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Groundwater protection: the science and practice of land surface zoning

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Abstract Protection of groundwater is intimately linked with land-use management. The scientific basis and practical application of land surface zoning to provide a rational framework within which to reconcile land utilization and groundwater protection interests is described and justified, with special reference to the current British approach. The following unpublished quotations from a UK discussion meeting at Birmingham in 1993 capture the spirit of this paper: (1) *"we have, somehow or other, to make complex hydrogeology intelligible to the farmer"* (A. C. Skinner), and (2) *"surely, nearing the end of the 20th century, it is not too much to ask that the water industry begin to address the question – on what land and during which period did their groundwater supplies originate"* (S. S. D. Foster).

INTRODUCTION

Background to paper

The starting point for this work is one which we believe is shared by most public-spirited hydrogeologists:

(a) groundwater is a vital natural resource under significant and increasing threat of pollution;
(b) every effort should be made to prevent any further groundwater quality deterioration, and to effect improvement where feasible, even given the slow response of most groundwater systems;
(c) while treatment at the point of abstraction often has to be the response once pollution has occurred (and may be necessary to address fully drinking water standards for pathogens and pesticides which are effectively surrogate zeros), it is not a sustainable basis for groundwater resource management;
(d) most land-use planners and environmental decision-makers are not sufficiently aware of the need for, or the methods of, protecting groundwater.

Most groundwater resources originate as excess rainfall locally infiltrating the land surface. Many activities at the land surface can thus threaten the quality and availability of these resources.

In theory it is possible to manage land entirely in the interest of groundwater gathering. In Germany and England there are a few isolated historic cases of water-supply companies owning entire recharge areas primarily to prevent bacteriological contamination of groundwater, although this is rarely acceptable on socioeconomic grounds. In practice, it is generally necessary to define groundwater protection strategies which, while they constrain land use, accept trade-offs between competing interests.

To implement such strategies we have to mesh hydrogeological understanding and requirements into land-use policies, which often have strong economic, and sometimes emotive, foundation. We also have to confront long-established practices and the problem of different professions not understanding each others methodologies or priorities. Groundwater protection therefore presents some demanding challenges.

This paper reviews the underlying principles and describes the approach which is being adopted in Britain. It is offered in the hope that some of the issues we have addressed and the solutions we have devised will be of value to others.

Basic elements of protection policy

Simple and robust matrices need to be established, which indicate what activities are possible where at an acceptable risk to groundwater (e.g. NRA, 1992; Foster, 1993). It is necessary to resist the temptation to set up too many zones, since this is not practicable, reduces understanding and risks losing credibility.

Instead of applying universal controls over land or soil use and effluent discharge to the ground, it is more cost-effective (and less prejudicial to economic development) to utilize the natural contaminant attenuation capacity of the strata overlying the saturated aquifer. This is the basic idea underlying the concept of aquifer pollution vulnerability.

If potable or sensitive use comprises only part of the total available groundwater resource, then it may not be cost-effective to protect all parts of an aquifer equally. A sensible balance also needs to be struck between the protection of groundwater resources (aquifers as a whole) and specific sources (boreholes, wells and springs). The logical development is to define source protection areas (SPAs) around existing (and designated future) sites of major potable water-supply. Such areas are also relevant to the conservation of groundwater and the sustainability of water-supply.

Land-surface zoning: pros and contras

Over the past 5 years or so, the value of such approaches has been disputed. Some hydrogeologists (the sceptics) have argued that:

(a) hydrogeological conditions are so complex in detail that no zoning scheme will encapsulate them;

(b) groundwater is everywhere vulnerable to surface-derived pollution (the only thing that differs geographically is the time-scale for effects to become manifest);

(c) zoning schemes will lead to groundwater pollution being tolerated in some areas.

