Land-Surface Zoning for Groundwater Protection

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ABSTRACT

A procedure for land-surface zoning, related to the protection of groundwater against both point and diffuse pollution, is described. The procedure is based upon two independent elements:

(i) Division of the entire land surface on the basis of the aquifer pollution vulnerability, which relates to protection of groundwater resources; and
(ii) A series of special protection areas for individual sources, in which various potentially polluting activities are either prohibited or strictly controlled.

The procedure is hydrogeologically based, but not so complex as to be unworkable in practice. For resource protection three classes of formation type are defined, with a further subdivision on the basis of depth to saturated aquifer. In the case of diffuse pollution, it will also be necessary to consider the nature of the soil cover in the area where the polluting activity occurs. For source protection, up to four special protection areas are specified, and the criteria used to define them are discussed.

Key words: Aquifer vulnerability; groundwater pollution; point/diffuse pollution; source protection areas.

INTRODUCTION

Measures taken to protect groundwater against pollution must make use of natural subsurface capacity to attenuate many (if not all) contaminants, otherwise they will be excessively conservative and unnecessarily restrictive on other interests. Other essential elements of a groundwater protection policy are that:

(a) It should strike a realistic balance between the protection of resources (aquifers as a whole) and sources (boreholes, wells and springs) used for public potable water-supply; and
(b) It must address the control of both point and diffuse sources of pollution.

Both resource protection and consideration of diffuse pollution have been neglected in many past protection policies.

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A procedure for land-surface zoning, as the general framework within which to mount groundwater protection policy, consists of two main elements:

(i) Division of the entire land surface on the basis of the vulnerability of the underlying aquifers to pollution; and
(ii) Areas related to the catchment of, and saturated zone flow times to, individual groundwater sources.

For any procedure to be consistent, it must be founded on hydrogeological concepts. However, it should neither be so complex as to be unworkable in practice nor restrict unnecessarily the use of scientific evaluation and judgement in individual cases.

A predominant consideration in the development of a realistic policy is that the number of defined zones needs to be kept to the minimum compatible with the range of different pollution-control measures envisaged. The latter would include constraints on new development exercised through planning consent procedures and increased vigilance and/or additional controls imposed on existing activities.

The basic elements of the proposed procedure are illustrated in Fig. 1.

RESOURCE PROTECTION

Concept of Aquifer Vulnerability

The vulnerability of an aquifer to pollution is dependent upon a set of intrinsic characteristics of the strata separating the saturated aquifer from the land surface[1]. These will determine the sensitivity of the aquifer to quality deterioration as a result of an imposed contaminant load. Aquifer vulnerability would then be a function of:

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

These two factors interact with certain characteristics of the contaminant loading on the subsurface, namely:

(i) The mode of pollutant disposition, especially in relation to the likelihood of any bypass of the soil and/or unsaturated zone, and the magnitude of associated hydraulic loading; and

