A three-tier approach to protect groundwater resources in South Africa

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Abstract

The quality of groundwater is affected by many activities occurring on the surface of the earth. A pro-active protection approach is required to avoid the costly and technologically difficult exercise of groundwater remediation. This paper reviews various approaches for groundwater protection and documents recent developments in this field. A comprehensive protection strategy consists of many elements, ranging from the protection of entire aquifers to localised water-supply sources. A three-tier protection concept, with the emphasis on a zoning approach, is proposed for South Africa. This will facilitate the protection of groundwater at various levels (national, regional and local) and will ensure that protection needs in the short, medium and long term are addressed.

Introduction

Early in 1991 a committee to investigate Groundwater Quality Management Policies and Strategies for South Africa was established (Braune and Hodgson, 1991). This committee not only provided focus and direction for the existing fragmented groundwater protection efforts but drew the attention of those both within and outside the groundwater community to the great need for groundwater protection in this country. Prior to this, most hydrogeological activity was tactical rather than strategic, being directed towards the location of sustainable sources of water supply at various levels. The Department of Water Affairs and Forestry has embarked on a programme of groundwater quality management and the formulation of policies and strategies which has again emphasised the need for country-wide groundwater protection. An immediate need is the formulation of a guideline for groundwater protection for the Community Water Supply and Sanitation Programme (CWSS) which is a part of the government's Reconstruction and Development Programme (RDP).

Groundwater protection has for some time been implemented in most European countries and North America. Review of overseas literature would appear to indicate that they do not experience the sanitation problems associated with rural development as evidenced in this country. Local literature on water supply and sanitation supports this view (Palmer Development Group, 1993; Jackson, 1994). There is consequently a great need to review international practices of groundwater protection in an attempt to adapt them to the South African situation.

An obvious feature of European groundwater protection practice is to designate the area immediately surrounding public (and some private) water supply sources for a high degree of protection. Isochrones of 50 to 400 d from sources are used for demarcating protection zones against degradable pollutants in Europe (an isochrone refers to the travel-time-related capture zone of a hypothetical pollutant coincident with groundwater movement). There is, however, no fixed rule regarding the number of days required for primary and secondary zones as summarised in Table 1. The primary zone is equivalent to a travel-time-related capture zone as often referred to in the literature.

A number of factors contribute to groundwater being vulnerable to contamination, these being the often considerable time lag between the entry of a particular contaminant into the groundwater system and its detection at supply or monitoring boreholes and springs; the fact that groundwater is not readily visible; and the persistence of many chemicals in subsurface environments. Many contaminants, originating from industrial, agricultural and mining activities, for example, are persistent or biodegrade very slowly and are not filtered out or adsorbed by the soil. A pro-active approach to groundwater protection is consequently required.

Contaminants can enter an aquifer through a variety of pathways, from simple percolation through soils to preferential pathways such as biochannels, cracks, joints, and solution channels in the unsaturated zone. Preferential pathways are particularly significant as they result in a short-circuiting of the favourable environment for contaminant attenuation found in the soil horizon.

Groundwater contaminants may be microbial, organic or inorganic in nature. They may also be sub-divided into persistent and non-persistent. The latter are capable of being removed naturally by chemical, physical and microbiological processes occurring selectively within the aquifer and overlying vadose zone. Bacteria in water are filtered out readily in soil and granular media though they may be carried for considerable distances in some flow regimes. As a precautionary approach, aquifer vulnerability classification and wellhead (source) protection programmes are in place in most of Europe and the USA. Table 1 provides a summary of groundwater protection zoning features evident in some European countries.

Prior to proposing a protection concept for South African conditions, a comprehensive review of commonly adopted approaches in the rest of the world is presented.

Classification approach

Most groundwater contamination incidents involve substances released at or slightly below land surface. Consequently it is shallow groundwater that is affected initially by such releases. Depicting the results of groundwater vulnerability classification in the form of maps provides a valuable tool for groundwater protection. The advent of Geographical Information Systems (GIS) has greatly facilitated the compilation and updating of such maps (Rundquist et al., 1991).