Whilst recognizing the technical basis of these arguments, other hydrogeologists (we would say the realists) believe that there is an overriding case for land-surface zoning as a general framework for the development and implementation of groundwater protection policy because:

(a) decisions will be made affecting groundwater in any event, and if land-use planners have no hydrogeological zoning this will mean less (not more) consultation;
(b) treating every case on an individual basis makes poor use of available professional and financial resources which require targeting;
(c) it is unrealistic to expect exclusive protection for all groundwater and a zoning strategy is an important element in ensuring that trade-offs between economic development and aquifer protection are made objectively;
(d) zoning strategies also have an important role to play in setting priorities for groundwater monitoring, environmental audit of industrial premises, pollution control within the agricultural advisory system and in public education generally.

RESOURCE PROTECTION STRATEGY

Development of vulnerability concept

The term vulnerability began to be used intuitively in hydrogeology from the 1970s in France (Albinet & Margat, 1970) and more widely in the 1980s (Haertle, 1983; Aller *et al.*, 1987; Bachmat & Collin, 1987). While the implication was of relative susceptibility of aquifers to anthropogenic pollution, the term was used initially without any attempt at formal definition. In Europe the first attempt at standardized production of vulnerability maps was made under an EC initiative, coordinated by Dr Jan Fried (e.g. Monkhouse, 1983).

The expression began to mean different things to different people and Foster (1987) suggested that the most logical and consistent definition would be to regard aquifer pollution vulnerability as the intrinsic characteristics of the strata separating the saturated aquifer from the land surface which determine its sensitivity to being adversely affected by a surface-applied contaminant load. It would then be a function of:

(a) the inaccessibility of the saturated zone, in a hydraulic sense, to the penetration of pollutants;
(b) the attenuation capacity of the strata overlying the saturated zone as a result of physicochemical retention or reaction of pollutants.

Groundwater pollution risk could then be defined as the probability that groundwater in the uppermost part of an aquifer will become contaminated to an unacceptable level by activities on the immediately-overlying land surface, and will be the result of interaction between the aquifer vulnerability and the contaminant loading applied at the location concerned (Foster & Hirata, 1988; Adams & Foster, 1992). These authors considered that integrated vulnerability mapping was worth pursuing for land-use planning and environmental impact assessment (provided its definition was clear and its limitations understood), and that inventories and audits of subsurface contaminant load were of high priority (e.g. Chilton *et al.*, 1990) and that both should be developed on a GIS-compatible basis.

Recently two major professional working groups have reviewed and pronounced upon the applicability of the vulnerability concept (NRC, 1993; IAH, 1995). Both came out in favour of its usefulness, but in our view neither succeeded in producing a definition of vulnerability sufficiently specific for the term to gain uniformity of application amongst professional hydrogeologists. We believe it should be made clear that vulnerability is a statement about the intrinsic characteristics of the strata (unsaturated zone or confining beds) separating the saturated aquifer from the land surface, which provides an indication of the impact of land-use decisions at that point on the immediately-underlying groundwater.

Some workers consider that a factor representing the natural mobility and persistence of pollutants in the saturated zone should be included in vulnerability, but we consider this illogical since it does not view vulnerability maps from the correct perspective namely that of planning and controlling activities at the land surface.

Limitations of concept

Subsurface water flow and contaminant transport are complex processes, in particular the degree of attenuation will vary significantly with type of contaminant and pollution process in any given situation. Thus a "general (integrated) vulnerability to a universal contaminant in a typical pollution scenario" has no validity in rigorous scientific terms (Foster & Hirata, 1988).

