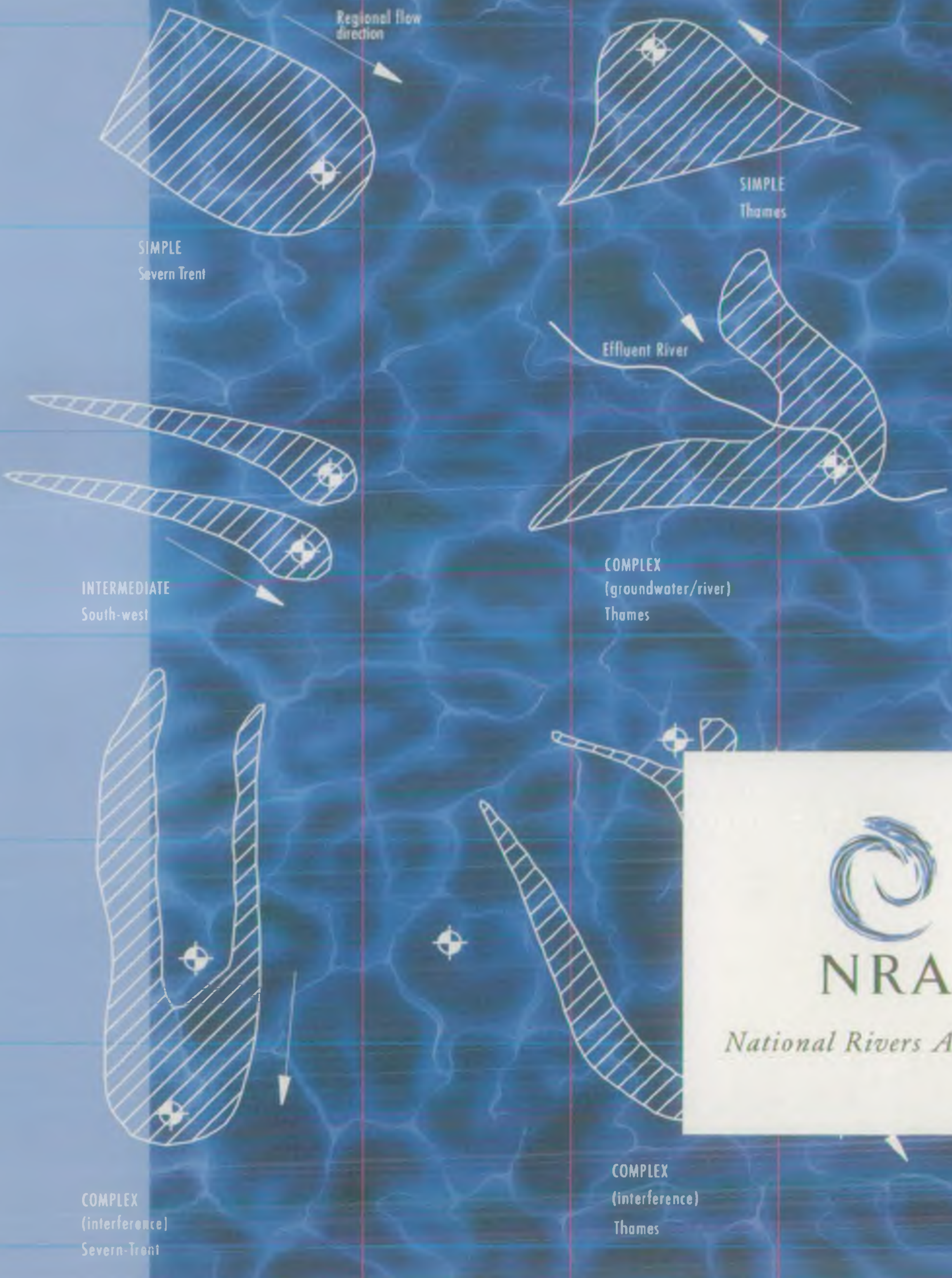
NRA Water Resources 27

GUIDE TO GROUNDWATER PROTECTION ZONES IN ENGLAND AND WALES



NRA

National Rivers Authority

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GUIDE TO GROUNDWATER PROTECTION ZONES IN ENGLAND & WALES

Edited by:
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FOREWORD

In 1992 the National Rivers Authority published its Policy and Practice for the Protection of Groundwater. The implementation of the policy depends upon the definition of groundwater source protection zones and on the preparation of vulnerability maps. This guide is one of two volumes which provide the background to the production and use of these two policy tools and complement the original policy document.

The companion volume to this Guide is the Guide to Groundwater Vulnerability Mapping in England and Wales.

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1 INTRODUCTION

1.1 LEGISLATIVE AND POLICY BACKGROUND

The National Rivers Authority (NRA) has a statutory duty to monitor and protect the quality of groundwater, and to conserve its use for water resources[1]. In 1992 the Authority published the Policy and Practice for the Protection of Groundwater (GPP)[2] to provide a framework for these duties. The GPP also provides a means to realise the Hague Resolution adopted by the Environment Ministers of the 12 member states of the European Union in November 1991. That Resolution recognises the need for the management and protection of groundwater on a sustainable basis by preventing its overexploitation and pollution.

The national GPP replaced a variety of different approaches to groundwater protection which had been employed by the former regional water authorities with three key elements:

- a series of statements on NRA policy with respect to the protection of groundwater
- a classification of groundwater vulnerability, including a programme of mapping at 1:100,000 scale
- the definition of groundwater protection zones via a phased programme of zone delineation as described in this guide

The policy statements and related maps and zones do not, in themselves, have a statutory status, but they enable the NRA to respond to various statutory and non-statutory consultations in a consistent and uniform manner. Moreover, these responses are designed to influence the policies and decisions of others whose actions can affect groundwater[3]. The latter is exemplified in the implementation of two EU environmental initiatives[4] which seek to reduce the pollution of aquifers by agricultural sources of nitrate. The UK Government's approach to the implementation of these initiatives in the form of Nitrate Vulnerable Zones (NVZs) and Nitrate Sensitive Areas (NSAs) will put in place statutory measures affecting approximately 5% of the land area of England & Wales. Both schemes have utilised the protection zones as part of the Authority's national programme to identify the catchments to potable groundwater abstractions with a nitrate problem.

Groundwater vulnerability assessment, and the identification by mapping of those areas of the land surface most at risk from human activities, is the principal line of defence in groundwater protection, because it relates risk to the whole of the groundwater resource. Measures for such **Groundwater Resource Protection** rely on the use of policy statements and associated matrices of acceptability[5], which tabulate what activities are possible and where, and which pose an unacceptable risk to groundwater.