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TABLE 1
SUMMARY OF GROUNDWATER PROTECTION ZONING FEATURES IN EUROPE

Countries	Wellfield*	Primary zone	Secondary zone
Austria	Immediate PA**	50 d PA	Partial PA
Belgium	20 m (24 h)	60,100,400 d	Time-dependent
Czech Republic	10-50 m PA	Internal special PA	External special PA
Finland	Intake area 20-50 m	60 d inner PZ	Outer PZ
France	Close PA 10-20 m	Extended PA	
Hungary		60 d	Hydrogeologic PZ (25-100 yrs)
Germany	Wellfield 10 m	Zone 2, 50 d	Zone 3, 2 km
Netherlands		60 d	PA 10, 25 yr/recharge area
Norway	Wellfield 10-30 m	60 d	Infiltration
Sweden	Well area	Inner PA 60 d, 100 m	Outer PA
Switzerland	Zone 15-20 m	Zone 2 10 d, 100 m	Zone 3, 200 m
UK		Inner PZ 50-100 d	Major aquifer
USSR	15-50 m	100-400 d	Time-dependent

* Wellfield: operating land with basic sanitation provided
Primary zone: bacteriological protection zone
Secondary zone: chemical protection zone.
** PA and PZ: Protection Area and Protection Zone, respectively

Methods for determining groundwater vulnerability

Numerous methods for predicting groundwater vulnerability have been developed from an understanding of the factors that affect the transport of contaminants at or near the land surface. These methods fall into three major classes:

- Overlay and index methods that combine specific physical characteristics that affect groundwater vulnerability, often giving a numerical score.
- Process-based methods consisting of mathematical models that approximate the behaviour of substances in the subsurface environment.
- Statistical methods that draw associations with areas where contamination is known to have occurred (Water Science and Technology Board, 1993).

Essentially, the type of technique employed will depend upon the availability of data and the ultimate use to which the vulnerability assessment will be put. It is interesting to note, however, that while process-based models attempt to incorporate a more complete description of the physical, chemical and biological processes affecting groundwater vulnerability, they may not necessarily provide more reliable results.

With the advent of the GIS, the inventory, archival, retrieval and display of spatial data and the link to numerical rating systems and simulation models has become a reality (Water Science and Technology Board, 1993). The production of computer-generated thematic maps that can display contamination potentials or the vulnerability of land areas greatly facilitates the planning and management of groundwater protection programmes.

There are two general types of vulnerability assessments. The first addresses specific vulnerability, and is referenced to a specific contaminant, contaminant class, or human activity. The second addresses intrinsic vulnerability and is used in vulnerability assessments that do not consider the attributes and behaviour of specific contaminants (Water Science and Technology Board, 1993).

Ramifications of groundwater vulnerability assessment

The Water Science and Technology Board (1993) have recently published a landmark review entitled "Groundwater Vulnerability Assessment: Predicting Relative Contamination Potential Under Conditions of Uncertainty". They suggest that the uses and needs for vulnerability assessments can be grouped into four broad categories:

- First, the assessments can be used in the policy analysis and development process to identify the potential for groundwater contamination and the need for protection, and to aid in examining the relative impacts of alternative ways to control contamination.
- Second, when scarce resources prevent uniform and high levels of spending, vulnerability assessments can be used in programme management to guide allocation and targeting of resources to areas where the greatest levels of effort are warranted.
- Third, vulnerability assessments can be used in some instances to provide information for land-use decisions such as alteration of land-use activities to reflect the potential for groundwater contamination.
- Finally, and perhaps most importantly, vulnerability assessments can be used to improve the general education and participation of the public in the protection of a region's groundwater resources.