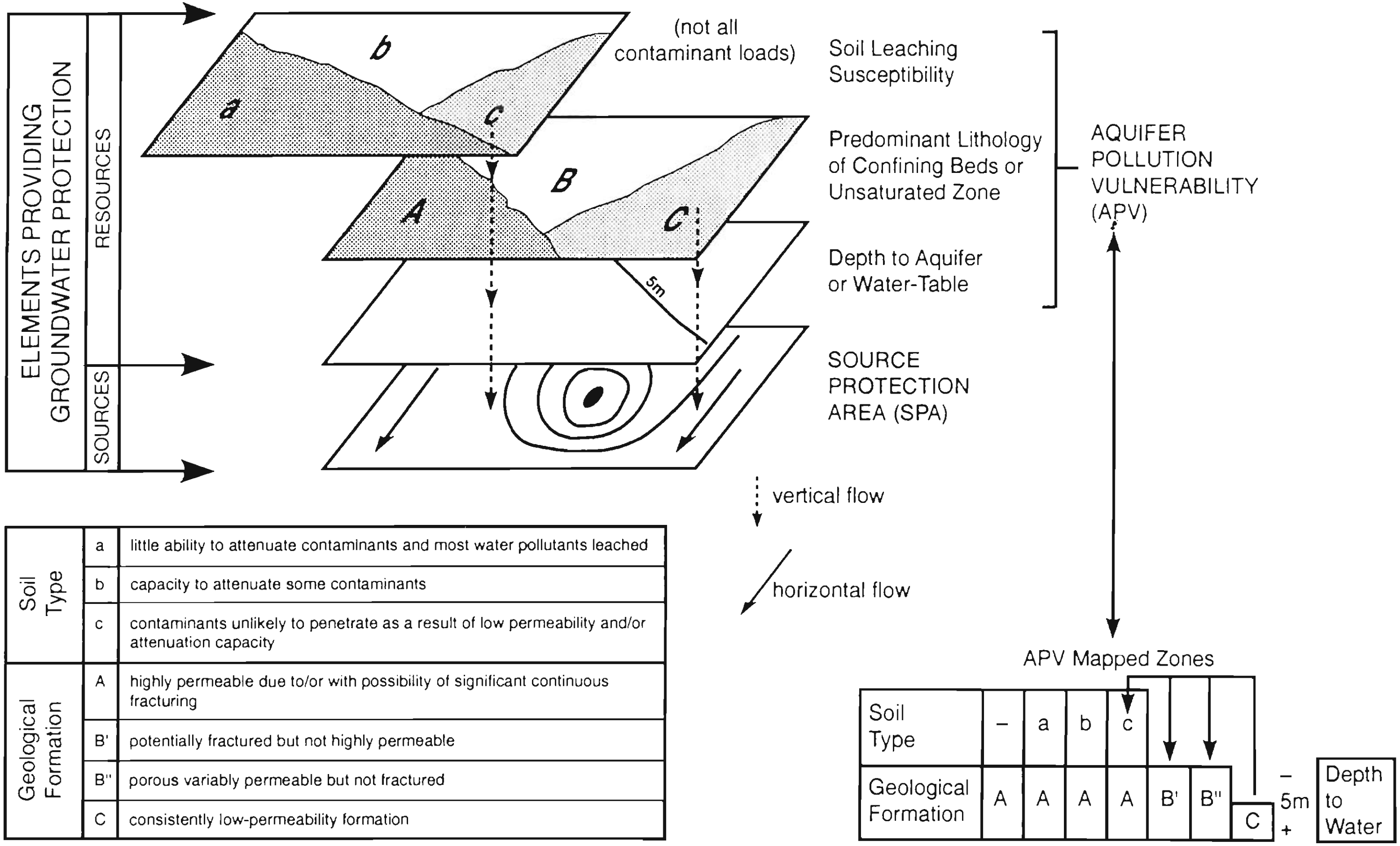
For this reason (Anderson & Gosk, 1987) suggested that vulnerability mapping would be better carried out for individual contaminant groups in specific pollution scenarios, and such an approach had already been adopted in certain instances (Seller & Canter, 1980; Le Grand, 1983). However, the implication would be an atlas of maps for any given area which would be difficult to handle for most applications, except the evaluation and control of diffuse agricultural pollution (Carter *et al.*, 1987; Sokol *et al.*, 1993; Loague, 1994).

