically with karst morphology. However, other index-based groundwater vulnerability methods are applicable, as stated in Kumar et al. (2015) and take into account some specific hydrogeological conditions of SSA.

4.3. Political and social challenges

The understanding of groundwater vulnerability to pollution and the need for its protection has led to the development of several policies to ease groundwater research across the European countries. The EU countries established parallel groundwater-related legislation which the WFD (2000) harmonised into a directive. This effort has significantly aided groundwater management and cooperative research. Such collaboration is lacking in SSA considering the transboundary nature of groundwater and aquifer diversities. Aquifers transcend political boundaries, socio-political borders, tribal and ethnic associations. This

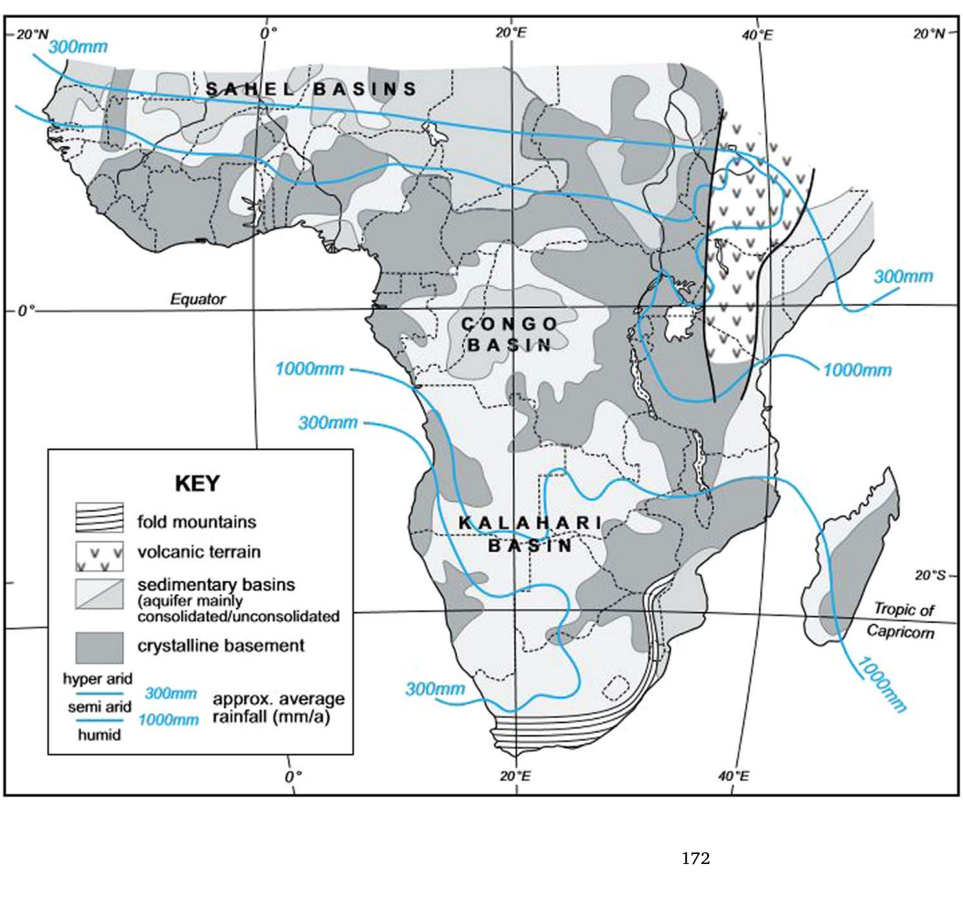

Fig. 2. Distribution of rock types hosting aquifers systems in SSA countries (Foster et al., 2006)

transboundary nature of aquifers calls for increased collaboration of researchers across borders and regions in SSA.

4.4. Scarcity of skilled hydrogeologists

SSA countries often have a limited number of qualified hydrogeologists. This scarcity of hydrogeologists is partly also due to the brain drain as qualified groundwater scientists find employment on other continents. The lack of groundwater experts and trained hydrogeologists has a negative effect on groundwater research on the continent (Adelana and MacDonald, 2008).