DRASTIC is a popular method to define degrees of vulnerability but it is relative and subjective in nature. Originally proposed by Aller et al. (1985), it is a numeric weighting and rating system

TABLE 2
BEAR AND JACOBS (1965) EQUATION AND SOME OF ITS MODIFICATIONS

Investigator	General equation	Feature
Bear and Jacobs, 1965	$\cosh Y + \frac{X}{Y}\sinh Y = \exp(X-T)$	Front shapes caused by water bodies injected into aquifers
Todd, 1980	where $X = ((2\pi bki)/Q)x$, $Y = ((2\pi bki)/Q)y$, $T = (2\pi b(ki)^2/sQ)t$, Q = pumping rate(m^3/d), b = aquifer thickness(m), k = hydraulic conductivity (m/d), i = hydraulic gradient, s = storage coefficient.	Determination of contribution zone
Southern Water Authority, UK, 1985		*Boundaries of contribution zone and isochrones along maximum hydraulic gradient*
Grubb, 1993	The investigators may use different equations but they are essentially the same as the above.	Contribution zone for confined and unconfined aquifers
Almendinger, 1994		Travel-time ellipse: approximation

with the following factors considered: Depth to water table; Recharge; Aquifer material; Soil type; Topography; Impact on vadose zone and Conductivity (hydraulic). In the field, DRASTIC can be simplified to two or three factors to accommodate the need for a rough estimation of vulnerability to pollution of the aquifers of interest. The results of the DRASTIC methodology can conveniently be depicted in the form of groundwater vulnerability maps.

Groundwater vulnerability maps

Depicting the results of groundwater vulnerability and risk assessment techniques on maps provides a convenient means of conveying spatial groundwater information to those involved in planning for groundwater protection as well as educating the public in the need to protect this valuable resource.

During the past 20 years a number of groundwater vulnerability maps at scales ranging from national to local have been produced, both in Europe and the USA (Anderson and Gosk, 1987). All the maps are similar in that the mapped area is divided into "more" or "less" vulnerable categories. More recently numerical and overlay techniques have enabled states such as Texas and Wisconsin in the USA to produce groundwater pollution potential or susceptibility maps (Hart, 1988; Schmidt, 1987).

Zoning approach

The goals of zoning are: (1) to keep any potential pollution sources out of a borehole catchment; (2) to reduce concentrations of degradable contaminants to acceptable levels through physical, biochemical and dilution mechanisms before they reach a borehole. Two elements normally required in the design of borehole protection zones are "catchment" and "isochrones". A catchment refers to the zone of contribution to a pumping borehole, which is the same as the zone of influence when the water table is perfectly flat. An isochrone refers to the travel-time-related capture zone of a hypothetical pollutant coincident with groundwater movement in the saturated zone. The shape and size of a borehole protection zone are dependent on both catchment and isochrones.

Hydraulic methods

This approach is used to delineate a flow system through the use of hydraulic techniques including pumping tests. The flow system is often presented on a water-table map with a flow network indicating various kinds of hydraulic boundaries of concern (US EPA, 1991). The flow system around a borehole or wellfield can be mapped with hydrogeologic information of the aquifers of interest. There are models which could be incorporated into the mapping. For example, the work of Bear and Jacobs (1965) has been modified for the purpose of wellhead protection. The US EPA has developed a computer model termed WHPA (wellhead protection area model) for this purpose (Blandford and Huyakorn, 1991).

Since the late 1980s, a concerted effort has been made to delineate travel-time-related capture zones of a borehole or wellfield.

Analytical models

Definition of the flow field resulting from pumping stress is based on subtraction (superposition) of the simulated drawdown distribution from a measured or an assumed regional hydraulic head distribution.

Working under the assumption of injected water being immiscible with native groundwater in a confined aquifer, Bear and Jacobs (1965) studied the front shapes caused by injected water bodies under steady flow conditions and derived the general equation of isochrones (Table 2). Later, this was used for wellhead protection purposes (Table 2).

Recently, Grubb (1993) proposed an analytical model for estimating steady-state capture zones of pumping wells in confined and unconfined aquifers. The limitation of these kinds of models is that they are too rigid to accommodate complicated hydrogeological settings. Bair et al. (1991b) developed CAPZONE, an analytical flow model which is able to deal with a leaky-aquifer situation.