However a sensible balance also needs to be struck between the protection of groundwater resources as a whole and of specific sources, not least because both land use and aquifers in England and Wales are already highly developed and heavily utilised. The definition of catchment protection zones around some individual sources is a logical development because it is unrealistic

1 Water Resources Act 1991, Sections 84 and 19

2 National Rivers Authority 1992: Policy and Practice for the Protection of Groundwater, usually abbreviated to GPP.

3 Department of the Environment, PPG12 : Development plans and regional planning guidance.

4 EC Nitrate Directive 91/676 and EC Agri-environmental (Council) Regulation 2078/92

5 The policies and their respective matrices can be found on pages 24–47 of the GPP

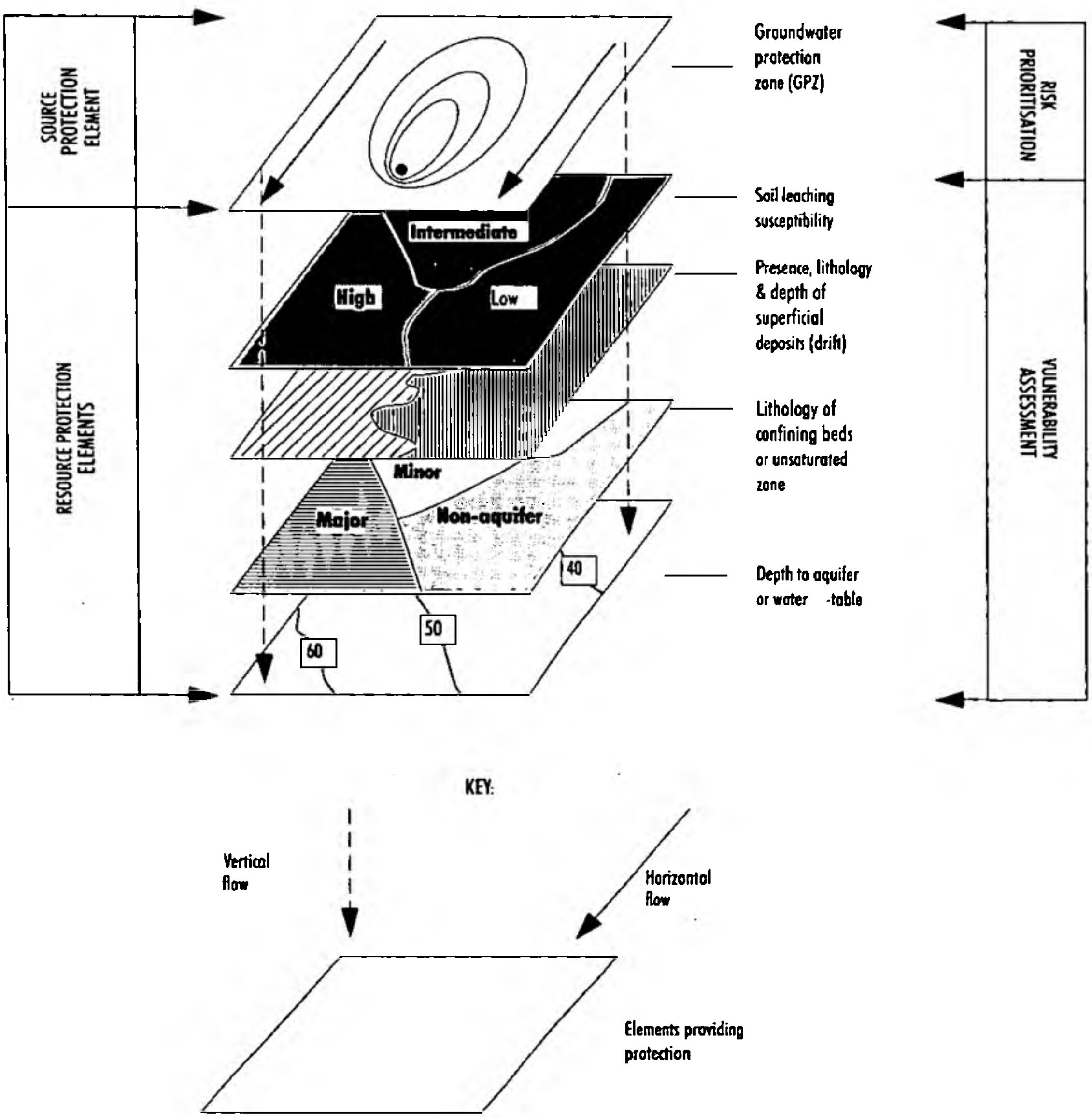
to expect the same degree of protection for all groundwater, and a zoning strategy is an important element in ensuring that an objective balance is struck between current economic development and aquifer protection. **Groundwater Source Protection Zones** (GPZs) limit the most restrictive policy statements to particular source catchments such as those used for major potable water supply.

Thus the NRA approach to groundwater protection comprises a dual strategy which seeks both to protect aquifers as a whole and also to safeguard specific sources of water supply (Figure 1.1). The conceptual basis for groundwater protection as a policy tool is that it provides a means of assessing the contamination risk to aquifers by human activities and thus prioritising where scarce resources should be directed for maximum protective effect.

1.2 PROGRESS IN PROTECTION ZONE DELINEATION

Zones to protect groundwater sources are not a new idea. Many examples can be found in the UK water supply industry of protected areas, relating to the perceived source catchment, within which activities were restricted or banned. This was in some ways easier than today because the management of local water supply was often in the hands of the same body that

FIGURE 1.1
Framework adopted for NRA national groundwater protection programme



controlled development, the local authority. Sometimes bye-laws were used. In the Margate Act 1902, for example, the water supply authority was given the power to control drains, closets, cesspools etc. over an area of 1500 yards from any well or adit. Brighton Corporation also obtained similar powers in 1924 covering a two mile radius around individual sources abstracting from the Chalk. An early approach to source protection, which was adopted widely by the UK water industry following the publication of a Ministry of Health Memorandum in 1948, comprised a 3 km fixed radius circular zone around the source.

In the 1970s simple standard shapes based on hydraulic equations started to be employed. A number of the former Regional Water Authorities also defined protection zones as part of their published aquifer protection policies. These were widely used in the day to day protection of groundwater sources, particularly during the planning procedure and waste disposal licensing process.

In Europe groundwater protection zones have also been part of groundwater protection strategy for many years although they have tended to achieve more widespread acceptance and generally have a statutory status. It is a common sight in many Northern European countries to see road signs indicating the beginning of a water protection zone.

In 1991 the British Geological Survey (BGS) was commissioned by the NRA to research the scientific background to land surface zoning for groundwater protection. BGS recommended the adoption of a system which zoned the land on intrinsic vulnerability, then subdivided the recharge capture area of particularly critical sources into inner, outer and catchment protection zones. For some sources, definition would continue to be carried out by manual means (see Section 5), while for those groundwater settings where sufficient hydrogeological data was available, two steady-state model computer codes were identified as capable of defining the zones.