4.5. Lack of funding, poor policies and legal tools

Inadequate mechanisms for policy creation and implementation, as well as poor governance, are major contributing factors for the lack of groundwater research in many SSA countries. Many of these countries lack regulation and enforcement of water laws. There is lack of legislative support to enable vulnerability assessment and inadequate capacity for implementation. Agencies charged with groundwater research and monitoring are mostly underfunded. Groundwater infrastructure development in rural areas is tackled locally by rural communities with limited funding (Foster et al., 2006). Solutions to the poor groundwater governance in SSA is contained in the comprehensive groundwater governance frameworks (Kumar et al., 2017; UNESCO-IHP, 2016), motivated by five groundwater networks (Global Environment Facility, World Bank, Food and Agriculture Organization of the United Nations, UNESCO-International Hydrological Programme [IHP] and the International Association of Hydrogeologists) for the betterment of groundwater resources.

5. Proposed methodology for vulnerability assessments in Sub-Saharan African countries

Marin and Andreo (2015) presented a guideline for the assessment of the vulnerability of karst aquifers and for the protection of springs emanating from these karst aquifers. This guideline can be adapted to be applicable to the assessment of groundwater vulnerability in SSA countries. The adapted guideline could serve as the basis from which SSA countries could develop their own set of guidelines based on the specific hydrogeological conditions that prevail in the specific country.

Step 1 – Hydrogeological studies and characterisation of the physical variables that affect the level of natural protection of aquifers

To a greater or lesser degree, all aquifers are vulnerable to contaminant impacts as long as recharge occurs. However, the earth materials overlying an aquifer may serve as a natural protection from impacts due to processes such as filtration and absorption. The initial step in vulnerability assessment involves a comprehensive study of the geological and hydrogeological conditions to delineate the aquifer and to investigate the properties of the overlying earth materials. The characterisation must include all processes that influence contaminant movement from the point of release to either the groundwater table (resource protection) or the well from which water is abstracted (source protection).

Due to the known lack of hydrogeological data and detailed maps in most SSA areas (Butler, 2010), other sources of information should be included when assessing groundwater vulnerability in SSA countries. These sources could include geological maps and reports, topographic maps, soil cover and vegetation maps, data on precipitation, as well as data on topsoil conditions with particular attention to run-off and infiltration. Data on water table elevations could be obtained from field measurements (particularly for source vulnerability evaluation) or derived from Landsat imagery for regional assessments.

Step 2 – Regional and localised vulnerability mapping, delineation of protection zones and pathway characterisation

In arid and semi-arid areas of the Sahel-Sahara and in Southern African areas (Fig. 2), vulnerability assessment could be challenging, particularly where the estimation of recharge from rainfall is challenging due to the low rainfall generally experienced and the variability in the duration and intensity of rainfall events. If recharge can be estimated through other methods, not based on rainfall volumes, such methods can be used in the vulnerability assessments. These methods include the chloride-mass-balance method, water balancing, and methods based on water table fluctuations (Butler, 2010; Edmunds, 2010).

Robins et al. (2007) suggested that vulnerability assessments in SSA countries should be done on field scale, rather than on a regional basis. They reasoned that the high degree of inhomogeneity associated with the widespread occurrence of weathered basements rocks necessitates investigations on a more local scale. They further concluded that vulnerability assessment should exclude aquifer recharge potential to ensure that poorly productive, but socially important, aquifers can be assessed and the questionable reliance on a long-term effective rainfall value can be avoided (Robins et al., 2007).

The WFD supports the downgrade of recharge potential in vulnerability assessment (Dochartaigh et al., 2005). This approach allows for assessing a single fracture or multi-fracture occurrence in an exposed basement aquifer common in SSA. Since fractured rocks are recognised to be highly vulnerable, providing little attenuation and easy pathways for contaminants to reach the groundwater resources (Robins et al., 2007), assessment on a localised scale will allow the delineation of those parts of the fractured aquifer system that has been impacted on, while excluding the unaffected areas of the larger aquifer system.

For vulnerability assessments, it is important to make a distinction between (1) fractured basement aquifers and (2) aquifers in fractured basement rocks that are also associated with a thick weathered zone; the latter are more vulnerable than the former due to the flow properties of intergranular materials present in weathered systems. Thick weathered basement aquifers, which are often major sources of water supply in SSA countries, should be assessed on a regional scale differently to fractured basement aquifers with little or no weathered overburden.

In West African countries, aquifers are in crystalline basements rocks and groundwater occurs in secondary porosity due to chemical weathering, fracturing, jointing and shearing. Over 60% of such aquifers are discontinuous (Pavelic et al., 2012). Therefore, source vulnerability assessment is recommended above resource vulnerability assessment in such conditions. Similarly, source assessment is also recommended where pit latrines and waste disposal sites are situated near wells which supply to households, as is the case in many major cities and towns in SSA (Lapworth et al., 2017). Considering the above scenario, Robbins et al. (2007) argued for re-rating of the index methods, such as DRASTIC, to include the significance of source pollution.