TABLE 3
A LIST OF COMMON SEMI-ANALYTICAL, NUMERICAL AND STOCHASTIC MODELS DEVELOPED FOR ZONING PURPOSES

Model types	Investigators	Features	Applied by
Semi-analytical	Nelson, 1978a; b	1st of its kind, pt*	
	Keely and Tsang, 1983, RESSQ	multi-wells	
	Javandel and Tsang, 1986	non-D-expression	
	Lerner, 1990, ROSE	recharge/boundaries	
	Blandford and Huyakorn, 1991, WHPA	integrated	Bair and Roadcap, 1992
			Springer and Bair, 1992
	Kinzelbach, 1995, PAT	recharge/boundaries	
Numerical	Shafer, 1987	2D, pt	
	McDonald and Harbaugh,1988, MODFLOW	3D, flow model	Springer and Bair, 1992
	Pollock, 1989, MODPATH	3D, transport model	and Barlow, 1994
	Zheng et al., 1992, PATH3D	3D, reverse pt	US EPA, 1991
	Kinzelbach, 1995, ASM	2D, pathline, isochrone, transport	
Stochastic	Bair et al., 1991a	Monte Carlo	Bair et al., 1991a
	Varijen and Shafer, 1991	Monte Carlo	

* pt: particle tracking.

Semi-analytical models

The semi-analytical models commonly combine an analytical flow model with a numerical transport model. Nelson (1978a;b) developed the first semi-analytical computer model for pathline tracing (Table 3). Later the same methods were used to delineate travel-time-related capture zones (Keely and Tsang, 1983; Javandel and Tsang, 1986). Following this approach, Lerner (1990; 1992) incorporated recharge and aquifer boundaries into delineation of capture zones. This approach provides a very good idea of significance of the effect of recharge and boundaries on the shape of zones.

Numerical models

Numerical flow models are commonly based on finite-difference or finite-element techniques which allow incorporation of complex aquifer configurations (Table 3). This method is used first to describe a flow regime by discretisation of the regional flow domain into a grid and then to incorporate a solute transport model into the system. The advantage of this method is that it can accommodate heterogeneous and anisotropic permeabilities inherent in most secondary aquifers. However, a prerequisite is that the medium can be treated as a porous medium or something similar because of the assumption of its initial analytical equations. One can take advantage of a wide range of models available in the market provided that the budget permits.

The widely accepted flow model appears to be MODFLOW, which is often coupled with a program called MODPATH to delineate travel-time-related capture zones (McDonald and Harbaugh, 1988; Pollock, 1989; Bair and Roadcap, 1992). Path3D (Zheng et al., 1992) is a three-dimensional particle-tracking program which uses a velocity interpolator consistent with the governing equations used in MODFLOW to predict the isochrones of hypothetical particles of water within a flow system but it ignores the effects of contaminant dispersion and diffusion. To delineate isochrones, particles can be placed in a small circle around a pumping borehole and their paths can be tracked backwards to either the water table or a groundwater flow divide.

Bair and Roadcap (1992), as well as Springer and Bair (1992), assessed validation of semi-analytical methods in leaky and stratified-drift aquifers by comparison with analytical and numerical flow models. The semi-analytical flow model employs the Thiem equation describing two-dimensional steady-state drawdown surrounding a well with superposition of a uniform regional flow field. They pointed out that the conceptual constraint of the semi-analytical method, performed by a pair of models termed DREAM/RESSQC, is due to the uniform flow field and transmissivity required by the flow model (DREAM).

Stochastic models

In addition to the above deterministic approach, Varijen and Shafer (1991) and Bair et al. (1991) employed a Monte Carlo simulation for determination of travel-time-related capture zones (Table 3). The approach offers an alternative method to the deterministic methods and appears to be especially favourable where there is a reasonable amount of uncertainty in the values of the input hydrogeological parameters either due to their scarcity, lack of reliability, or the heterogeneous character of the geologic bodies.

Hydrogeochemical studies

This provides an indirect approach to final demarcation of protection areas. Two aspects can be identified under this approach.