We consider that a more practical way forward for general planning purposes is to use integrated vulnerability maps, but make every effort to spell out adequate "health warnings" against their misuse (Foster & Hirata, 1988). Such warnings have been elegantly expressed in a recent US review (NRC, 1993) in the form of three "laws of groundwater vulnerability": first – "all groundwater is to some degree vulnerable", second – "uncertainty is inherent in all vulnerability assessments", third – "there is risk that the obvious may be obscured and the subtle indistinguishable". It is our view that the latter is especially true the more complex is the system of vulnerability assessment.

The British approach

The scheme currently adopted in the UK (NRA, 1992; Foster & Adams, 1992) is to classify, by lithology and thickness, the predominant strata above the saturated aquifer as the principal indicator of pollution vulnerability.

Four major classes were recognized (Fig. 1). In deciding the criteria for lithological classification there was concern that too much emphasis might inadvertently be placed on recharge time lag, and vulnerability would then become more a measure of when (as opposed to if and which) pollutants reach the aquifer. Thus greatest emphasis was put upon the likelihood of well-developed fracturing being present, since this is considered the most critical factor increasing vulnerability and reducing the chance of contaminant



Soil Type	a	little ability to attenuate contaminants and most water pollutants leached
	b	capacity to attenuate some contaminants
	c	contaminants unlikely to penetrate as a result of low permeability and/or attenuation capacity
Geological Formation	A	highly permeable due to/or with possibility of significant continuous fracturing
	B'	potentially fractured but not highly permeable
	B''	porous variably permeable but not fractured
	C	consistently low-permeability formation

Fig. 1 Elements of groundwater protection and scheme of aquifer vulnerability classification (derived from Adams & Foster, 1992).

elimination, given that hydraulic surcharging is associated with many pollution scenarios.

This scheme is broadly compatible in terms of final vulnerability class with the earlier GOD scheme for vulnerability index estimation (Foster, 1987; Foster & Hirata, 1988), but on balance it was considered preferable not to use indexation, because of the danger of obscuring the basic hydrogeological data on which estimates are based.

A particularly important aspect of both schemes is clear interpretation of the classes of relative vulnerability established (Table 1). In this way we believe it is possible to overcome many (if not all) the objections to the use of integrated vulnerability in groundwater protection policies.

A novel element of the new British approach, is the way the soil zone is incorporated into the overall scheme. Most of the processes causing pollutant attenuation and/or elimination in the subsurface occur at much higher rates in the biologically-active soil zone, as a result of its higher organic matter and clay mineral contents and very much larger bacterial populations.

Soils are thus classified into three categories by relative susceptibility to leaching and in areas of high hydrogeological vulnerability are taken as modifying the overall vulnerability ranking (Fig. 1). Since in urban areas, in particular, the soil is often removed during construction or the subsurface pollutant load is applied below its base in excavations (such as pits, trenches or lagoons), the soil zone is assumed to be absent.

A number of hydrogeological conditions, including the presence of influent rivers, layered superficial strata and overconsolidated (fractured) clays, still present problems for vulnerability assessment and mapping. Moreover, any installations (such as quarries, mine shafts, etc.) which reduce or bypass protective aquitards also need special attention.

Table 1 Practical significance of relative classes of aquifer pollution vulnerability.

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 or readily transformed, in many pollution scenarios
Moderate	Vulnerable to some pollutants but only when continuously discharged/leached
Low	Only vulnerable to conservative pollutants in long-term when continuously and widely discharged/ leached
Negligible	Confining beds present with no significant groundwater flow

Comparison with DRASTIC methodology

By far the best known, and probably the most widely applied, scheme of vulnerability assessment is the **DRASTIC** methodology (Aller *et al.*, 1987). It attempts to quantify relative vulnerability by the summation of weighted indices for the following seven hydrogeological variables: **D**epth to groundwater (X5), natural **R**echarge rates (X4),

Aquifer media (X3), **S**oil media (X2), **T**opographic aspect (X1), **I**mpact (effect) of vadose zone (X5) and hydraulic **C**onductivity (X3). The weighting for each variable is given in parentheses, but changes (especially for parameters *S* and *T*) if vulnerability to diffuse agricultural pollution alone is under consideration.