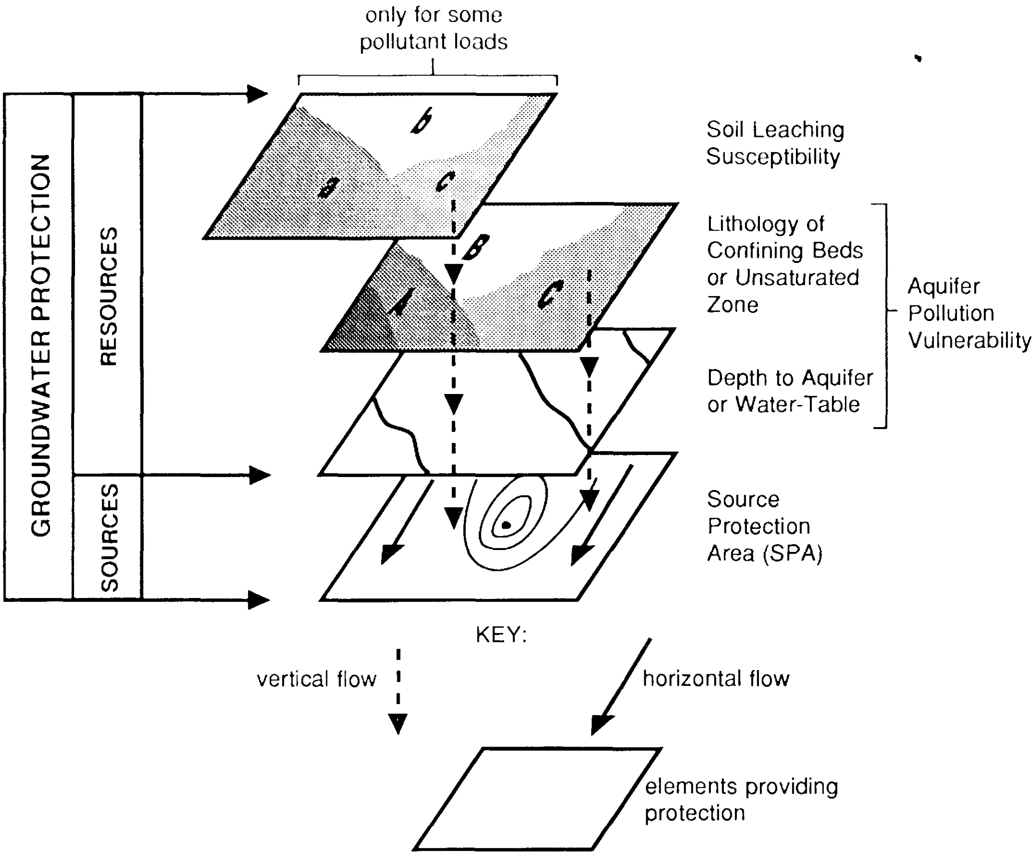


Fig. 1. Conceptual framework for groundwater protection

(ii) The contaminant class in terms of its mobility and persistence.

The general vulnerability concept has serious limitations because in rigorous scientific terms 'the general vulnerability to a universal contaminant in a typical pollution scenario' has little meaning. Thus previous authors[(2)] have proposed that vulnerability mapping should be carried out for specific individual contaminants and pollution scenarios, and another[(3)] has published an empirical method to estimate subsurface pollutant degradation. This approach would be scientifically ideal, but would generate an atlas of maps that would be complex for general land-use planning purposes, and a simpler basis will normally be required[(1)].

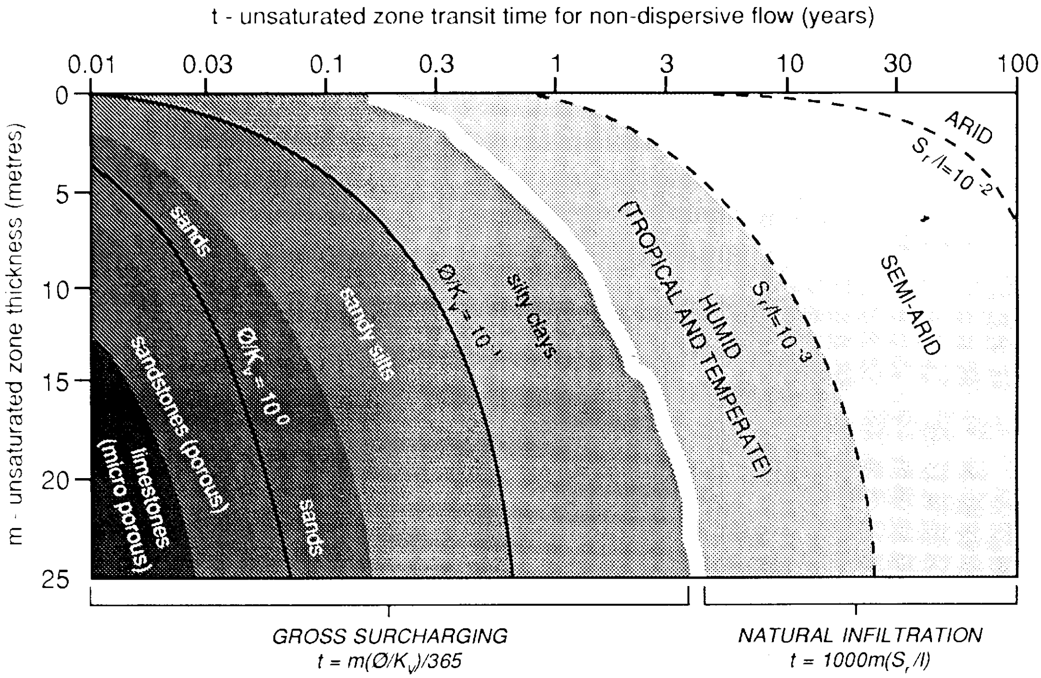
Role of Unsaturated Zone

Due to both its strategic position between the land surface and the saturated zone, and its potential for pollutant attenuation and elimination, the unsaturated zone represents the first line of natural defence of unconfined aquifers. Because water movement in the unsaturated zone is normally slow and restricted to the smaller pores with larger specific surface, and the chemical condition is normally aerobic and frequently alkaline, there is considerable potential for:

- *(a)* Interception, sorption and elimination of pathogenic bacteria and viruses;
- *(b)* Attenuation of heavy metals, and other inorganic chemicals, through precipitation (as carbonates, sulphides and hydroxides), sorption or cation exchange; and
- *(c)* Sorption of many, and biodegradation of some, natural and synthetic organic compounds.

However, it must be noted that due to the complexity of groundwater flow and pollutant transport in the unsaturated zone, its ability to attenuate pollutants can be difficult to predict[(1)]. The degree of attenuation will depend upon (i) the hydraulic loading of the pollution event, (ii) the chemical nature of the pollutant, and (iii) the chemical environment of the unsaturated zone. In effect, for persistent, mobile pollutants the unsaturated zone will merely introduce a time-lag before arrival at the water-table, without significant attenuation. In most other cases the degree of attenuation will be highly dependent upon unsaturated zone flow regime and residence time.