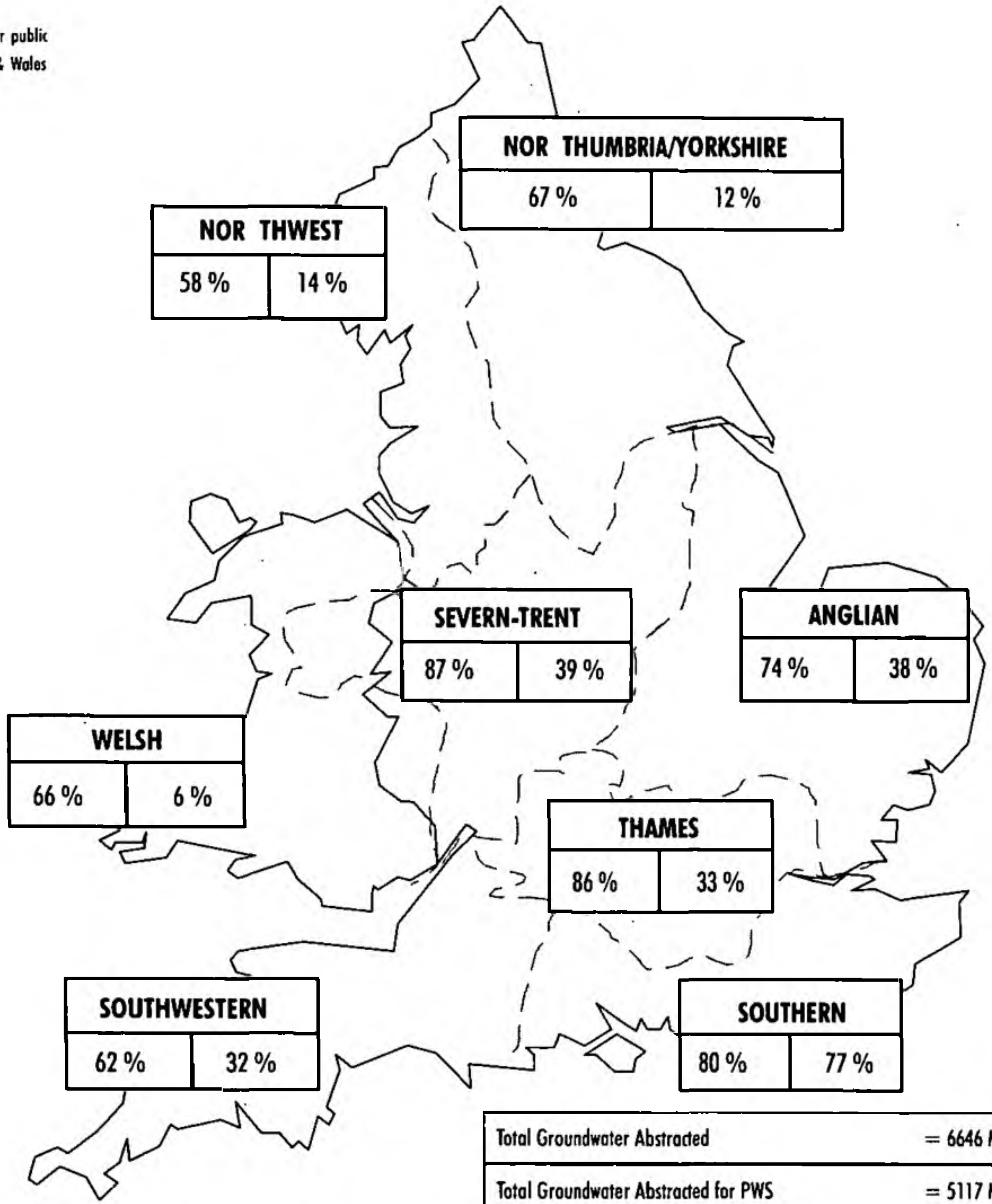
In 1991 the NRA conducted a pilot study to develop the identified delineation techniques for 750 of the most important public supply sources in England and Wales at a first-pass level[6], as Phase I of the national programme of GPZ definition. A second phase (GPZ II) was undertaken in 1993–94 to refine over 150 priority sources which were candidates for NVZ and NSA designation. The third phase of this project, to define zones around approximately 1250 public supply, non-public potable and sensitive commercial sources, runs from 1995 to 1997.

The NRA's emphasis on the zoning of public and large private potable supplies reflects the importance of groundwater nationally as a source for drinking water. Over 75% of all licensed groundwater abstractions in England and Wales are used for this purpose.

In addition to the volume of groundwater abstracted for public water supply which is illustrated in Figure 1.2, there are estimated to be upwards of 76,000 small private potable groundwater abstractions that are exempt from licensing and for which abstraction data are not available. Most of these are concentrated in rural and upland areas, for example in Wales, the Southwest and the Pennines.

6 'first-pass' in GPZ terms has come to be used for the first stage in zone definition when available data are brought together and synthesised into a technically reasonable simulation of the hydrogeological setting. Refinement may subsequently be required, both to incorporate more data which have come to light, or to spend more time on the model setup and simulations to improve model calibration and representativeness.

FIGURE 1.2
Groundwater use for public supply in England & Wales (1992)



Total Groundwater Abstracted	= 6646 Ml/d
Total Groundwater Abstracted for PWS	= 5117 Ml/d
Average % of Groundwater used for PWS	= 77%
% of total PWS	= 29 %

KEY

NRA Region	
% of all groundwater used for public supply	% of total public water supply derived from groundwater

Source: Digest of environmental protection and water statistics No 16 (1994). HMSO.

1.3 THIS GUIDE

The techniques by which groundwater protection zones have been defined have been subject to constant technical innovation, and this process of evolution will actively continue. With such positive developments in mind, this guide to protection zone procedures has been produced in a two volume format. The present volume forms a general introduction and is intended as an informed background guide to the zone delineation process. Together with the Vulnerability Mapping Guide which is being produced in parallel, it complements the GPP and is directed towards the following readership:

- NRA officers, and particularly non-specialists in groundwater protection
- water companies
- developers and their agents
- planning, central government and other statutory authorities
- interest groups

The emphasis in this Guide is on general principles and procedures. Readers interested in the detailed protection zone methodology are directed to the Manual[7], which is a technical specialist volume produced for those involved directly in zone delineation or in giving detailed advice on the interpretation of the resultant zones. In keeping with the evolving nature of protection zone techniques, the accompanying manual is to be published in loose-leaf format, with regular updates, and users are advised to liaise with NRA Regional contacts or with the NRA Groundwater Centre prior to undertaking zone delineation to ensure that the most appropriate methods are being employed.

7 The Manual of standard zone delineation methodologies can be obtained from the NRA Groundwater Centre, Sapphire East, 550 Streetsbrook Road, Solihull B91 1QT.

2 PRINCIPLES OF PROTECTION ZONE DELINEATION

2.1 HYDROGEOLOGICAL BACKGROUND

When rain falls, a part infiltrates the soil. While a proportion of this moisture will be absorbed in the soil zone and taken up by the roots of plants, some will infiltrate deeper, under the influence of gravity, eventually accumulating above an impermeable layer, saturating the pore space of the ground (*groundwater*). The level to which the ground is fully saturated (the *saturated zone*) is known as the *water table*. The ground above this is known as the *unsaturated zone*. Underground strata that can both store and transmit groundwater are known as *aquifers*.

The total volume of water in storage is usually very large relative to the rate of flow through the system, but not all aquifers are the same (Figure 2.1A-D). Unconsolidated granular sediments, such as sands (A) contain pore spaces between the grains and thus the water content or *porosity* can exceed 30% of their volume, but this can reduce progressively with the occurrence of finer materials such as silt or clay, and with the subsequent deposition of minerals that can cement the grains together (B). In highly consolidated rocks (C) groundwater is found only in fractures and the *effective porosity* rarely exceeds 1% of the volume of the rock mass. However, in the case of limestones, these fractures may become enlarged by solution or preferential flow, to form fissures and, in some strata such as the Carboniferous Limestone, caverns (D). All of these groundwater settings are found in the aquifers of England and Wales.

All freshwater found underground must have a source of *recharge*. This is normally rainfall, but can also sometimes be rivers, lakes or canals where leakage occurs into the underlying aquifer. Groundwater systems are dynamic and water is continuously moving slowly downgradient from areas of recharge to areas of discharge. Tens, hundreds or even thousands of years may elapse during the passage of water through this subterranean part of the hydrological cycle.

Shallow aquifers in recharge areas are generally *unconfined*, but elsewhere, and at greater depths, groundwater is often found to be *confined* by impermeable strata, or partially confined by low permeability strata such as glacial drift. In this case water is encountered under pressure, and when wells are drilled, rises to a level called the *potentiometric surface*.