Step 3 – Validation of vulnerability assessments

The various groundwater vulnerability assessment methods each have different objectives, pathways and targets, and numbers of available assessment parameters. Vulnerability assessments are also done on different aquifer types and in different geomorphological conditions. These factors result in differences in the vulnerability maps created using different vulnerability assessments methods. Therefore, the focus of validation of vulnerability assessments should be on validating the input parameters used during the assessments, and not on validating the vulnerability maps themselves, as is often done at present.

Common groundwater vulnerability validation methods employed by researchers include:

1) using the hydrographs of chemical parameters to determine the relevant signature and water flow;
2) bacteriology;
3) tracer techniques;
4) water balancing;

5) calibrated numerical simulations; and
6) analogy studies (Daly et al., 2002).

Due to the lack of available data, applications of most of these outlined methods may be challenging in a SSA context. However, adopted validation techniques could only serve as a check to see if the vulnerability maps are correct or wrong. It is incorrect to validate vulnerability maps derived from combinations of parameters with a single parameter. This represents one of the limitations of validation. To this end, validation should be carried out with the combination of common tracers such as chloride and bacteriology with dissolved oxygen (Butscher et al., 2011; Oke, 2015) or with hydrography of chemical data (Nguyet and Goldscheider, 2006a).

For the assessment of drinking water and other resources, validation should be both quantitative and qualitative, using a standard such as the drinking water guidelines of the World Health Organization. Methods based on the residence time of conservative chemical substances in the saturated and unsaturated zones are used widely in the SSA (Butler, 2010; Cook et al., 1992; Edmunds and Tyler, 2002; Tyler et al., 1996), and may also be very good vulnerability validation techniques. Conservative chloride is recommended for the estimation of travel/residence time. This is because it is easily accessible, inexpensive to analyse and locally and regionally applicable (Edmunds, 2010). Where available, natural isotope data or artificial tracers (Jeannin et al., 2001) could be used to validate the travel times of the contaminants from the source to the target, which could further support vulnerability assessments made with the techniques that are based on travel times.

6. Suggested methods to vulnerability mapping for Sub-Saharan African countries

Robins et al. (2007) highlighted the inapplicability of most European methods in assessing vulnerability of SSA due to reasons stated earlier; however, groundwater vulnerability researches have been successfully carried out in SSA by either applying an existing methodology or assessment based on newly developed methods. Examples of the mainly successful vulnerability approaches applied to SSA can be subdivided into the following and are hereby recommended to be used on a country-wide application:

6.1. Travel time approach

The idea of vulnerability assessment by consideration of the travel time of contaminants from source to target was recommended by Fried (1987). This method was used by Saayman et al. (2007) for the intrinsic vulnerability assessments at Secunda, Mpumalanga and the Coastal Park waste disposal site in Cape Town, South Africa. The travel time of a conservative contaminant from surface to the aquifer was calculated based on a simple formula:

$$T_{time} = \frac{Z.\,\theta}{V_d}$$

where: T_{time} = travel time in years, Z = thickness of the vadose zone in metres, θ = average moisture content or volumetric water content of the vadose zone, V_d = the average recharge rate in m/day. The limitations of this method include not considering the concentrations of infiltrating contaminants, land use and other human activities that generate contaminations. The travel time approach can be used in tracking contaminants that flow into unconfined aquifer systems in sedimentary and weathered basement aquifers.

6.2. Parametric approach

This is the most common vulnerability assessment method applied to SSA aquifers. Parametric methods include the Rating System, Point Counts System Models (PCMS) and Matrix Factors. DRASTIC is the most widely used parametric method in SSA. DRASTIC and its modified forms have been applied for vulnerability assessments by various authors, including the following: Lynch et al. (1997) and Musekiwa and Majola (2013) (South Africa); Issiaka et al. (2006) (Abidjan Quaternary aquifer, Côte D'Ivoire); Parfait and Daouda (2015) (Abomey-Calavi area in Benin); Munga et al. (2006) (Kisauni area, Kenya); and Ojuri and Bankole (2013) (selected parts of the Lagos aquifer, Nigeria). Makonto and Dippenaar (2014) used the Weighted Overlie Vulnerability Method for assessing the Letaba Catchment of Limpopo, South Africa. Ouedraogo et al. (2016) applied the DRASTIC methods to assess the African continent. Robins et al. (2007) suggested re-rating of the DRASTIC methods to include information on water quality from individual boreholes in areas where pit latrines or waste disposal sites occur.