Under conditions of average rainfall it is reasonable to assume that transit times in the unsaturated



S_r = specific retention
I = annual infiltration (mm./a)
$Ø$ = effective porosity
K_v = saturated vertical hydraulic conductivity (m/d)

Estimates are based on grossly simplified formulations of natural rainfall infiltration and gross hydraulic surcharge. Since the variations in I and K_v are much greater than those of S_r and $Ø$, it is evident that, for a given thickness of unsaturated zone, the transit time is predominantly controlled by I in the former case, and by K_v in the latter case. The very large reductions in transit times in the presence of hydraulic surcharging are also apparent.

Fig. 2. Estimation of unsaturated zone transit times (developed from Foster 1987[1])

zone will be a function of the annual infiltration rate and a moisture content approaching the specific retention after prolonged drainage. However, most pollution scenarios involve heavier hydraulic loadings than average rainfall infiltration, and major recharge events often involve exceptionally intense rainfall. Therefore it is important to consider the effect of hydraulic load on unsaturated zone flow regime and residence time. Under conditions of gross hydraulic surcharge, saturated flow conditions will be approached and therefore transit times will be dependent upon lithology and, essentially, will be a function of effective porosity and saturated vertical hydraulic conductivity (Fig. 2). In practice this case will rarely be reached under field conditions, but nevertheless in most strata (other than fine-grained unconsolidated sediments) great sensitivity is exhibited, with radical reductions in unsaturated zone transit time. Lithological character, and especially the grade of consolidation and degree of fissuring of the unsaturated zone, will be the key factor in the assessment of aquifer vulnerability to pollution.

Significance of Soil Zone

Most of the processes causing elimination and/or attenuation of pollutants in the unsaturated zone occur at much higher rates in the biologically-active soil zone, as a result of its higher clay mineral and organic matter contents and very much larger bacterial populations. However, in many point sources of contamination the subsurface pollutant load is applied below the base of the soil zone in excavations such as pits, trenches, lagoons, soakaways and quarries, and thus should not be included as contributing to groundwater protection in these cases. However, the soil zone will be of more importance in connection with diffuse agricultural pollution, since it exercises a major control over the leaching of nutrients and pesticides.

Proposed Approach

The above considerations form the basis of the approach which was adopted. Some authors have elected to rank the geological characteristics comprising vulnerability and to generate an overall vulnerability index[4,5]. On balance it is considered preferable to retain hydrogeological variables in vulnerability mapping, and three main classes are recognized (Fig. 3), with a subdivision of the 'variably permeable' class dependent upon the nature of its porosity/permeability. Subclasses in the two permeable groups are based on unsaturated zone thickness.

Influent rivers are an additional consideration, where these have significant extension upstream of their influent sections on class C areas. It is evident that any potentially polluting activity occurring within the catchment to the watercourse in these areas could lead to transport of contaminant to the influent sections and thus affect groundwater quality. Therefore, surface-water catchments upstream of influent sections would be designated as being 'of interest to groundwater'.

Sink holes, mine shafts, abandoned boreholes and any other form of conduit between the surface and aquifers should also be considered in the context of aquifer pollution vulnerability, since they constitute potential entry points into aquifers for any pollutants found on the land surface and also need to be mapped. Similarly it is important that any proposed activity in class C areas which might involve substantial reduction in the thickness of the protecting surface strata (e.g. landfill waste disposal in quarries) should be carefully assessed.

SOURCE PROTECTION

The objective of source-protection areas is to provide a special additional element of protection for selected groundwater sources (boreholes or springs). This is achieved by placing tighter controls on activities within all, or part, of their recharge area.

Recharge Capture Area

The outermost protection area that can be defined for an individual source is its recharge capture area. This is the area within which all aquifer recharge, whether derived from precipitation or surface watercourses, will be captured at the source concerned. In practice this definition requires further specification, and it is customary to consider the licensed (not actual) abstraction rate and the long-term average