Quality monitoring

The quality monitoring should be designed to determine a baseline value of the aquifer involved, to periodically monitor pollution

TABLE 4
ATTENUATION MECHANISM OF SOME DEGRADABLE CONTAMINANTS IN THE SOIL-SUBSOIL-GROUNDWATER SYSTEM

Group	Sources	Representative	Degradation in subsurface	Control factors
(1) Microbial organisms	Mainly domestic/ agric. point sources, sometimes diffuse sources	Faecal coli; streptococci; viruses; parasites	Rate of die off; filter out	Soil types; temperature; pH etc.
(2) Organics	Waste disposal, industrial spills; chemical and heavy industrial; agric. practices	TOC; phenols; some hydrocarbon; pesticides etc.	Sorption; hydrolysis; redox; decomposition	Retardation factor, half life; aerobic respiration, soil pH
(3) Nitrogen	Agric./domestic/ sewage point and diffuse	Nitrate; nitrite; ammonia	Redox: denitrification	pH-pE; Aerobic/ anaerobic conditions

indicators in pumped water and to detect any toxicity in the groundwater where applicable. After initial implementation of protection zones, monitoring is the only way to validate the demarcation. In this case, the following pollution indicators would be included: faecal coliform, faecal streptococci, nitrate, chloride, temperature, electrical conductivity, ammonium, nitrite, iron and others as appropriate.

Flow regime evaluation

Such a study would utilise water chemistry and isotopes to identify recharge features, groundwater ages and flow regimes. Common isotopic parameters which could be used include ^{3}H, ^{14}C, ^{2}H and ^{18}O. In shallow unconfined aquifers where strong dispersion is absent, the ratio of ^{3}H and its stable daughter, ^{3}He, can be used to date groundwater with ages up to 50 years (Solomon and Sudicky, 1991; Solomon et al., 1992). It can provide not only a reference to groundwater travel time but also constraints valuable for model calibration. In highly fractured, cavernous aquifers, a tracer test may be introduced to confirm flow system mapping. Although hydrogeochemical investigation itself does not readily delineate protection zones, it can serve as a powerful and independent check on travel-time-related zones outlined by the other methods. Since it does not require the measurement of hydraulic parameters, fair distribution of sample points in space is ideal for estimating isochrones.

Studies of hydrogeochemical processes such as dissolution vs. precipitation, adsorption, redox, ion exchange, etc. would help to identify a realistic transport model to fit into a flow model for zoning purposes. The delineation of a borehole protection area should be supported by hydrogeochemical findings.

Three-tier protection concept

As outlined above, in Europe a judicious approach of groundwater protection entails combination of two aspects:

- Vulnerability classification
- Wellhead protection or source protection.

This approach has been adopted by some countries in Europe and North America.

It is convenient to depict the movement of a hypothetical contaminant as vertical travel controlled by properties of the unsaturated zone and horizontal travel governed by hydraulic gradient. This gives rise to two different and equally important concepts: vulnerability mapping and wellhead protection zoning.

As mentioned earlier, there are certain paths by which contaminants get into contact with the groundwater system. Since groundwater is stored underground, to protect it requires preventing potential contaminants from becoming transported together with recharge water to the aquifer concerned. Both vulnerability mapping and protection zoning are geared to delineate areas to be controlled in an attempt to keep the contaminants out of the groundwater system or at least to maintain the concentration of contaminants at a tolerable level in terms of accepted drinking-water standards. The only difference between the two is that the vulnerability mapping takes into consideration processes occurring in the soil and unsaturated zones at a regional scale while the source protection is focused on mapping of a flow system with respect to a production borehole. Pumping a borehole alters the natural flow regime in its vicinity, resulting in the need for zones related to this altered flow pattern. Apart from its value in reconnaissance studies, vulnerability mapping provides a supplementary means of indicating the relative significance of a zoning approach.

Some degradable contaminants in the soil-subsoil-groundwater system include:

- most of the microbial organisms like faecal coliform bacteria, viruses, algae and parasites;
- some organics like phenols, some hydrocarbons and volatile halogenated alkanes, pesticides; and
- nitrogen.

