Available online at www.sciencedirect.com
ScienceDirect
Journal of African Earth Sciences 47 (2007) 30–38
Journal of African Earth Sciences
www.elsevier.com/locate/jafrearsci

Adapting existing experience with aquifer vulnerability and groundwater protection for Africa

N.S. Robins [a,*], P.J. Chilton [a], J.E. Cobbing [b]

[a] British Geological Survey, Maclean Building, Wallingford, Oxfordshire OX10 8BB, UK
[b] CSIR Natural Resources and the Environment Unit, P.O. Box 395, Pretoria 0001, South Africa

Received 16 January 2006; received in revised form 29 June 2006; accepted 16 October 2006
Available online 1 December 2006

Abstract

Whilst groundwater vulnerability mapping and the delineation of resource and source protection zones have become an appropriate set of management tools for Britain as incorporated in European policy, much of semi-arid Africa is still dealing with more pressing issues centred on water supply coverage. There are a number of fundamental differences with Britain which disallow conventional vulnerability mapping and land zonation in much of Africa. Firstly, the scale of groundwater occurrence in weathered basement aquifers does not encourage vulnerability mapping to be undertaken at a field scale, whereas the Karoo and some of the larger areas of unconsolidated sedimentary aquifers could more readily be zoned according to aquifer vulnerability. Secondly, analysis needs to disregard the productivity (or recharge potential) of the aquifer so that poorly productive but socially important aquifers can be assessed. Such practice also avoids the need to identify a value for effective rainfall, a problematical value in semi-arid climates given current uncertainties. Thirdly, it is difficult to protect the many small and dispersed groundwater supply sources typical of many African communities when compared with the fewer and larger sources characteristic of Britain and Europe. Some aspects of European groundwater management practice have been transferred to the African context, notably by South Africa, but there are other practices that should not be attempted. Lessons from experience in South Africa highlight capacity to implement as a key inhibiting factor. Examples of vulnerability assessment and land zonation in a variety of African settings indicate only limited success so far with standard vulnerability assessment and land zonation techniques. Alternative means of quantifying the problem of the optimum proximity of the pit latrine from the well are highlighted, with a minimum separation of 10 m suggested for typical weathered basement rocks.

Keywords: Aquifer vulnerability; Source protection; Groundwater protection; Groundwater management; Africa

1. Introduction

The use of aquifer vulnerability maps and the designation of zones in which human activities are limited to protect both aquifers and groundwater sources are not new. One of the earliest examples of the use of zoning was introduced in Barbados in 1964 (Chilton et al., 1990). Whilst Europe has forged ahead with groundwater management and protection tools (Ward et al., 2004), Africa has been less able to adopt such policies whilst faced with the more pressing tasks and pre-occupations of developing groundwater to improve supply coverage. These pre-occupations include coping with decentralisation and other institutional changes, the HIV aids pandemic and the recurrent droughts, which have collectively blurred the focus on groundwater management in many countries in southern and eastern Africa. Indeed, Pietersen (2005) highlights the idea that conventional approaches to groundwater management need reassessing in many countries where the institutional, legal and technical frameworks are simply not in place.

However, a recent regional groundwater vulnerability initiative by the Southern African Development Community (SADC), and on-site sanitation issues relating to local groundwater sources, notably in Uganda (Barrett et al.,

* Corresponding author. Tel.: +44 491 692337; fax: +44 491 692345.
E-mail address: nsro@bgs.ac.uk (N.S. Robins).

1464-343X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jafrearsci.2006.10.003

2000) as well as the river basin management programme in South Africa indicate that Africa is beginning to take heed of the need to include vulnerability assessment and groundwater protection strategies in its management of water resources. Furthermore, as the proportion of populations served by water supply and sanitation increases over the coming years with efforts to meet the Millennium Development Goals, the scope for the latter to impact on communities will in turn increase, and the need to take account of protecting as well as developing groundwater will become more acute.

To meet these new challenges, groundwater management in Africa needs to embrace both the assessment of aquifer vulnerability and the use of protection zones. Three important characteristics of the hydrogeology and groundwater development in Africa will, however, need to be taken into account:

1. The range of scales of groundwater occurrence must be appreciated. Some aquifers, including the Karoo and the larger areas of granular superficial deposits such as the Shire Valley in Malawi and the Cape Flats in the Western Cape, lend themselves to conventional vulnerability assessment and protection zonation. Other areas, such as the shallow weathered basement aquifers of southern and eastern Africa or the shales of West Africa, are more difficult to assess and these require more detailed characterisation before source and resource protection zones can be defined.
2. A significant problem lies with the vagaries of the semi-arid African climate. Although the long-term average rainfall has statistical meaning, it may bear little relationship to operational and management considerations from year to year. Any approach to vulnerability assessment that gives less weight to the role of long-term recharge from rainfall, or conversely to aquifer productivity is, therefore, attractive. Scale issues are also important in controlling recharge. Local geomorphology and topography in the form of hollows, inselbergs, slopes, bunded fields, and local fracture systems, dykes and other geological features play a major role in modifying drainage and concentrating recharge. In these settings, aquifer vulnerability cannot reasonably be assessed on any other than a local scale.
3. The scale and distribution of groundwater abstraction need to be taken into account. Thus it is quite reasonable to establish protection zones around a relatively small number of large abstraction boreholes or wellfields, a common situation in Europe, but this is not easy to achieve for large numbers of smaller capacity wells or boreholes widely dispersed over the aquifer outcrop, as is commonly the case for rural supplies in Africa. The conventional approach of zoning cannot easily be applied, and the best strategy for protecting groundwater may be to ensure careful borehole siting in relation to pollution sources, together with good construction practice and adequate sanitary seals.