When pumping occurs at a borehole or well, the action of the pump in withdrawing water causes a reduction in pressure, so there is a *head* difference created between the water in the borehole and that in the aquifer, causing a steady lowering in the surrounding pressure surface (water table in unconfined aquifers, potentiometric surface in the confined situation), which spreads outwards with time as pumping continues. A similar gradient is created towards the outflow point(s) of springs. As groundwater moves from regions of high head to regions where it has a lower head, it is possible to predict the direction in which groundwater will flow by mapping the water table or potentiometric surface, as observed in monitoring boreholes. Around each pumping well, or flowing spring, discharge therefore creates an area which will drain towards the source, separated by a *groundwater divide* outside of which flow will pass by. This groundwater divide marks the *capture zone* of the source.

It is important to distinguish between the capture zone and the *cone of depression* around the well, because the latter is synonymous with the zone influenced by

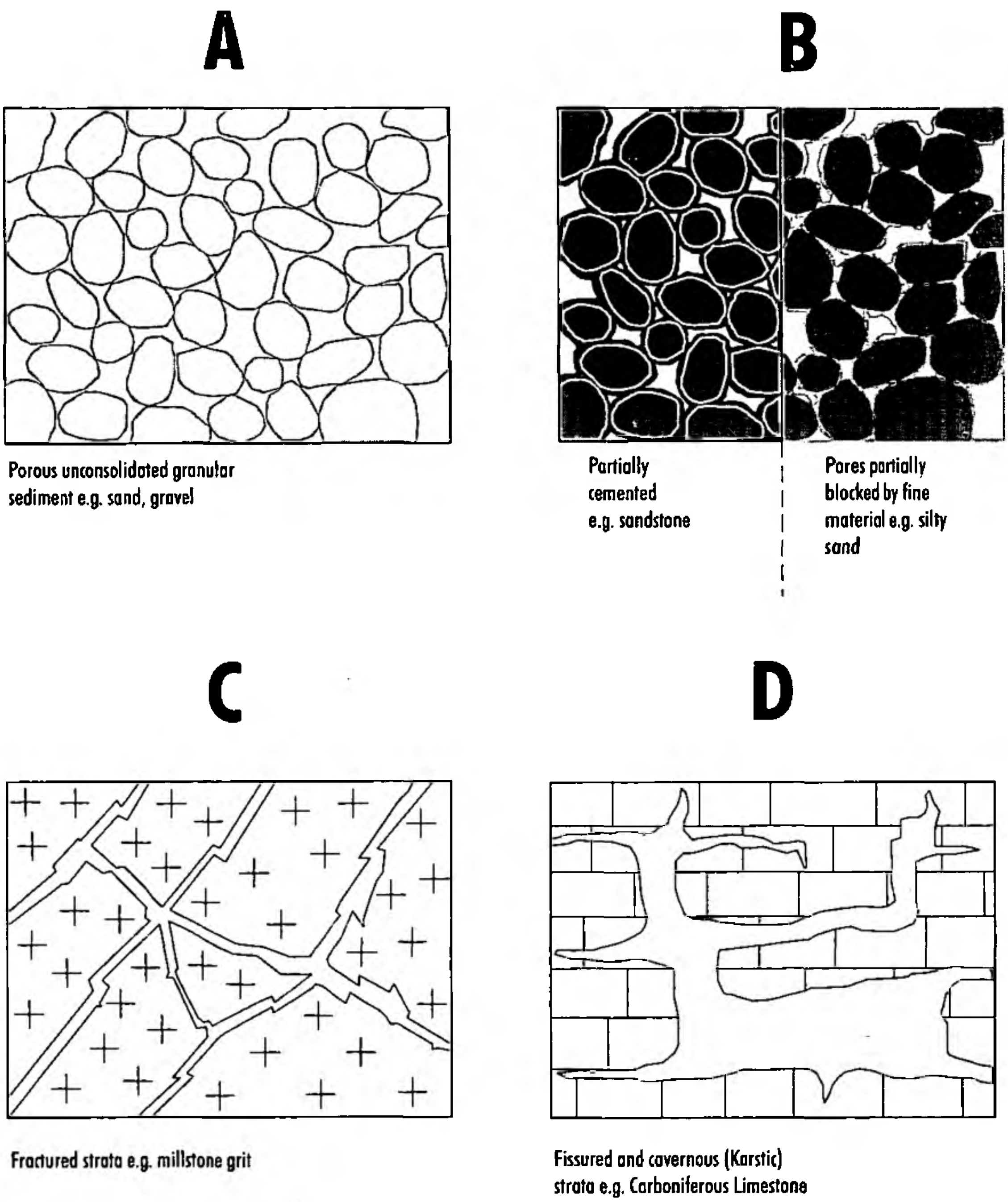
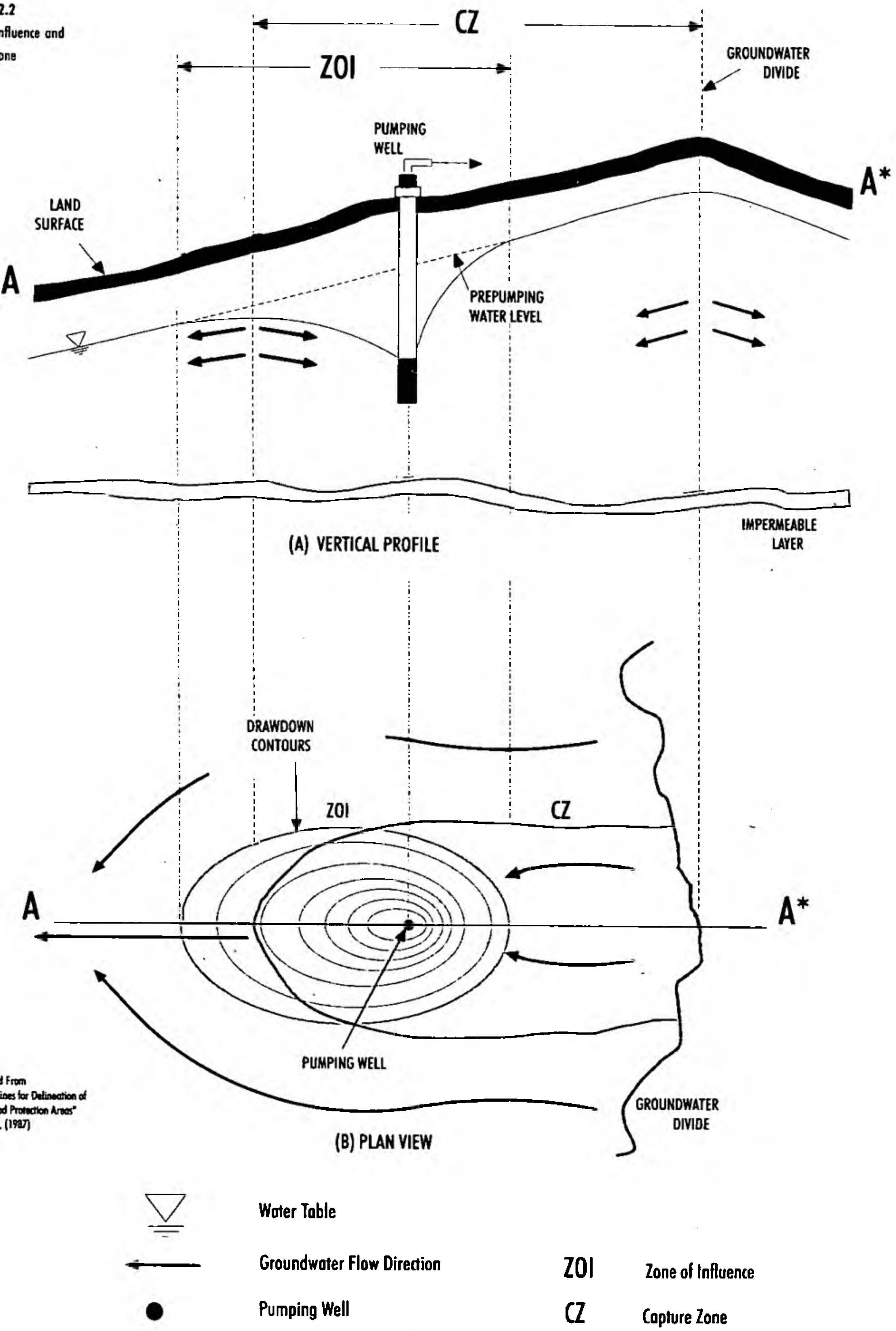