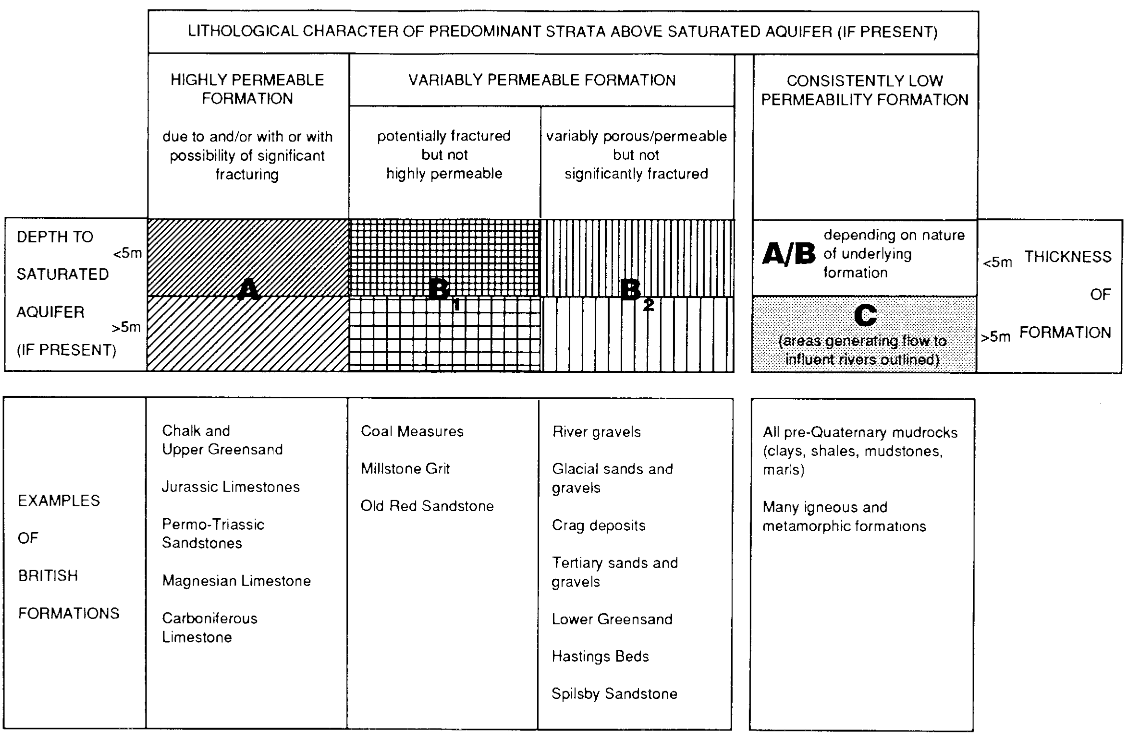


Fig. 3. Definition of zones based on aquifer vulnerability

recharge rate when calculating such areas. It is accepted that in an extreme drought the actual capture area may be larger than that protected. The area of interference caused by a pumping borehole should not be confused with its area of capture.

In order to eliminate the risk of unacceptable source contamination, all potentially polluting activities would have to be prohibited or controlled to the required level within this capture zone. This will often be untenable, due to socio-economic pressure for development. Therefore some division of the recharge capture zone is required, so that the more severe constraints will only be applied in the areas closest to the source. This subdivision could be based on a variety of criteria, depending on the perceived pollution threat, including: horizontal distance, horizontal flow time, proportion of the recharge area, saturated zone dilution, and/or attenuation capacity. For general application Adams and Foster[6] concluded that horizontal flow time and distance criteria are the most appropriate factors.

In practice, the dilution and attenuation capacity of the saturated aquifer are difficult to quantify and predict, although the latter will (in a general sense) increase with increasing horizontal flow distance and flow time. Intuitively, dilution might appear to be a useful criterion to delimit source-protection areas within the capture zone to a source. However, consideration of two simple examples will give an indication that this is not necessarily so. In the case of continuous discharge of a pollutant into an aquifer (e.g. from a leaking storage tank) at a fixed rate (q), the dilution at a continuously pumping borehole (at rate Q), will be q/Q irrespective of the distance of the pollutant source from the borehole. For instantaneous sources (e.g. a transport accident), consideration of a simple model in which radial flow to a borehole is superimposed on uniform regional flow with no recharge gives a further indication of the unsuitability of dilution as a criterion. With increasing distance upstream from the borehole, groundwater flow becomes essentially rectilinear. The dilution upon arrival at the borehole of a fixed volume of pollutant introduced between two specific flow lines in this region of rectilinear flow is independent of distance, ignoring hydrodynamic dispersion which is difficult to predict.

Special protection of a proportion of a recharge area may be the preferred solution to alleviate diffuse agricultural pollution of groundwater under certain circumstances, but even then the question of which part of the recharge capture zone should be protected inevitably arises.

No more than 2 or 3 sub-divisions of the total capture zone will generally be practical: the operational courtyard area, an inner protection zone related to the control of pathogenic contamination, and perhaps an outer protection zone to allow differential control of point-source or diffuse-source pollution in the remaining area.

Operational Courtyard

The innermost protection area is the operational courtyard which comprises a small area of land around the source itself. It is highly preferable for this area to be under the ownership and control of the groundwater abstractor. In this area no activities should be permitted which are not related to water abstraction itself, and even these activities need to be carefully assessed and controlled to avoid the possibility of pollutants reaching the source, either at the wellhead directly or via adjacent disturbed ground. Specification of the dimension of this area is necessarily somewhat arbitrary. It will be dependent to some degree on the nature of the geological formations present, but a radius of 30 m would appear reasonable from experience in the UK.