Strategies for groundwater protection in Africa are needed that take account of these factors. This paper reviews current practices in the UK (Europe) and Africa, and discusses which of these are appropriate both for the prevailing hydrogeological characteristics and the institutional and cultural constraints which prevail in many African countries. Where practices are not easily adaptable, traditional approaches to groundwater protection will have to be augmented by other measures, which are briefly reviewed.

2. The aquifer vulnerability concept

The objective of defining and mapping aquifer vulnerability is to help planners to protect groundwater as an essential economic resource and to act as a foundation for the designation of protection zones. The concept of aquifer vulnerability derives from the assumption that the physical environment may provide some degree of protection of groundwater against human impacts, especially with regard to pollutants entering the subsurface. Aquifer vulnerability thus combines the hydraulic inaccessibility of the saturated zone to the penetration of pollutants, with the attenuation capacity of the strata overlying the saturated zone (Foster, 1998). Attenuation as a result of physico-chemical retention or reaction of pollutants includes the processes of biochemical degradation, sorption, filtration and precipitation. The properties of the soils and rocks which determine the inaccessibility (how easily and quickly water and pollutants move) and the attenuation capacity vary from place to place. These variations can be described and depicted in map form for use by land use planners.

Although the general concept of vulnerability has been in use for more than thirty years, there is no strict definition of the term, and it has come to mean different things in different contexts (Vrba and Zaporozec, 1994). In particular, hydrogeologists have debated whether vulnerability should be determined in a general way for all pollutants, or specifically for individual pollutants such as nitrate, pesticides or atmospheric deposition. In practice, the limitations of existing subsurface data are such that most approaches use *intrinsic* vulnerability, a function of the hydrogeological properties, rather than the *specific* vulnerability to a single pollutant or group of pollutants.

2.1. Assessing vulnerability

Aquifer pollution vulnerability refers to the intrinsic characteristics of the aquifer that determine whether it will be adversely affected by a pollutant loading. Vulnerability assessment is based on likely travel time from the ground surface to the water table; the greater the travel time the more potential there is for pollutant attenuation. Typical classes of vulnerability are shown in Table 1, in which extreme vulnerability describes highly fractured

Table 1
Broad classification of aquifer vulnerability (after Morris et al., 2003)

Vulnerability class	Definition
Extreme	Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
High	Vulnerable to many pollutants except those highly absorbed and/or readily transformed
Low	Only vulnerable to the most persistent pollutants in the very long term
Negligible	Confining beds are present and prevent any significant vertical groundwater flow

Table 2
Hydrogeological environments and their associated potential groundwater pollution vulnerability (after Morris et al., 2003)

Hydrogeological environment		Typical travel times to water table	Attenuation potential of aquifer	Pollution vulnerability
Alluvial and coastal plain sediments	Unconfined	Months–years	High–moderate	Moderate
	Semiconfined	Years–decades	High	Low
Intermontaine valley fill	Unconfined	Months–years	Moderate–high	Moderate
	Semiconfined	Years–decades	Moderate	Moderate–low
Consolidated sedimentary aquifers	Porous sandstones	Weeks–years	High	Moderate–high
	Karstic limestones	Days–weeks	Low–moderate	Extreme
Coastal limestones	Unconfined	Days–weeks	Low–moderate	High–extreme
Glacial deposits	Unconfined	Weeks–years	Moderate	High–moderate
Weathered basement	Unconfined	Days–weeks	Low	High–extreme
	Semiconfined	Weeks–years	Moderate	Moderate
Loessic plateaux	Unconfined	Days–months	Low–moderate	Moderate–high

rocks with a shallow water table and little chance for pollutant attenuation.

Generic transit times to the water table are shown in Table 2. Given that a groundwater residence time of one month is generally sufficient to eliminate most pathogens (Morris et al., 2003), it is instructive to note that different hydrogeological regimes offer different potential vulnerability regimes (Table 2).

Conventional methodologies to assess groundwater vulnerability involve indexing and weighting of relevant properties or GIS format overlays of relevant properties. The most popular indexing system is DRASTIC (Aller et al., 1987), which incorporates Depth to water [x5], natural Recharge rates [x4], Aquifer media [x3], Soil media [x2], Topographic aspect [x1], Impact effect of vadose zone [x5] and hydraulic Conductivity [x3] along with their respective weightings in brackets. Thus in a weakly permeable aquifer with relatively low recharge rates the vulnerability is low, whereas a more permeable aquifer with greater recharge potential, and which is exposed at the surface is highly vulnerable and in addition its groundwater is usually a significant resource. As a consequence, Basement shales, greywackes, crystalline and other fractured rocks with little if any matrix porosity have usually been classified as of low vulnerability. The low vulnerability rating was not problematic, since such aquifers were considered as containing little groundwater, and population densities and, therefore, pollution pressures in these areas are often low. The method has been successfully applied in a number of countries, although in most cases shortcomings have been identified. Rosen (1994), for example, identified that DRASTIC tends to underestimate the vulnerability of fractured rocks. The large number of characteristics included means that data requirements are invariably difficult to meet, and critical parameters may be masked by others which have little or no bearing in the vulnerability in a particular setting.