FIGURE 2.1
Common aquifer geological settings

abstraction. Figure 2.2 illustrates the difference. The capture zone consists of the up-gradient and down-gradient areas that will drain into the pumping well. If the water table is perfectly flat (which is rare) the capture zone will be circular and will correspond to the cone of depression. However, generally the water table is sloping *ie* there is a regional groundwater gradient, and the two do not correspond. This is because the *hydraulic gradient* of the water table downstream may be extensively modified by pumping, but water will only flow towards the well where the pumping-induced change in gradient is sufficient to fully reverse the regional gradient. The point on the divide directly downstream of the source where this occurs is called the *null point.*

As pumping continues, the capture zone will increase and extend, in particular up-gradient towards the closest groundwater divide, until the rate of abstraction is matched by the recharge over the

FIGURE 2.2
Zone of influence and capture zone



Adapted From "Guidelines for Delineation of Wellhead Protection Areas" US EPA, (1987) capture zone area, when effectively a steady-state situation is reached. The entire capture zone is known as the *source catchment*.

All the zoning conducted under the GPZ programme has assumed that (approximately) steady-state conditions exist and accordingly the *protection zones* have been delineated using steady-state computer models (Section 5). Within a source catchment, a series of lines representing equal travel times for groundwater flow to the well (*isochrons*) can be drawn around the well. Under the GPZ programme, 50-day and 400-day isochrons have normally been used to delineate time of travel protection zones (see Section 2.2).

The relatively simple picture of groundwater flow described above is in reality much more complex because aquifers, like most geological strata, are non-uniform. They may be *anisotropic* (their properties vary in different directions) and/or *heterogeneous* (their properties vary from place to place within the rock). Most sedimentary rocks for instance are strongly anisotropic with respect to *permeability*, because they contain grains that are not spherical but are elongated in one direction, so that when deposited they tended to settle with their long axes more or less horizontal. This can cause the permeability parallel to the bedding to be greater than that in other directions. Heterogeneity can occur vertically, when different lithologies such as shale and sandstone are interbedded, or laterally, with variations in, for example, pore size or the proportion of fine material.

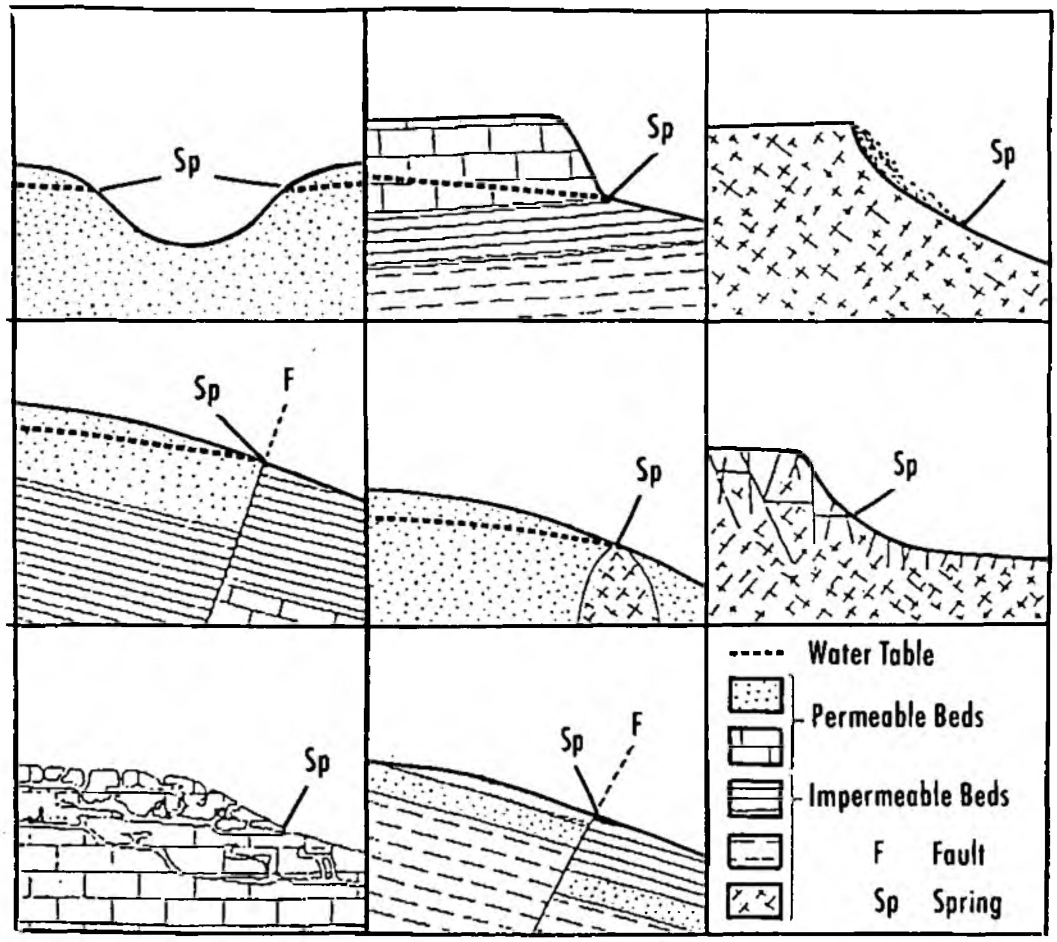
Even after deposition and consolidation, a rock's properties as an aquifer may be due more to later structural events than its original lithology. Flexing or folding during the geological past can induce fracturing and sometimes faulting in aquifers, which may provide enhanced routes for the flow of water, while the natural processes of solution in a limestone like the Chalk have produced flow through an extensive system of fissures, turning a formation with poor intergranular permeability into the most productive aquifer in Western Europe. Faulting can equally inhibit groundwater movement by causing impermeable strata to be in contact with permeable strata, or by providing semi-permeable smear zones.

In many areas groundwater abstraction takes place from springs, that is from points of groundwater discharge at the surface. Springs present slightly different problems for protection zone delineation in that the abstraction is governed by essentially natural groundwater flow driven by gravity. The size of the capture zone is thus dependent on the total flow to the spring, rather than the proportion of the flow which may actually be abstracted. Spring flow may be intermittent, reducing drastically or even dry up during summer months as the water table falls. Springs often occur at the junction of geological discontinuities, such as lithology changes, faults or barriers, the nature and extent of which may be at best only partially understood (see Figure 2.3). There may be considerable uncertainty on their actual location, with infiltration galleries and pipe systems, whose construction records may have been lost, draining poorly defined seepage areas. Even if only a portion of the spring's annual flow is utilised, protection should apply to the total spring catchment.