Inner Protection Zone

An inner protection zone, based on the distance equivalent to a specified horizontal flow-time, has been widely recommended for the prevention of pathogenic contamination of groundwater sources. The time used has varied significantly: 400 days by Thames Water[7]; 100 days by Yorkshire Water[8]; 60 days in The Netherlands[9] and Belgium[10]; 50 days by Southern Water[11], Anglian Water Authority[12], Germany and Austria[10], and 10 days in Switzerland[13]. Lewis *et al.*[14] reviewed all published case histories of groundwater contamination by pathogens. They concluded that the horizontal travel distance of bacteria and viruses in the unsaturated zone is governed principally by groundwater flow velocity. In reported pollution incidents the horizontal distance between the borehole or spring and the proven source of pollution was equivalent to no more than the distance travelled by groundwater in 20 days, despite the fact that pathogens are capable of surviving in the subsurface for up to 400 days. The value of 50 days is thus considered a reasonable basis to define the inner protection zone, and conforms to existing practice in many cases.

Outer Protection Zone

An outer protection zone may be necessary to allow differential control of point-source or diffuse-source pollution in the remaining area. However, the current scientific uncertainty about the rates of subsurface degradation of other types of contaminant, together with the complexity of subsurface dispersion and dilution processes, mean that the criteria used for its definition will inevitably be somewhat arbitrary.

The larger the area defined, the greater will be the chance of dilution, attenuation and elimination of degradable toxic contaminants, and consequently the less will be the risk of unacceptable pollution of the groundwater source. Additionally, the larger the