An alternative indexing system in use in some countries is GOD, which considers Groundwater occurrence including recharge, Overall lithology and Depth to groundwater, also using a scoring system (Foster, 1987; Vrba and Zaporozec, 1994).

3. Vulnerability mapping in the UK

The UK originally adopted a scheme based on overlaying the geological characteristics of particular formations (Table 3) and the soil leaching potential to derive national aquifer vulnerability maps (Robins et al., 1994). These maps were strongly weighted towards aquifer permeability and had a number of shortcomings. They classified highly and moderately permeable aquifers into sub-classes based on three soil leaching classes and assumed that all weakly permeable rocks were not vulnerable as they had negligible hydraulic conductivity. Furthermore, the important element of unsaturated zone travel time represented by depth to the water table was excluded because inadequate data were then available, and any protective cover afforded by superficial clay-bound material was ignored with the proviso that site-specific investigation of the superficial cover is needed to determine its pollutant transport characteristics. Nevertheless, these maps, which are available at 1:100,000 scale for England and Wales and parts of Scotland and at 1:250,000 for Northern Ireland, have become essential decision support tools for planning and other uses.

3.1. Dealing with fractured rocks

A judgement was made for the volcanic and igneous, and the Lower Palaeozoic and Precambrian rocks in the

Table 3
Geological classification of UK formations for aquifer vulnerability map series (after Robins et al., 1994)

Highly permeable aquifers	Moderately permeable aquifers		Weakly permeable rocks (aquifers)
Highly permeable formations usually with the known or probable presence of significant fracturing. Highly productive strata of regional importance	Fractured or potentially fractured but with high intergranular permeability	Variably porous/permeable but without significant fracturing	Formations with negligible permeability
Includes: Chalk and Upper Greensand, Jurassic limestones, Jurassic sandstones, Magnesian Limestone, Lower Greensand, Carboniferous Limestone	*Includes*: Coal Measures, Millstone Grit, Devonian sandstones and some igneous and metamorphic rocks	*Includes*: River gravels, Glacial sands and gravels, Palaeogene sands and gravels	*Includes*: Clays, shales, marls and siltstones, Mercia Mudstone and most igneous and metamorphic rocks

UK as to the degree of secondary permeability provided by the presence of fractures. For the most part, this was judged to be negligible, although some strata were considered to be moderately permeable. This decision was based on the available understanding of these strata to sustain useable water supplies in a UK context, and it dismissed most of these rocks as weakly permeable and effectively non-water bearing. This judgement considered more than just the occurrence of fractures, but rather the likelihood of interconnected fractures that formed an aquifer unit with at least some storage and in which groundwater flow and pollutant transport could take place. Applying this approach in Africa would result in the Basement Aquifer being interpreted as of low vulnerability simply because it could not sustain the scale of supplies available in the UK. However, given the collective magnitude of the large number of low-yielding supplies, and their immense social and economic value to the rural communities that they sustain, the converse is true: the basement aquifer is a major regional water supply source and, therefore, a major regional aquifer which must be considered as vulnerable and in need of protection.

The variety of fractured rocks coupled with a range of unsaturated depths indicates that a broad range in vulnerability is possible. Many workers allude to this, Morris et al. (2003), for example, state that extreme vulnerabilities are associated with highly fractured aquifers, including karst limestone, with a shallow water table as they offer little chance for contaminant attenuation. However, it is tempting to dismiss attenuation in vadose fracture systems because of the perceived speed of transport from surface to water table. In many situations attenuation can take place in the soil horizon and continue to some extent in poorly dilated fractures below, but this cannot readily happen where the water table is shallow, e.g. <2 m (Daly, 2005). Even thin soils may contain some organic carbon, and this provides an active zone for ion exchange and sorption to take place. Attenuation is, therefore, possible in some fracture systems. However, the soil can easily be bypassed (e.g. from contaminant sources such as pit latrines) or the soil may be absent. Applying the precautionary principle, however, suggests that all fracture systems should be considered vulnerable until they can be demonstrated otherwise.

4. The coming of the European Water Framework Directive

Within the European Union, the Water Framework Directive 2000/60/EC "establishing a framework for Community action in the field of water policy", was introduced in December 2000 and now dominates the water management and protection strategies of member states. The Directive (WFD) expands the scope of protection to all waters (surface and groundwater) with the aim of meeting specific environmental objectives by 2015. In order to achieve the objectives and to manage surface and groundwater in an integrated way, the WFD introduces River Basin Districts and requires that a River Basin Management Plan be produced for each District. As part of this process, an assessment of the risk of groundwater failing to meet these objectives must be undertaken, and involves assessment both of the nature and magnitude of pollution pressures and of the vulnerability to pollution of groundwater.