2.2 BASIS OF SOURCE PROTECTION ZONES (GPZs)

One important factor in assessing the risk of an activity to an existing groundwater source (spring, well or borehole) is its proximity. More specifically the pollution threat depends on whether the activity is located within the catchment of that source and on the horizontal flow

FIGURE 2.3
Typical occurrence of Gravity Springs



Source: *Principles of hydrology*, Ward R C (1967), McGraw-Hill

time to the abstraction point. The NRA's approach has adopted a tripartite zonation in which source capture zones are subdivided into three generally concentric zones, two of which are determined by the travel time of potential pollutants within the saturated zone, and one by the source catchment area itself (Figure 2.4). These three zones are each subject to a set of policies contained within the GPP[8].

Inner Zone I is defined by a 50-day travel time from any point below the water table to the source and, additionally, as a minimum 50 m radius from the source. It is located immediately adjacent to the well and the selection of the 50-day isochron is based principally on accepted biological (principally bacteriological) decay criteria[9]. It is designed to protect against the products of human activity which might have an immediate effect on the source. Zone I includes the area immediately around the wellhead, which is subject to especially strict controls. Although Zone I is not usually defined where the aquifer is confined beneath substantial low permeability strata, it is employed as a precautionary measure where deep unsaturated zones or patchy drift cover are present, in recognition of the uncertainties of vertical unsaturated flow, especially in the presence of fissuring. It is also used in the confined situation where adjacent deep structures warrant precautionary procedures eg tunnels, vertical access shafts and deep foundations.

8 The policies and their respective matrices can be found on pages 24–47 of the GPP.
9 Adams B and Foster S, (1992), Land-Surface Zoning for Groundwater Protection. J. IWEM, 6, 312–320

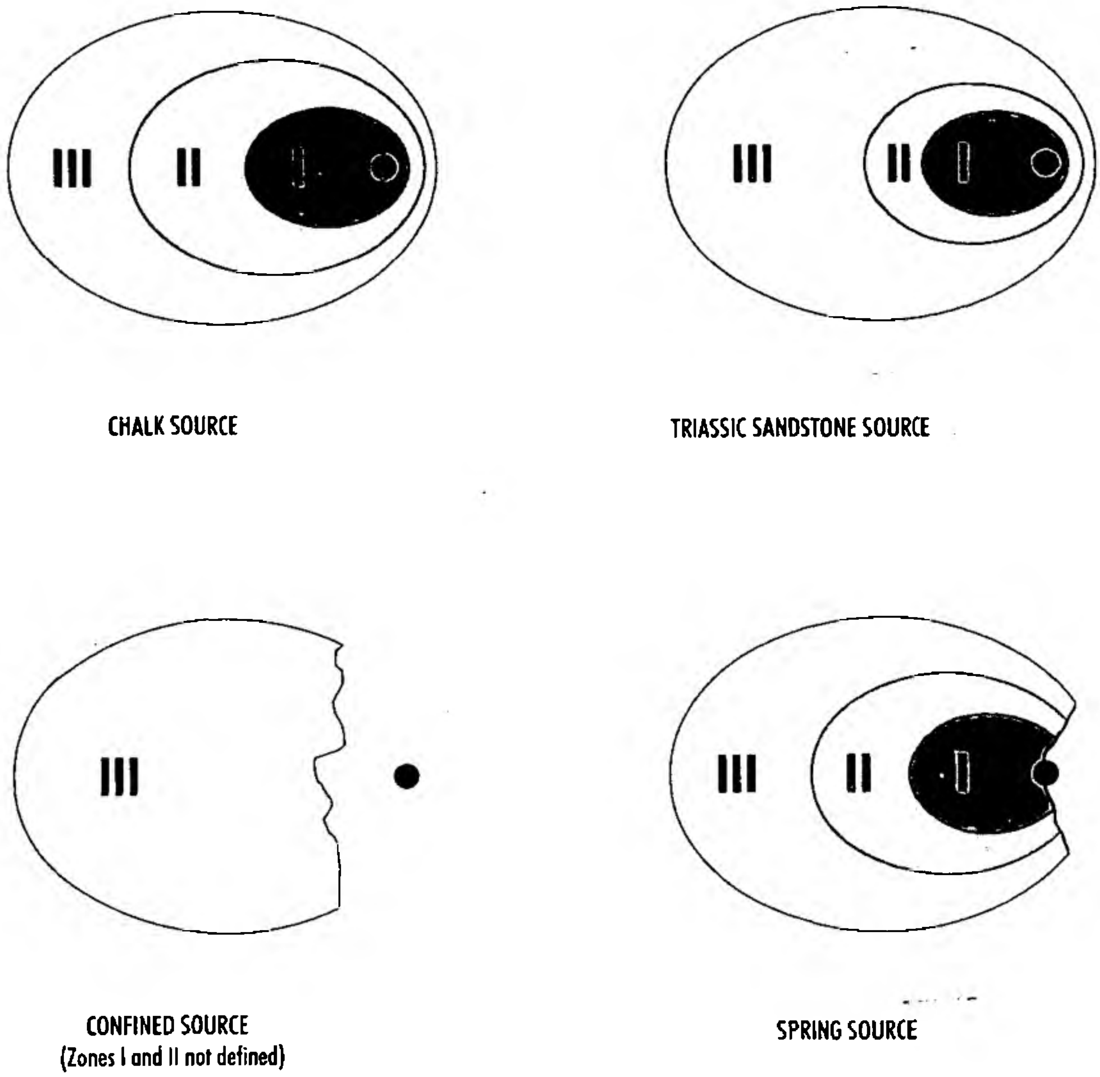


FIGURE 2.4
Schematic diagram of the relationships between source protection zones

Outer Zone II is defined by the 400-day travel time or 25% of the source catchment area, based on the protected yield of the source, whichever is larger. The travel time is derived from consideration of the minimum time required to provide delay, dilution and attenuation of slowly degrading pollutants. The zone is generally not delineated for confined aquifers.

Source Catchment Zone III is defined as the area needed to support the protected yield from long-term groundwater recharge (effective rainfall). In areas where the aquifer is confined beneath impermeable strata, this source catchment may be located some distance from the actual abstraction.

Both groundwater-related Nitrate Vulnerable Zones and Nitrate Sensitive Areas were delineated using the Zone III source catchment of nitrate contaminated sources[10].

The source abstraction rate used to derive GPZs is the *protected yield*. Ideally this should reflect the authorised quantities within the abstraction licence as follows:

- *licenced maximum daily quantity* regarded as the short term protected yield and used to derive the Inner Zone I.

10 In both cases, rules devised to map actual field boundaries made use of a further set of zones which have been devised to assess uncertainty in catchment definition (see Section 6)

- *licenced annual quantity* divided by 365 to give mean daily quantity or long term protected yield and used to derive the Outer Zone II and the Source Catchment Zone III.