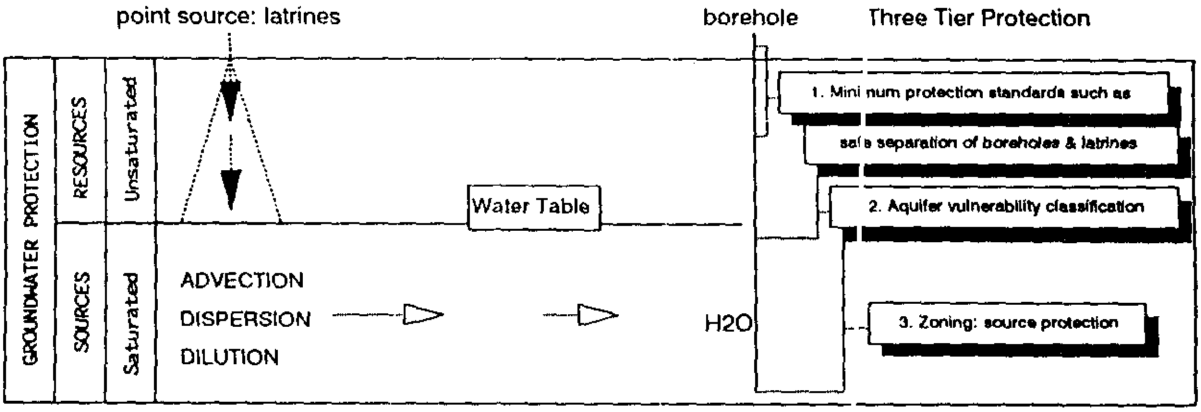

Figure 1
Sketch of three-tier protection

TABLE 5
SUMMARY OF THREE-TIER PROTECTION CONCEPT

Three tiers	Approaches	Purpose and scope	Who involved	Degree of protection
First tier	Minimum protection standards, guidelines such as safe location of latrines, etc.	Minimising impact of point sources in all aquifers country-wide	Different sectors that impact groundwater	Minimum but basic
Second tier	DRASTIC vulnerability classification: 1.matrix 2.GIS maps	Regulating point and diffuse sources at regional scale	Central and provincial government	Preliminary but strategic
Third tier	Zoning: 1.deterministic 2.stochastic	Providing for attenuation of contaminants at priority aquifers	Local government and local authorities	Detailed but differentiated

The first group of contaminants are believed to be generated from domestic and agricultural sources and can be filtered out through natural attenuation mechanisms. The second group, most likely from accidental spills of industrial and agricultural activities, can be transformed through sorption and hydrolysis processes under favourable physical and chemical conditions. The threat of this group, especially pesticides, does not as yet appear to be great in this country (Weaver, 1993). The third group includes different products like nitrate, nitrite and ammonia. Nitrate pollution has been reported to be a big problem in areas like the Springbok Flats and delineation of vulnerable areas has consequently been advocated (Tredoux, 1993). Nitrate pollution is also associated with stockfarming and on-site sanitation in some rural areas (Xu et al., 1991). Some attenuation processes of these potential pollutants are listed in Table 4.

The RDP has as one of its objectives the provision of clean, safe water supply and adequate sanitation for all rural households (ANC, 1994; DWAF, 1994). The impact of various sanitation systems commonly practised in the rural communities while simultaneous groundwater abstraction and on-site sanitation are implemented, requires investigation. Point source pollution from the rural communities and agricultural practices poses a threat to aquifer systems which have not yet been widely recognised. Many incidents of pollution in rural areas were reported to be associated with point sources such as solid waste dumping sites, pit latrines and cattle kraals. It has been reported, for example, that pollution from domestic origin accounts for 70% of the cases of the groundwater contamination in the Congo (Moukolo, 1986).

To follow a realistic protection approach in South Africa, one must incorporate measures minimising the impact of point sources resulting from unsanitary disposal of human excreta and animal waste in rural environs. An integrated approach for this country would be embodied in a concept of three-tier protection of aquifers. The sketch (Fig. 1) illustrates the process of a hypothetical pollutant getting into a groundwater system and the scope of the three-tier protection, this being a phased protection concept.

First tier: Minimum protection standards

The first tier is focused on the establishment of minimum requirements for groundwater protection for various development projects which could impact groundwater. These projects can be grouped into the upliftment in rural areas; economic expansion-related developments; and waste disposal practices. To minimise