The WFD upsets the conventional approach to aquifer vulnerability assessment by requiring designation as a groundwater body (the basic groundwater management unit) any distinct body of groundwater in a geological formation, the body capable of supplying at least 10 $m^3\ d^{-1}$. This is a low threshold and even weakly permeable geological formations that were previously considered as non-aquifers contain groundwater that needs to be protected. This threshold would, of course, include the weathered Basement Aquifer of Sub-Saharan Africa.

Thus, a new set of approaches to defining vulnerability is being developed to address the requirements of the Water Framework Directive by disassembling conventional vulnerability assessment (Ó Dochartaigh et al., 2005). One approach is to remove the element of recharge or productivity from the vulnerability assessment and concentrate on transport and attenuation properties in the source-pathway-receptor concept. The importance of recharge in the vulnerability designation is thus downgraded, as the resource potential and hence economic value of the groundwater is no longer deemed a significant factor.

This approach recognises the vulnerability of groundwater in, for example, a single fracture or group of fractures in an exposed basement aquifer. Whether the whole groundwater body, if defined as the receptor, is vulnerable (i.e.

whether concentrations of pollutant are likely to be elevated across the entire body) will then depend on the degree of interconnection of the fractures and whether pollution is diffuse (e.g. an agricultural source) or point-source (e.g. a pit latrine) in origin.

The outcome of this approach is that fractured but poorly productive basement rocks are assessed as highly vulnerable whereas DRASTIC and the old UK system would have assessed them as having low vulnerability (Ó Dochartaigh et al., 2005). The fractured rocks are now perceived to be highly vulnerable, with an easy and rapid pathway to the saturated zone with little opportunity for attenuation. This is because each fracture may be vulnerable to pollution at a single point on the ground surface above it, although neither the overall groundwater body, nor baseflow discharging from it, need be overly contaminated.

This method could provide a mechanism by which the low productivity Basement Aquifer of Africa can be assessed. However, given that intergranular materials can be sub-divided on grain size and permeability (Fetter, 1994) there is probably a need to subdivide categories of vulnerability for fractured rock systems. For example, fractured basement is less vulnerable than fractured and weathered basement, which in turn is less vulnerable than karst limestone. However, the message is clear that all these categories are vulnerable to pollution to a greater of lesser degree.

4.1. The protection zone concept

Having delineated the more vulnerable areas, drinking water supplies may be protected by source protection zones within which human activities are restricted to reduce the risk of groundwater pollution. The size of the source protection zone will depend on the geology of the aquifer, including the degree of fracturing and its overall transmissive properties. For public water supplies, the innermost zone in the UK contains the land within 50 m of the abstraction point, beyond which is a nominal 50 day travel zone to the source within which most pathogens are expected to die-off. Two further zones at a greater distance from the borehole are also defined in which specified activities are discouraged. These are designed to protect from chemical pollution. Having decided that groundwater in an aquifer or parts of an aquifer (a groundwater body in WFD parlance) is vulnerable and at risk, protection zones can be delineated in which risk producing activities are inhibited. However, stopping people from doing something they have legitimately done for a long time raises a number of social and cultural issues – what is the cost to the communities of inhibiting previously acceptable activities, and should communities be compensated and if so by whom?

Some zonation may be more readily achievable than others. For example the simple concept of placing a well up-gradient from a pit latrine and up-gradient from a village is obvious to any trained hydrogeologist. It can be made obvious to a village elder once the logic of groundwater flow has been explained to him. Therefore, some degree of protection of the immediate capture area around a well, and even sanitary protection of the well-head itself, can usually be achieved simply through education and discussion. The area for a source protection zone is an expression of the yield versus the anticipated annual recharge (Burgess and Fletcher, 1998), so that a normal minimum and maximum value for recharge can be used to provide an inner and outer limit to the zone.

Experience with the DFID funded ARGOSS project (Lawrence et al., 2001) in Uganda has highlighted the issue of faecal bacteria being transported from latrine to spring or borehole. The guideline document resulting from this project lays down a set of rules for determining the optimum horizontal separation between sanitation facility and drinking water source in a variety of different hydrogeological environments to effect viable source protection. This work has been trialled successfully in Uganda and is advocated as sensible practice for basement aquifers in Sub-saharan Africa which do not otherwise lend themselves to conventional vulnerability assessment.

Other more widespread zonation comes at a cost, and dialogue with farmers and industrialists is an essential part of design and implementation. In the UK, a pilot set of land zones to control agricultural pollution (the Nitrate Sensitive Areas) was instigated in a dialogue with the farming community. Farmers within the zones were compensated for loss of crop yield due to reduced applications of nitrogen. Subsequent delineation of zones (the Nitrate Vulnerable Zones) has been required by the EU Nitrate Directive. These zones are more extensive but require less stringent controls on farming activities, and are implemented without compensation. However, an essential part of the procedure remains dialogue and consultation with the communities themselves.