However, protected yields may be less than the licenced quantities in the following circumstances:

- *Licence quantity unobtainable* usually when the maximum licenced daily quantity exceeds the hydraulic capacity of the borehole or the aquifer. In this case the protected yield should be regarded as the maximum that can be physically obtained[11].
- *Licence quantity unsustainable* in terms of exceeding the available groundwater resource. In this case licenced quantities of all the sources should be adjusted downwards so that the protected yield total for the aquifer unit does not exceed the available resource.
- *Licence quantity unreasonable* as it far exceeds the current rate of abstraction. In this case the protected yield should be based on the recent abstraction rates together with any reasonable forecasted increases.

Ideally and wherever practical, protected yields lower than licensed quantities should be derived after discussion with the source operator.

Any tendency to regard either the 50-day or the 400-day travel time criteria as excessively conservative, in that it takes no account of the timelag due to percolation down through the unsaturated zone, should be balanced against the following factors:

- rapid by-pass flow through sub-soil fissures can significantly reduce attenuation and retardation normally associated with the unsaturated zone
- the travel time is calculated using mean saturated flow velocities derived from the local hydraulic gradient. There is an implicit assumption that mean velocities reflect intergranular flow conditions; where fissuring is developed pathways for faster-than-average flow are available
- Some contaminants may be entering the ground under significant hydraulic loading eg beneath soakaways; others may have physical properties which favour more rapid ground infiltration rates than water, such as non-aqueous phase halogenated solvents which have higher densities and lower viscosities than water.

2.3 ZONE DELINEATION

There are a number of distinct steps in the process of zone delineation which are shown diagrammatically in Figure 2.5.

The most important stage in the whole process is probably *data acquisition*, because a zone can only be as representative as the quality of data which underpin it. Information is required not only on the hydrogeology, to understand the groundwater setting, but also on well construction, water levels, operational regime of the source, areal recharge, and interaction with surface watercourses. No well or spring can be zoned in isolation, and so it is axiomatic that the information collected should relate not only to the immediate environs of the source itself, but also to the surrounding area, whose extent will vary with individual circumstance but will almost certainly extend either to cover the aquifer resource unit in which the source is located, or to a radius of 5 km if no such unit has been defined.

11 Research programmes are being undertaken by United Kingdom Water Industry Research (UKWIR) and the NRA on methods of determination of the reliable yield of sources and resources (aquifers) respectively, which will assist in the process of defining protected yields.

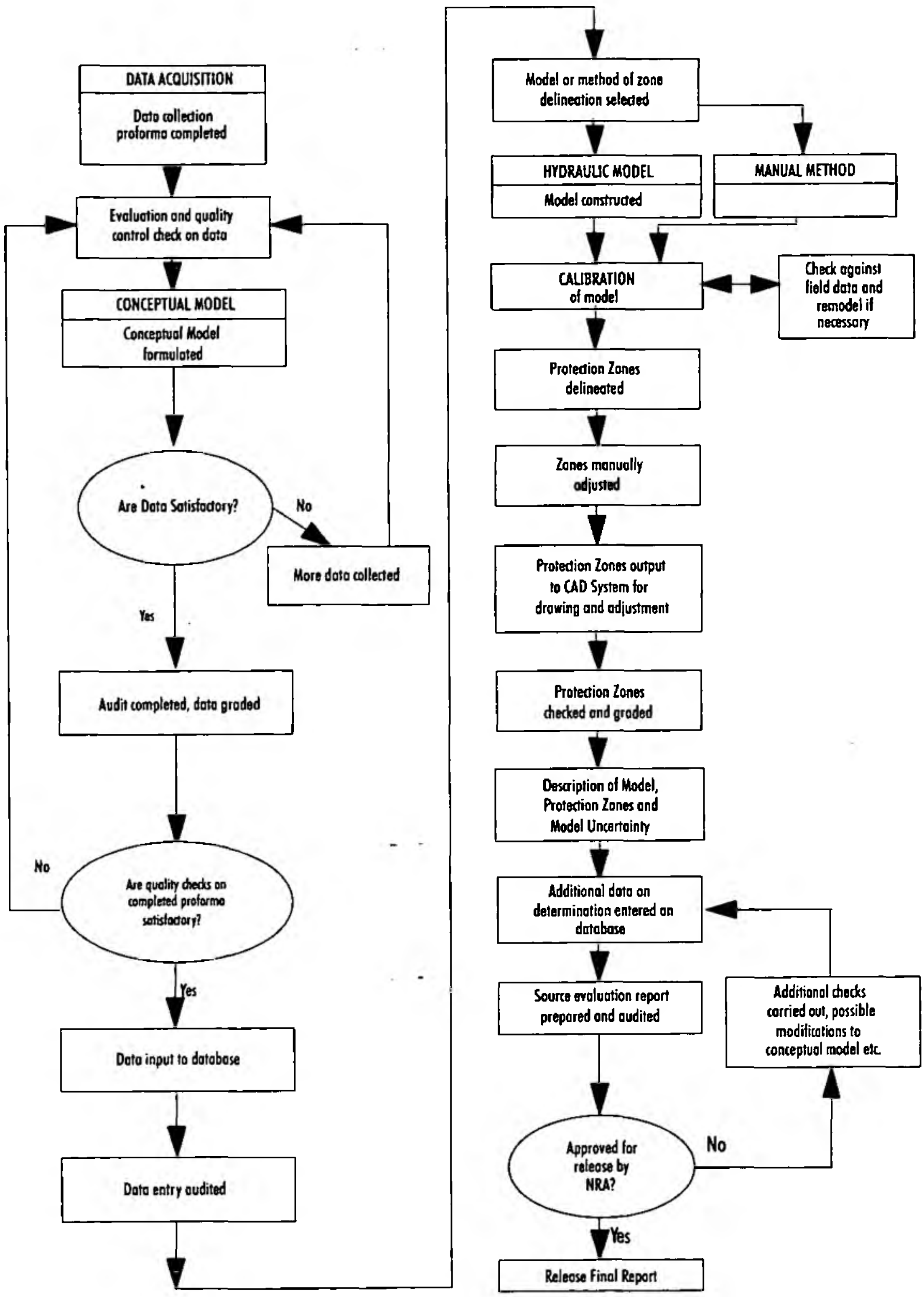


FIGURE 2.5
Overview of zone *determination process*

Two sets of standard forms have been devised, as part of the GPZ process, to aid comprehensive data collection. Their choice depends on whether the source is relatively isolated or is one of a number being delineated simultaneously in the same aquifer unit or model. At this stage any supporting maps (such as geology, hydrogeology, water level contour or isopachyte[12] maps), well cross-sections or construction diagrams should also be incorporated as part of the data set.

Once the data have been compiled, the information is synthesised into a *conceptual model* with the objective of providing a clear concise statement on the groundwater setting. This can be used:

- where manual zoning definition is employed both to crystallise current understanding of the local hydrogeology and to highlight where knowledge is deficient
- where modelling is undertaken, to help the modeller set up a simulation which will be as representative of actual conditions as the constraints of that particular model will allow.

Following on from the development of the conceptual model, the choice of zone definition technique is one of degree, based on:

- the quality of data available and the degree of understanding of the groundwater setting
- the operational importance of the source concerned
- the human and financial resources available for the particular zoning exercise.

Figure 2.6 shows the range of seven sets of techniques currently available to define the protection zone area around a source. These range from the arbitrary fixed radius circle, through simple analytical solutions to complex sub-regional numerical models. More overview information is provided in Section 5 of this Guide, while details may be found in the accompanying Manual. Note that all solutions must be used in conjunction with standard hydrogeological mapping techniques to ensure that the results make geological sense; indeed the latter may be the only technically justifiable option where fissure flow is particularly important, as in karstic[13] conditions.