The method has been the subject of various evaluations comparing DRASTIC vulnerabilities to actual incidence of pollution: nitrate in Ohio-USA (Baker, 1990) the pesticide alachlor statewide in the USA (Holden *et al.*, 1992), nitrate in NSW-Australia (Bates *et al.*, 1993), VOCs in Nebraska-USA (Kalinski *et al.*, 1994) and groundwater acidification in Nyköping-Sweden (Rosen, 1994). All of these evaluations revealed benefits, but also numerous shortcomings, of this methodology. It should be noted, however, that the evaluations themselves may not be strictly objective unless the subsurface contaminant load causing groundwater quality deterioration was distributed uniformly in the area under investigation.

While being totally sympathetic with the motivation of the architects of DRASTIC, we believe that the method generates a vulnerability index whose meaning is rather obscure and whose significance is unclear. This is a consequence of the interaction of too many rather spuriously-weighted parameters, some of which are not independent but quite strongly correlated. More specifically we:

(a) believe that it underestimates the vulnerability of fractured, compared to unconsolidated, aquifers (Rosen, 1994);

(b) argue that including a parameter reflecting contaminant mobility in the saturated zone is an unnecessary complication, for reasons stated earlier.

In summary, the fact that similar indices can be obtained by a very different combination of circumstances leads to the danger of decision making by numbers, rather than by science. We, therefore, much prefer an approach to classification which does not obscure the source data.

SOURCE PROTECTION AREAS

Basis for definition

Source protection (called wellhead protection in the USA) is also an essential part of groundwater protection. It provides the special vigilance against pollution, in respect of water destined for sensitive human uses, primarily for reticulated public supplies. As a concept it is long established, being part of legal codes in some European countries for over 100 years. However, increasing hydrogeological knowledge and changes in the nature of threats to groundwater mean that the concept needs to evolve.

Source protection areas (SPAs), also known as zones (SPZs), defend against contaminants which decay with time, where subsurface residence time appears to be the best measure of protection, and against non-degradable contaminants where flowpath-dependent dilution must be identified. Both are necessary to provide a comprehensive and practical definition.

Current British practice (NRA, 1992; Adams & Foster, 1992) is based upon three zones:

(a) Zone III (Catchment Area): the catchment of the source defined in area by water balance considerations and in geometry by groundwater flowpaths.

(b) Zone I (Microbiological Protection): defined by the mean 50-day saturated zone travel time, based upon pathogen decay criteria, and includes the operational courtyard. Experience has shown that, in high-storage aquifers prone to fissure flow, it is prudent to establish a limiting criterion of 50 m radius to prevent travel time zones from getting too small.
(c) Zone II (Outer Protection): it has been found necessary to further subdivide the overall catchment area, and this zone is, somewhat arbitrarily, defined by the 400-day saturated zone travel-time to provide delay, dilution and attenuation of slowly-degrading contaminants and to allow gradational land-use controls between Zones I and III.

Limitations to concept

The source protection area concept is a simple and powerful one, which is readily understood by land-use planners and others who need to make the often-difficult public decisions generated by groundwater protection policies. However, many technical challenges can be posed by those who demand either greater protection or less restriction, and the test of any concept is whether it deals fairly with these competing criticisms, in the context of the risks and the circumstances it has to address. Three complaints are made, often simultaneously by different interest groups; either the zones are too big, or they are too small, or that they are subject to such uncertainty that they cannot be used fairly to set land-use policy.