5. The African experience

Although there are relatively few major African cities that rely on groundwater, those that do, including Pretoria, need to safeguard their groundwater resources from urban pollution. The Zambian capital Lusaka draws over half its needs from the ancient fractured dolomitic limestone aquifer that lies beneath the city. The limestones act as a highly diffusive system with high transmissivity and low storage. As such they lend themselves to conventional land zonation, being in many ways a parallel to the major Chalk aquifer system of England, which is successfully managed with protection zones. Nkhuwa et al. (1999) and Nyambe and Maseka (2000) describe local overpumping and the development of compaction sink holes in the city area. However, the local piezometry indicates that a key recharge zone for the aquifer is that of the Lusaka Forest Reserve. This is an area that has been progressively deforested since 1985 with land use increasingly dominated by small holdings and this has tended to increase runoff at the expense of recharge. Although this area is highlighted as a key potential resource protection zone, there has been no attempt yet to advocate zonation. However, many of the urban supply sources now have 1000 m radius protection zones around them.

Kampala is partly dependent on groundwater and the Ugandan town of Iganga is wholly dependent on groundwater. Analysis of data from protected springs, wells and boreholes in weathered basement indicates that dug wells are more liable to be contaminated by pathogens than protected springs, and that properly constructed boreholes are least vulnerable (Howard et al., 2002). The Ugandan experience suggests that a horizontal separation between sanitation facility and groundwater source of 10 m is usually adequate, even during the rainy season when the transport of faecal coli from the surface is greatest (Barrett et al., 2000).

Vulnerability can also be a useful tool with which to prioritise protection zonation in large urban areas. Mato (2004) reports a system used in Dar es Salaam to define a protection index for individual sources (WYVUL) which is derived from: groundWater quality, Yield, DRASTIC Vulnerability index, social importance or Use of the source and Land use. The social importance of the source is an important and often overlooked parameter – the definitions used in this study are shown in Table 4. Although zonation has not been implemented, the prioritisation is used as a long term planning tool and the recommended groundwater management strategy for Dar es Salaam includes: identification of pollution sources, establishment of databases and information management, development of a vulnerability map, assessment of protection needs and priorities, initialisation of monitoring network, and improved institutional coordination and public participation (Mato, 2002).

Aquifer vulnerability, as a planning tool, was also applied on the coastal sand aquifer at Calabar in south-eastern Nigeria. The aquifer supplies much of the area and when threatened with industrial development was assessed using the key parameters: aquifer properties, laterite thickness and depth to water table. In this way the aquifer land area was split roughly equally into three areas of lower, medium and higher vulnerability to pollution (Edet and Merkel, 2004).

At Yeumbeul in Senegal, 7000 families draw water from traditional wells in a shallow sandstone aquifer. The distance from well to nearest latrine ranges up to 36 m and a correlation of nitrate concentration in well water has been found with distance from, and age of, the nearest latrine (Tandia et al., 1999). Extrapolation of the data indicates the optimum horizontal separation between well and latrine to be 50 m. The aquifer can be divided into three vulnerability zones: the least vulnerable where the depth to water is greater than 5 m even after the rains, a middle range from 2.5 to 5 m and the most vulnerable where the water table is less than 2.5 m depth.

Table 4
Rating for use of groundwater in the Dar es Salaam WYVUL model (after Mato, 2002)

Water supply status	Rating
Groundwater not used as alternative domestic source	1
With piped water supply (service only 4 days per week) groundwater is alternative source	6
With piped water supply (service less than 4 days per week) groundwater is main alternative source	8
Without piped supply, groundwater only supply	10

UNEP et al. (2006) report investigations into groundwater vulnerability and protection at selected urban and peri-urban environments using a variety of techniques including DRASTIC. The work identified a number of issues, including:

- the importance of the single physical parameter depth to water (the vadose zone),
- the lack of legislative support for groundwater protection zonation in most African countries,
- and the important realisation that the poorest communities are those most at risk, i.e. the social parameter needs to be added into groundwater vulnerability assessment.

5.1. Lessons from South Africa

There has been a fundamental change in the way water resources are developed, used and managed in South Africa in recent years. The old "riparian" scheme based on land ownership, in which water resources belonged to the land owner, has been replaced by a system which recognises that the basic needs of people (potable water and adequate sanitation) must first be met, with sufficient water retained to sustain the environment. The progressive decentralisation of water management to Catchment Management Agencies is an important part of the new system, but the National Government remains the public trustee of the nation's water resources. The principles, including the legal foundation, are laid out in the National Water Policy (1997) and the National Water Act (1998), and are summarised in the National Water Resources Strategy (DWAF, 2004).

South Africa's groundwater resources are generally underutilised and less effectively managed than its surface waters. This is partly because groundwater in South Africa largely occurs in fractured aquifers, including karst limestones, where water can be difficult to find and borehole yields are often low, and partly a result of the former legal framework. The potential of many South African aquifers is, therefore, not yet fully understood, and there remains a lack of groundwater information.

Groundwater in South Africa is now recognized as an important national asset and an integral part of the water cycle. Since the cost of supplying dispersed rural communities with surface water is often prohibitive, it is increasingly recognised that groundwater is the only realistic option for a sustainable supply of safe water in many areas. Groundwater is also the sole water source for several small and medium sized towns (particularly on the relatively arid west coast), and contributes to the bulk supply in larger towns and cities such as Pretoria.

Groundwater protection in South Africa is a relatively new concept. Efforts to protect groundwater can be separated into two strands:

- guidelines and policy on the protection of individual sources, particularly in rural areas where these are threatened by on-site sanitation, and
- the development of broader policies and practises for the protection of regional aquifer bodies.