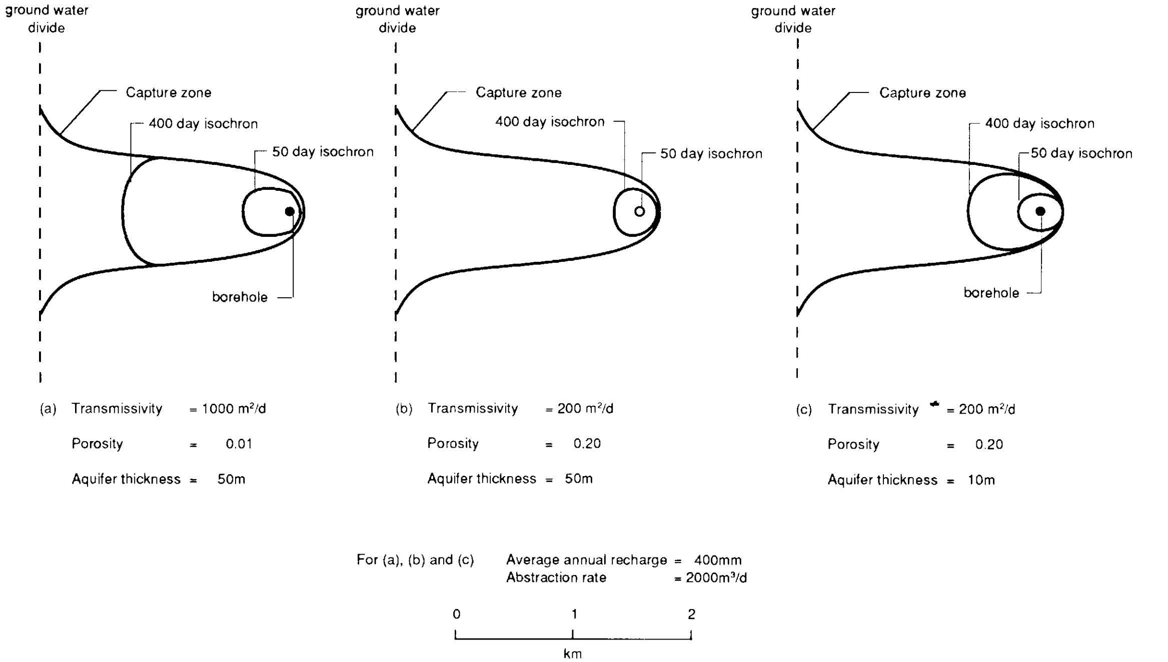


Fig. 4. Comparison of source protection areas for different aquifers

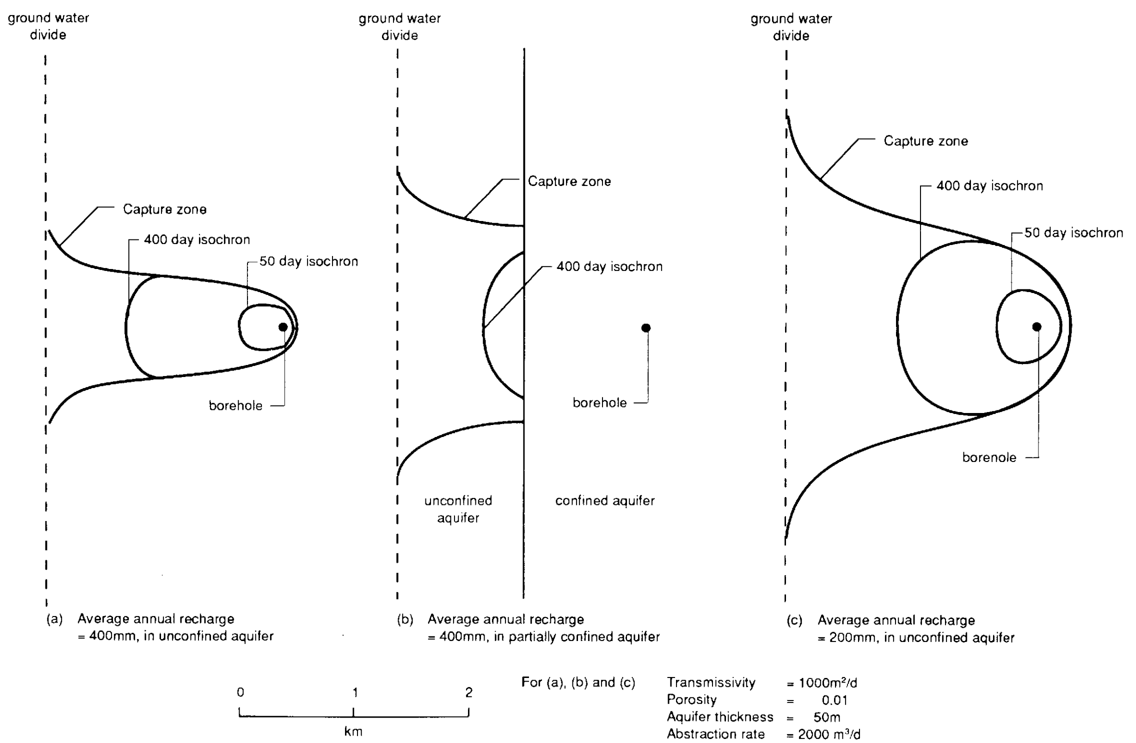


Fig. 5. Comparison of source protection areas under differing recharge conditions

area defined, the longer will be the time available to take remedial action to control the spread of pollution, at least in cases where the polluting incident is immediately recognized and notified.

For consistency the area of the outer protection zone should be defined on the same basis for all groundwater sources. This could either be as a fixed percentage of the area of the capture zone or on a fixed time of horizontal groundwater flow. A possible compromise, bearing in mind that both point-source and diffuse-source pollution need to be controlled, is to use the horizontal flow time one order of magnitude greater than that used for the inner protection zone (say 365–500 days), but to set a minimum limit of say 25% on the proportion of the overall recharge capture zone protected.

Computation of Dimensions of Source Protection Areas

An indication of the variation in size and shape of source-protection areas under differing hydrogeological conditions is given in Figs. 4 and 5. It should be noted that, whilst the definition of the recharge capture area is mainly dependent on the recharge regime, any protection zone based on horizontal flow time can also be highly sensitive to errors in the estimation of aquifer parameters. Ideally three-dimensional groundwater flow modelling would be used to delineate source protection areas; however, in practice there is rarely, if ever, adequate information on aquifer vertical permeability and hydraulic head variations, and two dimensional aerial formulations with cautious parameter selection are the best that can be achieved.

In Fig. 4 the recharge capture zone is identical in each situation, with its total area being equal to the average abstraction rate divided by the long-term average recharge. In Fig. 5 differing recharge conditions are illustrated: the conditions in Fig. 5(a) are identical to those in Fig. 4(a), but Fig. 5(b) shows the effect of the source being located in a fully confined aquifer with its recharge capture zone distant, uphydraulic gradient in the unconfined area, but of equal areal extension to that in Fig. 5(a). Comparison of Figs. 5(a) and 5(c) shows the effect of decreased recharge.

Aquifer properties (transmissivity, 'active' porosity and 'effective' thickness) exercise the dominant control over the size of the protection areas defined by horizontal flow time, as illustrated by isochrons in Figs. 4 and 5. Sensitivity to variation of these parameters will be immediately evident, and it is essential that realistic estimates are used. The estimation of realistic values for porosity and thickness may present significant problems in the case of fissured porous aquifers and layered aquifer systems respectively, but the dangers of over-estimating these parameters will be apparent from Fig. 4. Both the computation of worst case scenarios and the use of a stochastic approach to modelling parameter uncertainty should be considered.

Special problems arise, especially with the definition of recharge capture areas, in situations where the groundwater divide is at a great distance and/or the regional hydraulic gradient is very low.

In every instance it will be essential to reconcile the definition of source-protection areas, whether computed by analytical or numerical models, with the available knowledge of local hydrogeological conditions.

It is evident that, where surface watercourses are influent within a capture zone to a source, any potentially polluting activity in the surface-water catchment upstream from the recharge capture area could affect groundwater quality and should be designated for special protection, albeit with less rigorous controls than those applying within the inner, and perhaps the outer, protection zones.