The NRA practice is for source protection zones to be defined on the basis of "protected yield", normally the quantity authorized to be abstracted, and the average infiltration which between them set the catchment area (Zone III). There are a number of hydrogeological situations where this simple approach is open to question. For example the annual variation of catchment area may be very large in karstic and other low-storage aquifers, suggesting that the maximum (rather than average) catchment area might be more appropriate. In this, and in other situations, where seasonal changes in flow regime are significant, local modifications may be required. Small sources (with yields of less than 0.5×10^6 l day^{-1}) also present special problems.

The 50-day travel time zone to protect against microbiological contamination is generally not thought to be excessively conservative. There is plenty of evidence suggesting longer subsurface survival for some pathogenic organisms. Any criticism that zones are too big, therefore, focuses on the use of only saturated aquifer transport to calculate zone geometry. In cases of very thick unsaturated zone this is not unreasonable criticism. However, there are good grounds not to compromise on the approach, because of the concern (particularly relevant in dual-porosity aquifers) that Darcy velocities are likely to overestimate pollutant travel times. Some pollutants are also introduced with hydraulic loading greatly in excess of natural rainfall.

The most serious limitation of the SPA concept arises when aquifers are subject to heavy pumping. If this is all for public supply then zones can be amalgamated and simplified, but if a significant proportion is for less sensitive uses and/or for seasonally-variable demands, such as industrial cooling or agricultural irrigation, interference between pumping wells produces excessively complex and unstable SPAs (Fig. 2(a)). Recourse to overall resource protection via aquifer vulnerability criteria may then be the

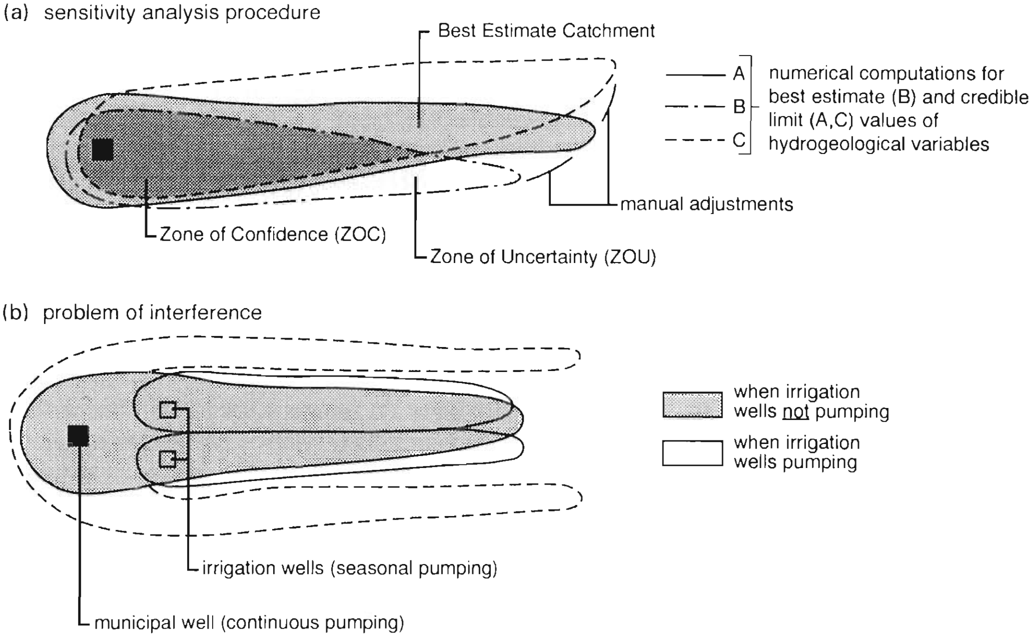


Fig. 2 Definition of source protection areas (SPAs).

only practical approach. The presence of surface watercourses gaining from natural aquifer discharge produces similar complications.