A technical guideline was drawn up in 1995 by the South African Department of Water Affairs and Forestry (DWAF) to address the problem of groundwater contamination by a variety of sources including pit latrines and waste-disposal sites (Xu and Braune, 1995). The guideline laid out minimum distances between boreholes and point pollution sources of between 15 and 50 m. It was proposed that the exact distance depend on three factors, namely depth to water table, the composition of the soil, and the characteristics of the aquifer, i.e. reflecting the DRASTIC system and ARGOSS. The guideline was followed by a practical series of protocols aimed at engineering and technical staff (DWAF, 1997; DWAF, 2003) involved with dry on-site sanitation (e.g. VIP latrines). The protection of larger individual groundwater sources for villages and towns is currently the responsibility of the municipality or water service provider, and there is as yet no consistent protection protocol.

Final responsibility for the protection of regional groundwater resources resides with DWAF, although in time the implementation of groundwater protection policy is expected to devolve to the Catchment Management Agencies. DWAF has laid out a policy and strategy for the general management of groundwater quality in South Africa (DWAF, 2000). This document gives standards and requirements for the general use and licensing of groundwater sources, classifies aquifer bodies, and specifies when remedial action is needed. A series of regulatory instruments are used to enforce these. Although source protection zones are mentioned as a possible means of protecting groundwater sources, these are not legally required, and nor are they commonly used.

Industrial developments are subject to an Environmental Impact Assessment (EIA) process in South Africa. The EIA considers the impact of the proposed development on water resources, including groundwater. In the case of a perceived threat to groundwater resources or sources, DWAF would be consulted to assess the risk and could recommend that permission for the development be denied. The risk posed to groundwater specifically by waste disposal activities is mitigated by a series of legal requirements laid out by DWAF (DWAF, 1998). These take account of the strategic importance of the underlying aquifer, with higher standards imposed for certain aquifers (e.g. those that are a sole source of water to a community). This is in keeping with the so-called "differentiated approach" to the country's aquifers, in which certain groundwater bodies are afforded greater protection than others. The "precautionary principle" and "polluter pays principle" are both generally recognised, and minimum standards for groundwater assessment and monitoring in the vicinity of a proposed waste disposal site are laid out.

Although groundwater sources have legal protection in South Africa today, and guidelines for risk assessment and groundwater protection (including protection zoning) exist, these are not always adhered to. For example, in September 2005 an outbreak of typhoid in the town of Delmas in Mpumalanga killed at least four people. Large parts of the town are supplied by boreholes drilled into a karstic dolomitic aquifer. The water is chlorinated before being made available for public supply. Following an earlier outbreak of typhoid in 1993, it was recognised that pollution of the groundwater by sanitation facilities on or near the dolomite was inevitable (Waner et al., 1998). However, informal settlements grew on the dolomite aquifer outcrop, and faecal pollution of the groundwater from pit latrines continued. The provincial government is currently examining the possibility of relocating more than 2000 families living on the outcrop.

In many towns in South Africa, public water supply boreholes are located in hard, fractured rocks such as the Karoo Supergroup. Drilling targets are often the fractured margins of dolerite intrusions. The geometry of these aquifer systems is generally complicated, and they resist easy protection zoning. At present many of these towns rely on treating groundwater supplies. Whilst most towns have some idea of the potential risk to their water supplies, few if any have identified formal groundwater protection zones.

5.2. Discussion

In Africa large numbers of small abstractions are commonly clustered around towns and villages over the weathered Basement Aquifer. For this situation, a groundwater protection strategy has to have several strands, but does not require conventional groundwater vulnerability assessment using the indexing methods such as DRASTIC. These include:

- care in siting sources in relation to existing on-site sanitation, the ARGOSS experience;
- good on-site source protection and borehole completion with proper sanitary surface seals;
- adequate surface works, including drainage channels, washing slabs and fences to keep away animals;
- local source zonation to inhibit specified activities, e.g. no access for animals and no new sanitation.

Conversely, although these same strands apply to the more productive aquifers such as the Karoo and the larger

Table 5
Suitability of main African rock types to vulnerability assessment and land zonation

Rock type	Suitable for vulnerability assessment	Suitable for land zonation
Crystalline basement		
Granitic plutons	No	No
Greenstone/mobile belt (Limpopo, Mozambique belt)	Not easy	No
Late Proterozoic sediments (Transvaal, Waterberg etc)	Not easy	Not easy
Consolidated sedimentary		
Non-marine sediments (Karoo, Continental Terminal and Nubian Sandstones)	Yes, with care	Yes, with care
Marine sediments (Jurassic and Cretaceous, Benui Rift, west and east coast of southern Africa)	Yes, with care	Yes
Unconsolidated sediments		
Alluvial in river deltas, wind blown sediments and internal drainage (Kalahari)	Yes	Yes
Volcanics		
e.g. Ethiopian and Lesotho highlands; Karoo	No	Not easy

granular alluvial deposits, assessment of groundwater vulnerability is worthwhile (Table 5). However, techniques that exclude recharge or productivity are most valuable as these overcome the need to know the actual effective rainfall, which may be highly variable, and indicate as potentially vulnerable the small capacity, but socially very important, aquifers as potentially vulnerable. The resultant analysis can then be used to identify the most vulnerable zones of each aquifer in order to discourage polluting activities in them.