IMPLEMENTATION

The approach is ideally suited to management by a Geographical Information System (GIS), since there are several 'layers' of information which need to be utilized in different combinations (Fig. 1) dependent upon the activity under consideration. However, introduction of a groundwater protection policy with the presented framework is by no means dependent upon a GIS.

An essential component of effective groundwater protection policy is an adequate groundwater quality monitoring system. An 'offensive' monitoring system would have the following objectives:

(i) Provision of data to evaluate the effectiveness of existing groundwater protection measures; and
(ii) Detection of incipient pollution of previously uncontaminated aquifers and worsening situations in previously polluted aquifers, in order to allow aquifer pollution-control measures to be implemented.

Due to the high cost of laboratory analyses and the impracticability of analysing unlimited numbers of determinands, the choice of parameters for regular monitoring should be dictated to some degree by the suspected pollution threat. Therefore it is essential that an inventory of potentially polluting activities is set up on a catchment or borehole-recharge-capture-area basis[15]. Ideally the inventory would include all potential groundwater pollutants used or stored in (and even transported through) the area concerned.

Evidently the implementation of an effective monitoring system, coupled with a pollutant inventory, will of necessity be a progressive exercise. The division of the land surface on the basis of aquifer vulnerability and source-protection areas will immediately define priority areas where monitoring and inventory should be instigated, and where special control of proposed new activities is required.

When division of the land surface is first initiated as a basis for groundwater protection policy, immediate consideration will need to be given to existing activities which, under the new policy, would not have been permitted in their present location. Once again effective monitoring will be required to investigate existing and potential problems. In many cases it may be possible to overcome existing problems by engineering solutions or improved practice but, inevitably, in some instances relocation of the activity will prove necessary if the resource or source in question is to be adequately protected.

CONCLUSIONS

It may appear scientifically attractive to consider each case on its merits when considering groundwater pollution risk and protection requirements. Whilst it is recognized that detailed local knowledge of conditions will always be relevant, it is considered that the presented approach for primary land-surface zoning forms a practical, yet scientifically-based, framework within which to mount a consistent groundwater protection policy capable of comprehension by the general public.

ACKNOWLEDGEMENTS

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REFERENCES

(1) Foster, S. S. D. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: *Proc. Int. Conf. on Vulnerability of Soil and Groundwater to Pollutants*. Noordwijk, The Netherlands, 1987.

(2) Andersen, L. J., and Gosk, J. Applicability of vulnerability maps. *ibid.*

(3) Rehse, W. Elimination und Abbau von organischen Fremdstoffen, Pathogenen Keimen und Viren in Lockergestein. *Z. dt. Geol. Ges.*, 1977, **128**, 319–329.

(4) Aller, L., Bennet, T., Lehr, J. H., Petty, R. J., and Hacket, G. DRASTIC: A standardised system for evaluating groundwater pollution potential using hydrogeologic settings. *NWWA/EPA Ser.*, EPA-600-/2-87-035, 1987.

(5) Foster, S. S. D., and Hirata, R. Groundwater risk assessment: a methodology using available data. *CEPIS Technical Report*, Lima, 1988.

(6) Adams, B., and Foster, S. S. D. National groundwater protection policy: hydrogeological criteria for division of the land surface area. *NRA, R & D Note 6*, 1991.

(7) Thames Water Authority. *Guidelines on the Protection of Groundwater Quality*. Draft report, 1988.

(8) Yorkshire Water Authority. *Aquifer Protection Policy*. 1989.

(9) Van Waegeningh, H. G. Overview of protection of groundwater quality. In: *Theoretical Background Hydrogeology and Practice of Groundwater Protection Zones. International Contribution of Hydrology, Volume 6*, Matthess, G., Foster, S. S. D., and Skinner, A. Ch. IAH/UNESCO, 1985, 159–166.

(10) Lallemande-Barrés, A., and Roux, J-C. Guide méthologiques d'établissement de périmètres de protection des captages d'eau souterraine destinée à la consommation humaine: manuels et méthodes. *BRGM Manuels et Méthodés No 19*, Orleans, France, 1989.

(11) Southern Water Authority. *Aquifer Protection Policy*, 1985.

(12) Anglian Water Authority. *Aquifer Protection Policy*, 1989.

(13) Blau, R. V. Groundwater protection zones in Switzerland: state of art. *Memoir IAH XXII Congress*, Lausanne, 1990.

(14) Lewis, W. J., Foster, S. S. D., and Drasar, B. S. The risk of groundwater pollution by on-site sanitation in developing countries. *WHO-IRCWD Report 01–82*, 1982.

(15) Chilton, P. J., Vlugman, A. A., and Foster, S. S. D. A groundwater pollution risk assessment for public water supply sources in Barbados. In: *Proc. Int. Conf. Tropical Hydrology and Caribbean Water Resources*. American Water Resources Assoc., San Juan, Puerto Rico. 1990.

