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Research paper

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