Monitoring is an obvious key to successful groundwater management. However, monitoring of sources and even sanitation surveys is not a priority in many sub-Saharan countries, although monitoring should be incorporated into management strategies as and when resources permit.

6. Conclusions

Groundwater vulnerability mapping and the delineation of resource and source protection zones have been important and widely used management tools in Britain and the rest of Europe for over 20 years. They comprise a system for assessing the vulnerability of unconfined aquifers to underpin land zonation policies to protect the underlying groundwater resource. In addition, source protection is undertaken by delineating travel time zones around an individual source.

Africa, on the other hand, is still dealing with more fundamental issues. These include institutional problems, the HIV aids pandemic, recurrent drought, coverage and sustainability of supply. Attempts to transfer British and European methodologies to the African context have so far met with little success, but there are good reasons why such transfer should be undertaken with caution:

1. The extensive weathered basement aquifers need to be assessed at local field scale because of the scale of variation within them, and regional scale vulnerability assessment and protection delineation is, therefore, not appropriate.
2. Vulnerability analysis in Africa can be undertaken on the Karoo and other aquifers. However, assessment should exclude aquifer recharge potential (or productivity) both 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. If DRASTIC is still being used the weighting against recharge should be reduced.
3. Protection of the many small and dispersed African groundwater sources by land zonation cannot usefully assume adequate protection, and other complementary measures are needed.

Some aspects of European groundwater management practice have already been transferred to the African context, but there are others that should not be attempted. Vulnerability assessment and land zonation has been attempted in a variety of settings, but these indicate only limited success through the application of standard vulnerability assessment and land zonation techniques. The problem of quantifying the optimum separation between pit latrine and well in the weathered basement aquifer is best adopted from available Guideline documents. A figure of 10 m is the currently accepted distance, although 50 m is cited from work in Senegal in fractured sandstone and advocated by DWAF (1997). Ideally, groundwater supplies should be located outside and uphill of the village area to avoid contamination.

Nowadays, the power of GIS compilation allows different sets of data to be combined to produce vulnerability evaluations. It also allows uncertainty to be described. DRASTIC and other indexing techniques are no longer the only techniques available, although they provide a foundation for bespoke GIS systems. Additional parameters worth consideration in vulnerability assessment are a social index describing poverty/wealth whereas parameters such as rainfall may be less valuable.

One key outcome of recent research is that there is insufficient legislative support to enable land zonation in most African countries, and inadequate capacity for implementation. Land zonation is fraught in urban and peri-urban areas.

In South Africa, groundwater is afforded considerable legal protection, and recent work by DWAF and others has contributed to a body of modern standards, principles and guidelines. However, the country suffers from a history of overlooking the full value of the national groundwater asset, and there are difficulties with implementing and enforcing the new policies. There is also a shortage of skilled groundwater professionals, and as a result, implementing national policy as regards aquifer vulnerability and groundwater protection remains a work in progress.

Acknowledgement

This paper is published by permission of the Director, British Geological Survey (NERC).

References

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G., 1987. DRASTIC: a standardised system for evaluating groundwater pollution potential using hydrogeologic settings. US-EPA Report 600/2-87-035.

Barrett, M.H., Johal, K., Howard, G., Pedley, S., 2000. Sources of faecal contamination of shallow groundwaters in Kampala. In: Sililo, O. et al. (Eds.), Groundwater: Past Achievements and Future Challenges. Balkema, Rotterdam, pp. 691–696.

Burgess, D.B., Fletcher, S.W., 1998. Methods used to delineate groundwater source protection zones in England and Wales. In: Robins, N.S (Ed.), Groundwater Pollution, Aquifer Recharge and Vulnerability. Geological Society, London, Special Publications, vol. 130, pp. 199–210.

Chilton, P.J., Vlugman, A.A., Foster, S.S.D., 1990. A ground-water pollution risk assessment for public water supply sources in Barbados. In: Proceedings of the International Symposium on Tropical Hydrology and Caribbean Water Resources, San Juan, Puerto Rico, pp. 279–289.

Daly, D., 2005. Site suitability for on-site wastewater treatment systems – the role of the water table. The GSI Groundwater Newsletter 45, 3–7.

DWAF 1997. A Protocol to Manage the Potential of Groundwater Contamination from On Site Sanitation. National Sanitation Coordination Office, Directorate of Geohydrology, Department of Water Affairs and Forestry, Pretoria. First Edition, March 1997.

DWAF 1998. Minimum Requirements for Waste Disposal by Landfill. Department of Water Affairs and Forestry, Pretoria. Second Edition, 1998.

DWAF 2000. Policy and Strategy for Groundwater Quality Management in South Africa. Water Quality Management Series. Department of Water Affairs and Forestry, Pretoria. First Edition 2000.

DWAF 2003. A Protocol to Manage the Potential of Groundwater Contamination from On Site Sanitation. Prepared for the National Sanitation Programme, Department of Water Affairs and Forestry, Pretoria. Second Edition, March 2003.

DWAF 2004. National Water Resources Strategy. Department of Water Affairs and Forestry, Pretoria. First Edition, September 2004.