DISCUSSION

(Abridged)

Dr L. Clark (Water Research Centre), opening the discussion, said that he was concerned about the authors' reference to the 50 day limit to aquifer protection zones because this was based upon the idea of homogeneous aquifers, which was something that he had never seen. He asked how, in reality, one assessed the degree of fissuring which was needed to quantify the vulnerability of the aquifer, and said that this was obviously very important in the UK in the Chalk aquifer.

He explained that the WRc had carried out a survey of Luton and Dunstable where, within a 1 km radius of a public supply borehole in the town centres, there were at least 20 different sources of solvents alone. He asked (a) how the authors would overcome this 50 day limit problem and (b), within the urban situation their views on the development of pollution control, the payment for pollution and the remediation of the pollution.

Dr Clark said that he had been involved in work on the pesticide problem for the last six years and that existing analytical techniques were not capable of implementing the EC Directive. In his opinion no analysis should be accepted as being true unless it had been confirmed by at least two methods, preferably one with mass spectrometry. Indications of precision and accuracy should be applied to every published pesticide analysis. To put this into perspective he referred to a Canadian trial which had shown that, at a respectable laboratory, if a pesticide was present at 1 μg/l a 200% error could be expected. This was ten times above the EC limit.

Mr T. R. E. Thompson (Soil Survey and Land Research Centre) said that his organization was interested in methods of classifying the soil zone according to the vulnerability to different groups of pollutants. He said that the stage seemed to have been reached where the interests involved in water management were seeking to intervene in the way in which the overlying land was used – the obvious example being agriculture. He said that if this was to be executed effectively it had to be carried out at local level. This would require very detailed information on the nature of the environment, i.e. the soil, the geology, and the hydrogeology. He said that such information was not currently available in the UK and he saw little opportunity at present of this improving, certainly with respect to the soil zone. He asked what the situation was like in other European countries and how one should overcome this problem.

Mr P. Del Olmo (Canal De Isabel II – Water Supply Co, Madrid) said that in order to better assess the idea of protection areas, he needed clarification on some of the practical aspects. For example, Mr Adams had referred to a recharge of 400 mm/annum and an abstraction of 200 m^3/d. He asked for an estimate of the water table depth and the average well depth.

Mr J. P. Lobo-Ferreira (Lab Nacional de Eng Civil) said that his organization had been carrying out some mapping of the vulnerability of Portuguese groundwater resources for a proposal for the future EC map on vulnerability for Europe that the EEC-DGXI was trying to establish.

He said that he was concerned about the subjective aspects of vulnerability mapping and the social importance of the groundwater resources. A normal consideration was that of porous media. In Portugal 75% of the groundwater resources were in fracture media, but most of the populated municipalities abstracted water from areas where groundwater resources were supposed to be unavailable.

He said that it was important to consider conservative pollutants, for example sodium chloride in coastlines, where the 50 day concept was of no importance because the pollutants would enter the groundwater probably during the next generation.

Authors' Reply

In response to Dr Clark, **Mr Adams** agreed that the 50 day zone was an aspect that would give rise to much debate, and the problem of actually defining it was one of the philosophical questions arising from the proposals that he had put forward.

He said that it was not for him to say how the proposals would be implemented in the UK, but (as he understood it) initially the zones would be defined on the best data available and the best understanding available. As more data and information became available the zones would evolve.

With regard to urban pollution control he felt that an important aspect was education – without this it would be difficult to stop such practices.

Responding to Mr Thompson, he said that in the case of the UK, part of the core programme of the geological survey was to improve the understanding of the geological background of the UK. Thus the database on hydrogeology was developing.

In reply to Mr Del Olmo, he explained that the two factors to which he had referred did not affect the particular area. He said that the area involved in those examples defined by the capture zone was defined from a balance of the total abstraction from the borehole as balanced by the recharge times the area of the capture zone. Hence the depth and the water well depth in definition of that zone were not important.

Following further explanation from Mr Del Olmo, he added that (in the examples referred to) horizontal travel times had been assumed and no consideration had been given to vertical flow. If the unsaturated zone was particularly thick then vertical flow times would be significant, but data would generally be limiting.

He agreed with Mr Lobo-Ferreira that the indexation method was very subjective and could lead to significant discrepancies in the way that particular situations were assessed. If indexation methods were to be used, he said that he would like to see the basic data remaining on the map so that someone else could interpret it or at least see how the original worker had interpreted that basic data.

With regard to socio-economic importance of particular groundwater supplies, he said that his point on vulnerability mapping was that this should have no relevance to the actual use of the water; an aquifer could be vulnerable even if the water was not going to be used for potable supply. He was interested in mapping vulnerability without respect to its use.

With regard to conservative pollutants, he said that the 50 day time zone was only intended to protect the source against pathogenic pollutants. Within the 50 day zone one would prevent any activities that could give rise to pathogenic pollution. One would additionally also prohibit the use of conservative pollutants within the outer zone. He said that he would not suggest that the 50 day time period was in any way meant to deal with conservative pollutants.