TABLE 6

A LIST OF AQUIFER TYPES IN SOUTH AFRICA AND SOME USA AQUIFERS STUDIED FOR ZONING PURPOSES

South Africa aquifer types	**Similar aquifers studied in USA**	**Investigators**	**Models**	**Comments**
Unconsolidated	1.Wooster,Ohio 2.Cape Cod, Massachusetts	Springer and Bair, 1992 Barlow, 1994	anal/semi/nume* Modflow/Modpath	Comparison Ss**, 2+3D and forward Pt***
Sandstone	Massilon sdt	Bair et al., 1991	Monte Carlo	
Fractured and cavernous dolomite	1.Silurian dolomite 2.Richwood,Ohio	US EPA, 1991 Bair and Roadcap, 1992	Modflow and path3d anal/semi/nume	4 layer comparison
Karoo formation	No information	No information	No information	No information
The other hard rocks	Central Wisconsin	US EPA, 1991	Modflow and path3d	3 layer

* anal/semi/nume: analytical, semi-analytical and numerical models;

** Ss: steady state;

*** pt: particle tracking.

the impact of such activities on groundwater resources, minimum requirements or guidelines for protection purposes must be established and implemented country-wide. For example, the first-tier protection for the CWSS entails the construction of boreholes up to sanitary standard and the installation of appropriate sanitation facilities on site. In addition, a safe separation distance between a borehole source and an on-site sanitation unit must be implemented (Xu and Braune, 1995). A pit latrine located beside phreatophytes, for instance, can have an adverse effect on contamination of a water-table aquifer through the mechanism of providing a short circuit to groundwater (Padmasiri et al., 1992). This tier provides a first line of defense and is especially applicable to rural developments. It is recommended that this protection tier be implemented first through the Community Water Supply and Sanitation Programme which is a top priority in the Department of Water Affairs and Forestry.

Second tier: Vulnerability classification

The second tier is aimed at dealing with widespread aquifer systems at regional or catchment level, to set differentiated protection in motion and to allow other parties to play an informed and pro-active role in protecting groundwater. This is equivalent to so-called "Resource Protection", which is usually achieved through the preparation of vulnerability maps at various scales. It includes measures prescribed by vulnerability classification. Various definitions for groundwater vulnerability exist, but they usually relate to an intrinsic property of the aquifer, and the overlying vadose zone, which renders the groundwater more or less sensitive to an infiltrating contaminant. Vulnerability is not an absolute property, but a relative indication of where contamination is likely to occur. Many factors impact on the degree of vulnerability of an aquifer to contamination, some of these being permeability of the unsaturated zone, thickness of the unsaturated zone, depth to groundwater level, aquifer recharge and the properties of an aquifer and its type.

A national-scale groundwater vulnerability map of South Africa has been produced using the DRASTIC methodology (Reynders and Lynch, 1993). This map is currently being refined using the coverage prepared as part of the national hydrological mapping study (Vegter, 1993). The preparation of this vulnerability map has clearly illustrated the potential of combining various data sets in a GIS environment.

Third tier: Designation of protection zones

The third tier is the designation of zones around a source, namely a borehole, wellfield or even a spring. Zoning is to be implemented in areas prioritised by the differentiated protection principle (Braune, 1994). The US EPA's definition of a wellhead protection area is "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are likely to move toward and reach such water well or well field" (US EPA, 1987).

In an ideal world, all borehole sources would be accorded the same high level of protection, as most groundwater sources can be considered as being vulnerable to contamination. However, from an economic perspective, such an approach is untenable. In addition, subsurface environments differ in their ability to attenuate pollutants. Consequently a differentiated protection principle is required in this country. Zoning requires representative parameters and a good understanding of geohydrological conditions at a local scale and consequently forms an advanced stage of groundwater protection (Table 5).

In short, the first tier involves short-term measures to ensure that potential sources of contamination, such as inappropriate sanitation and poor borehole construction are dealt with immediately. This is particularly important in rural areas. Vulnerability mapping provides the second tier, which is a medium-term objective. The third tier, essentially a long-term objective in this country, is geared to produce the results that are sufficiently accurate and realistic to use as basis of controls in land use in a borehole, spring or wellfield area identified by the differentiated protection principle. Wellhead or source protection areas should be seen as a vital part of the three-tier protection concept, but must go hand-in-hand with measures such as pollution source elimination and product controls.

In practice, adequate protection depends on not only the capacity of natural protection but also the nature of development programmes. For instance, the primary objective of the CWSS, in terms of protection, should be focused on the first-tier protection. This is because technically, it is premature to try to delineate protection zones if no details of hydrogeological data are available. Economically it may not be cost-effective either.