The EUZIT (Excel-based Unsaturated Zone Index Tool) and modified UGIF vulnerability assessment methods developed in South Africa by Saayman et al. (2007) are other examples of parametric methods designed for the saturated and unsaturated zones. These authors created a data base combining travel time, physical and chemical properties and hydraulic properties. A rating factor was applied to each of the parameters according to the estimated importance and the method that was used to assess the vulnerabilities of aquifers at the Coastal Park Waste Site as well as a site at Goedehoop, South Africa. Nick (2011) applied the PI method to assess the vulnerability of aquifers in Lusaka (Zambia) and surrounding areas. He chose the PI method due to its accuracy and the fact that it accounts for both karst and non-karst aquifers. A simplified version of the PI method for data-scarce areas, such as SSA, was applied to tropical mountainous karst areas by Nguyet and Goldscheider (2006b).

Oke et al. (2016) applied the RTt method to assess the vulnerability of the shallow aquifers of the Dahomey Basin of southwestern Nigeria. The RTt method was developed with reduced parameters often applied in groundwater vulnerability assessment. The DART method developed by Dennis and Dennis (2012), was designed in South Africa and applied to assess the South African aquifer systems. DART uses four parameters (depth, aquifer type or storativity, recharge and transmissivity) which focuses more on groundwater sustainability and quality studies.

Most methods using parametric approaches have been applied to all types of aquifers systems in SSA, such as the karst system, fractured rock, weathered basement rocks and sedimentary rock. Limitations of the DRASTIC method, as with other parametric methods, are that results can be ambiguous and open to more than one interpretation (Lim et al., 2009). Dominant flow classification in the PI method is unclear and does not leave room for possible flow processes outside the listed range (Oke, 2017). Daly et al. (2000) suggested the use of permeability to evaluate the protective properties. This will eliminate the uncertainty contained in the PI protective function. The main hindrances to the use of the RTt method are its lack of factors that account for large water bodies, karst topography, contaminant types (Oke, 2015), as well as human activities that generate contamination in SSA countries such as pit latrines, soakaways, overpopulations. Other methods that have limitations that do not account for human activities, land use and fate of contaminants, are the DRASTIC, EUZIT and DART methods.

6.3. Numerical approach

Schwartz (2006) applied numerical models to vulnerability studies in Namibia. Aquifer vulnerability was classified based on the residence time range from < 1 year in areas with carbonate rocks to > 500 years in desert areas. This was reported to be compatible with the groundwater response to rainfall (Schwartz, 2006). The simulated net infiltration rates were compared with the recharge values calculated indirectly with the chloride-balance method (Herczeg and Edmunds, 2000) for the six groups of lithologies and profiles with soil thickness in the range of 0–1 m. Using numerical modelling, three practical questions put forward by Brouyère et al. (2001) should serve as guide, namely: If pollution occurs, (1) when will it reach the target (travel time)? (2) at which concentration? and (3) for how long will the target be polluted? The best merits of numerical methods are that it can consider large inherent properties and parameters of an area through which groundwater get contaminated.

7. Conclusions

This paper highlighted the disparities in groundwater vulnerability definitions, the stages of formulating the vulnerability concepts and the challenges of assessing groundwater vulnerability in SSA countries. Most African countries lack country-wide groundwater vulnerability maps, and in the need to provide one for the SSA, the target of protection most be identified. SSA countries need to test the recommended methods of groundwater vulnerability assessment in this paper on a country wide-scale to determine which methods are most appropriate in different hydrogeological environments and at different scales.

The guidelines outlined in the paper are to assist the SSA countries in managing challenges associated with groundwater research and protection. The advantages of using the suggested guidelines in a SSA context is the allowance to factor in local African geological and hydrogeological conditions (weathered overburden aquifers, fractured basement rock aquifers, alluvial sedimentary aquifers, desert conditions and arid environments) into the vulnerability assessment methods. Some of the suggested methods also accept assessment based on information or data availability, time and resources available. This paper will guide the SSA countries in identifying peculiar challenges of assessing groundwater vulnerability, identifying an appropriate methodology of assessment and prioritising the need for aquifer vulnerability assessment.

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