Edet, A.E., Merkel, B.J., 2004. An aquifer vulnerability assessment of the coastal plain sand aquifer, Calabar, Southeastern Nigeria, using a GIS index approach. In: Groundwater Vulnerability Assessment and Mapping, Abstracts, International Conference, Ustroń, Poland, p. 56.

Fetter, C.W., 1994. Applied Hydrogeology. Prentice Hall Inc., New Jersey.

Foster, S.S.D. 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenbooden, W., van Waegeningh, H.G. (Eds.), Vulnerability of Soils and Groundwater to Pollution. TNO Committee on Hydrological Research, The Hague, Proceedings and Information, vol. 38, pp. 69–86.

Foster, S.S.D. 1998. Groundwater recharge and pollution vulnerability of British aquifers: a critical review. In: Robins, N.S. (Ed.), Groundwater Pollution, Aquifer Recharge and Vulnerability. Geological Society, London, Special Publications, vol. 130, pp. 7–22.

Howard, G., Nalubega, M., Barrett, M., Pedley, S., Kulabako, R., Haruna, R., Johal, K., Taylor, R. 2002. Impact of on-site sanitation on groundwater supplies in Kampala and Iganga, Uganda. Appendix B IN: ARGOSS, 2002, Assessing risk to groundwater from on-site sanitation: scientific review and case studies, British Geological Survey Commissioned Report CR/02/079.

Lawrence, A.R., Macdonald, D.M J., Howard, A.G., Barret, M.H., Pedley, S., Ahmed, K.M., Nalubega, M. 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. British geological Survey Commissioned Report CR/01/142. Available from: <http://www.bgs.ac.uk/hydrogeology/argoss/docs/ARGOSSManual_144.pdf>.

Mato, R.R.A.M. 2002. Groundwater pollution in urban Dar es Salaam, Tanzania, assessing vulnerability and protection priorities. Ph.D. thesis, Technische Universiteit Eindhoven.

Mato, R.R.A.M. 2004. Modeling and mapping groundwater protection priorities using GIS: the case of Dar es Salaam city, Tanzania. In: Groundwater Vulnerability Assessment and Mapping, Abstracts, International Conference, Usrtroń, Poland, p. 100.

Morris, B.L., Lawrence, A.R., Chilton, P.J., Adams, B., Calow, R.C., Klinck, B.A., 2003. Groundwater and its susceptibility to degradation, a global assessment of the problem and options for management. United Nations Environment Programme, Nairobi.

Nkhuwa, D.C.W., 1999. The need for consideration of groundwater resources in urban planning in Lusaka, Zambia. In: Chilton, P.J. et al. (Eds.), Groundwater in the Urban Environment: Selected City Profiles. Balkema, Rotterdam, pp. 201–208.

Nyammbe, I.A., Maseka, C., 2000. Groundwater pollution, landuse and environmental impacts on Lusaka. In: Sililo, O. et al. (Eds.), Groundwater: Past Achievements and Future Challenges. Balkema, Rotterdam, pp. 803–808.

Ó Dochartaigh, B.É., Ball, D., MacDonald, A.M., Lilly, A., Fitzsimons, V., Del Rio, M., Auton, C.A., 2005. Mapping groundwater vulnerability in Scotland: a new approach for the Water Framework Directive. Scottish Journal of Geology 41 (1), 21–30.

Pietersen, K. 2005. Multiple criteria decision analysis to support groundwater management in South Africa (with a case study in Namaqualand). Abstracts of the Biennial Ground Water Conference, Pretoria, March 2005, pp. 393–401.

Robins, N.S., Adams, B., Foster, S.S.D., Palmer, R., 1994. Groundwater vulnerability mapping: the British perspective. Hydrogéologie 3, 35–42.

Rosen, L., 1994. A study of the DRASTIC methodology with emphasis on Swedish conditions. Ground Water 32, 278–286.

Tandia, A.A., Diop, E.S., Gaye, C.B., 1999. Pollution par les nitrates des nappes phréatiques sous environnement semi-urbain non assaini: exemple de la nappe de Yeumbeul, Sénégal (Nitrate groundwater pollution in suburban areas: example of groundwater from Yeumbeul, Senegal). Journal of African Earth Sciences 29 (4), 809–822.

UNEP et al., 2006. Groundwater Pollution in Africa. UNEP/UNESCO/AMCOW.

Vrba, J., Zaporozec, A. (Eds.), 1994. Guideline on Mapping Groundwater Vulnerability. International Association of Hydrogeologists, Hannover, International Contributions to Hydrogeology, p. 16.

Waner, S., Kfir, R., Idema, G.K., Coetzee, D.J., Rasmussen, K., Koornhof, H.J., Klugman, K.P., 1998. Waterborne outbreak of typhoid fever in Delmas. The Southern African Journal of Epidemiology and Infection 13 (2), 53–57.

Ward, R.S., Streetly, M.J., Singleton, A.J., Sears, R., 2004. A framework for monitoring regional groundwater quality. Quarterly Journal of Engineering Geology and Hydrogeology 37 (4), 271–281.

Xu, Y., Braune, E., 1995. A Guideline for Groundwater Protection for the Community Water Supply and Sanitation Programme. DWAF, Pretoria.