Implications

The establishment of protection zones generally will be a compromise between what is desirable and what is feasible. Zoning regulations could have adverse economic effects on a community if an inappropriate amount of land were to be placed in an area zoned for stringent protection. When considering public health, however, the delineated area should not result in underprotection.

The management techniques that can be used in source protection zones can be a mix of regulatory and non-regulatory. Regulatory approaches involve placing a system of legal constraints on land use or on particular activities that have a potential to contaminate groundwater. This could include zoning ordinances, design and operating standards, and source prohibitions, that is, regulations that prohibit the presence or use of chemicals or hazardous activities within a given area.

Non-regulatory tools, which can complement regulations, include public education, voluntary-based management practices, government co-ordination, inspection and training programmes.

Once source protection zones have been delineated, it will be difficult to order all potentially polluting activities such as squatter camps, dry cleaners and petrol stations out of the area (Bishop, 1993). For this reason a priority setting approach which allows one to screen potential contamination sources on the basis of risk, is required. A follow-up monitoring exercise is very important to verify the protective measures prescribed (Ward, 1989).

Although protection is preferable, aquifer remediation and restoration are important as many cases of contamination already exist. Considerable research is being carried out abroad (mainly the USA) into technologies such as bioremediation, air-stripping and other on- and off-site remediation measures. As a last resort, it may be necessary to revert to pumping in order to just contain the pollution plume.

Future effort

Groundwater systems react slowly. Consequently a pro-active approach to protecting South Africa's groundwater is essential. Much research has been carried out overseas on aquifer vulnerability mapping, zoning techniques, contaminant transport modelling and aquifer remediation. There is a need to test these approaches locally and, where necessary, refine them for South African conditions.

Three major research thrusts in terms of groundwater protection are required. Firstly, there is a great need to devise protection approaches appropriate for rural areas where groundwater provides vital drinking water supplies relatively cheaply and usually requiring minimal treatment.

Secondly, the "unique" fractured-rock conditions prevalent over much of South Africa (nearly 90% areal extent) mean that the "classic" zoning approaches developed in Europe and the USA may not always be appropriate for South African conditions (Table 6). There are already a number of hypothetical models available (Table 2, 3). Their verification and a standardisation of appropriate techniques are required such as outlined in Table 6. Considerable research is currently underway in terms of understanding the occurrence, movement and development potential of groundwater in fractured rock aquifers in South Africa. The application of zoning techniques will need to build on this basic research.

Finally, there is a great need to provide information on groundwater vulnerability, zoning and water quality to decision-makers and the general public. Research into generating this information rapidly and in a user-friendly manner for the above users is required.

In addition to the above-mentioned research effort, one of the most effective ways of protecting groundwater is to encourage its use. Groundwater protection is a long-term strategy. Consequently it needs to be demonstrated how short-term financial inputs and effort will result in long-term benefit. The target group must perceive that the protection action is beneficial to themselves, hence the need for a public education and participation strategy.

Vulnerability techniques, for example, lend themselves to the production of aquifer vulnerability maps which depict the spatial variability of aquifer vulnerability and can be useful tools when prioritising regional groundwater protection programmes. This is particularly important when educating planners, decision-makers and the general public who may not have a good understanding of groundwater and yet can play a decisive role in its protection.

The role of public participation should not be underestimated in the success of a groundwater protection programme. Consumers have a vested interest in the quality of their drinking water. Consequently action groups can be established to monitor activities within source protection zones.

Summary

An integrated groundwater protection in the South African context is embodied in the three-tier protection concept discussed in this paper. It consists of the establishment of minimum protection requirements at national level, vulnerability classification at regional level and differentiated source protection at local level. The three-tier protection offers a comprehensive approach to groundwater protection strategy with the final emphasis on a zoning approach. The techniques of zoning around borehole sources need to be verified and standardised locally. To adopt an appropriate approach requires a realistic assessment of economic, hydrogeologic, environmental and sometimes political factors. In addition to research effort, one of the most effective ways of protecting groundwater is to promote its awareness through sound usage.

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