Dealing with uncertainty

Perhaps the greatest concern is the lack of precision of source protection areas. Land-use planners who are used to maps which follow physical surface features are uncomfortable with protection zones which lack the same permanence and which can vary, either if hydrogeological knowledge or circumstance change. A conservative strategy for the hydrogeologist is to define the maximum protection zone, that is the envelope of all credible zones. By itself this approach is only likely to be acceptable in public policy terms where protection of water is of overriding importance. In most circumstances, there are balances of interest to be struck which would not accept a zero risk approach. In consolidated porous aquifers (such as the English Chalk) in particular, major uncertainties about the applicable values of effective porosity and saturated thickness can lead to corresponding uncertainty in the definition of Zones I and II (Foster, 1993).

The question of uncertainty must not be dismissed, however, because it is important that users of protection areas know the basis on which they are defined. The NRA practice is, therefore, to define its protection zones within an uncertainty framework.

The most critical variables affecting zone geometry are recharge rate, hydraulic conductivity and effective porosity. Best estimate and credible limit values for each of these variables are determined from available data and all combinations which achieve acceptable hydraulic head distributions are used to compile an envelope of protection zones. From this envelope, three zones are defined (Fig. 2(b)):

(a) Best-Estimate Catchment Area: which is the published protection zone used for public policy purposes, and is the only zone to satisfy groundwater balance considerations;
(b) Zone of Confidence (ZOC): defined by the overlap of all plausible combinations;
(c) Zone of Uncertainty (ZOU): the outer envelope formed by the boundaries of all plausible combinations.

The confidence index (area ZOC/area ZOU) is a useful measure of relative uncertainty and can be used to indicate where additional resources can be most usefully deployed.

Although the ZOC is the area of greatest confidence, it will not normally be of sufficient area alone to provide adequate protection to the source. However, in Britain it is used for controls on soil nitrate leaching to groundwater, where it has been the basis for compensation paid to farmers for restrictions on nitrogen use. It is argued that concentrating control measures in a limited, but confidently-defined zone, gives a more certain return on public funds expended.

Definition of zones

The most certain source protection zones will be defined where data availability is best and can be used to establish a regional groundwater flow model with robust boundary conditions. Flowpath-defined source protection zones can be directly and confidently derived from such models. The confidence test described above can be readily undertaken in the knowledge that interference between all sinks and sources has been readily accounted for, and the approach extended to consider time variable changes in catchment geometry if this seems likely to be significant.

Although this route will be increasingly followed in the future, present numerical model limitations mean that other techniques must be applied. In Britain, some 80% of the 800 zones defined up to the end of 1994 have been done using steady-state two-dimensional model codes, the predominant one being FLOWPATH, which has proved to be a robust and practical tool in many hydrogeological environments. Where hydrogeological complexity is greater, and data availability justify, the MODFLOW-MODPATH-MODELCAD programme suite shows promise in protection zone definition.

In order to deal with situations where lack of data and aquifer heterogeneity combine to make modelling inappropriate, a suite of manual techniques are used to provide the best-estimate protection zones. Groundwater environments where these have been most commonly applied are in karstic or semi-karstic aquifers, situations where seasonably-variable spring discharges are the dominant sinks, and in hard-rock aquifers. The general principle employed is that any zone is better than no zone at all, and that even a circular (or in the case of springs, semi-circular) zone will be declared to provide a precautionary marker that more investigation will be required if threatening land-use change or other activity is proposed.

CONCLUDING REMARKS

Vulnerability mapping and source protection areas are two different but complementary tools for protecting groundwater. The zones they delineate can be readily used for the construction of acceptability matrices for various types of potentially-polluting activity. Together they can:

(a) increase awareness of risk, by forming the basis for risk management and minimization programmes;
(b) provide a credible and defensible input to land-use management planning;
(c) help regulatory agencies and water users prioritize their deployment of human and financial resources;
(d) promote public understanding of the problem of groundwater protection and help enlist their support.

There is already evidence that the approach now being adopted in Britain is meeting these goals.

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