Figure 2.6 is also meant to convey a sense of progression, in that as the understanding or data availability of a source improves, so it may become practicable to represent more of the real complexity of the hydrogeological environment by utilising a more sophisticated technique. This progression was, for example, employed in Phase II of the national GPZ programme to refine first-pass models.

The techniques described in detail in the associated Manual are proven methodologies. However, it should be noted that capture zone definition is an active area of on-going applied research and therefore it is likely that delineation techniques will continue to develop.

For methods 1–4 shown on Figure 2.6, the zone geometry is simple and can be drafted manually. However apart from very simple situations, (such as the rare case of radially symmetrical flow) the recharge capture zone and the inner and outer protection zones (which are based on time of travel) cannot be directly constructed. Instead most models employ a method called particle tracking, in which the movement of water towards a

12 An isopachyte map shows variations in the thickness of a particular rock unit, and can provide an indirect indication of transmissivity changes in the aquifer. The transmissivity is the product of the field permeability (hydraulic conductivity) and the aquifer saturated thickness.

13 Karst refers to the system of fissures, caverns and solution features characteristic of many limestone terrains; the Mendips, Peak District and Yorkshire Dales are all areas of karst.

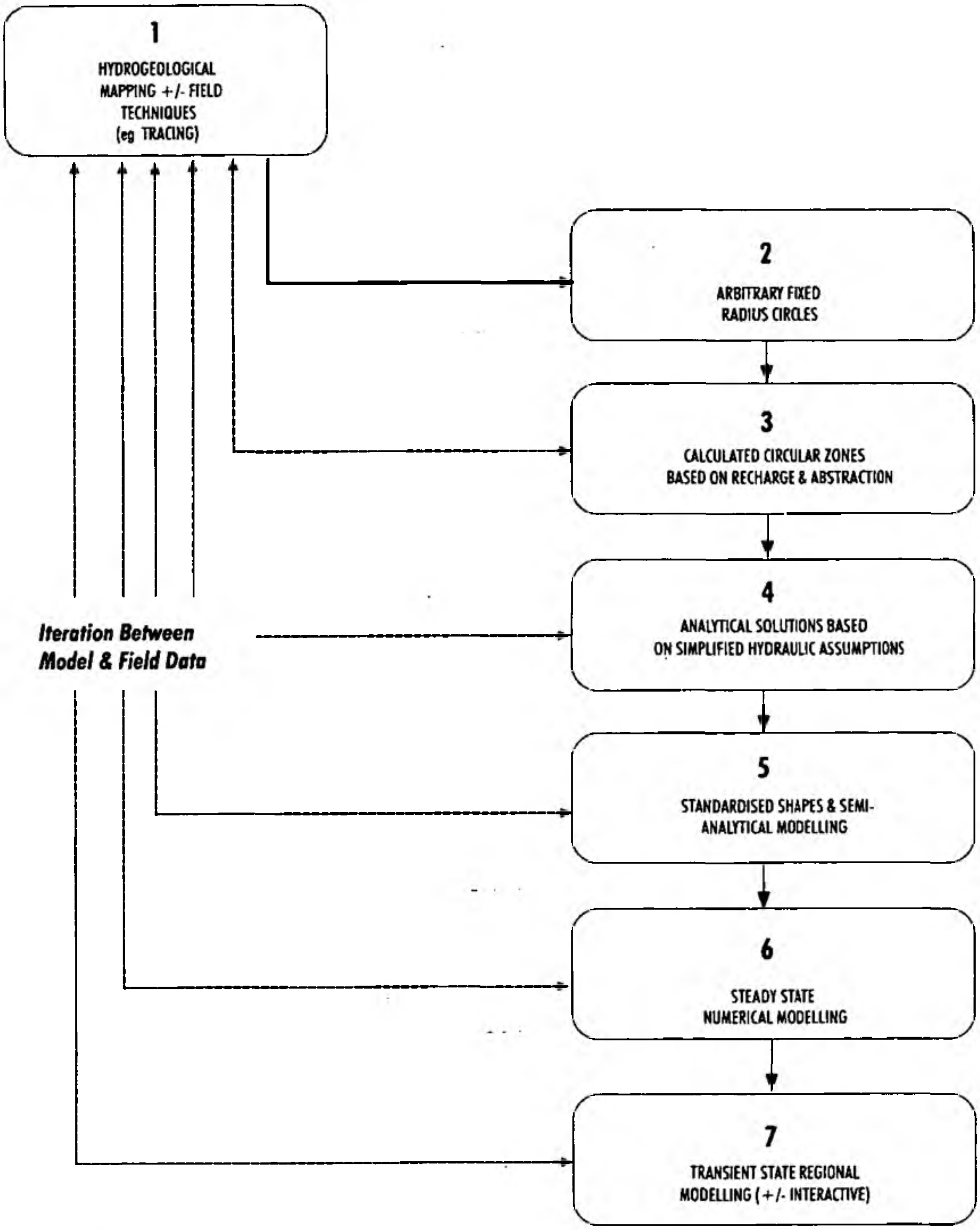


FIGURE 2.6
Principal techniques currently available to define capture zones for groundwater sources

source during pumping can be tracked in small steps by either semi-analytical or numerical means. The tracking produces pathlines emanating from the source in different directions, enabling an outline of an *isochron*[14] to be built up. Specifying the time of travel as 50 days or 400 days, or at steady-state produces a capture zone. The resultant isochron is then either obtained directly as output from the models or determined within CAD software from the file containing particle track coordinates.

For most purposes, once a model has been acceptably calibrated, protection zones are produced, based on the best estimate of the parameter values. However, any model must inevitably be open to uncertainties, because it is physically

14 An isochron is a closed curve which represents specific groundwater times of travel through the saturated zone to the source.

impossible to verify in the field at all locations all the parameters it represents in the simulation. With this in mind, a methodology for sensitivity analysis has been developed which can be applied as a framework to assess the impact of the uncertainty in estimating hydrogeological parameters. An overview of this method is given in Section 6.

It is important to realise that trying to represent uncertainty inevitably involves a trade-off. A conservative strategy is to define the maximum protection zone, that is the envelope of all credible zones. But 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.

To date, the uncertainty analysis has been utilised in the derivation of Nitrate Sensitive Areas (NSA) and Nitrate Vulnerable Zones (NVZ), to target those areas in which there is a high degree of confidence that the land lies within the capture zone of a source. This is to assist the extensive voluntary changes in farming practice, in exchange for compensation payments.

Once protection zones have been delineated, either by manual or modelling techniques, the results should be inspected to assess whether adjustments are needed. The system of rules governing zone adjustments has been developed empirically to provide protection zones which are both robust and practicable to apply, and it is likely that it will undergo modest development as more experience is gained in modelling capture zones. Possible adjustments to the computed zones are described in Chapter 7.

Once individual zones have been defined and any necessary adjustments carried out, the protection zone maps, showing Inner, Outer and Source Catchment zones overlying an Ordnance Survey base are produced. The use of CAD software facilitates the importation of the zonal maps into regional or national maps, where they could, for instance, be combined with aquifer vulnerability maps for risk assessment purposes.

2.4 SCOPE OF, AND CONSTRAINTS ON, ZONE DELINEATION

The NRA's programme for GPZ definition starts with consideration of all significant Public Water Supply and private boreholes that supply water to potable or equivalent standards eg. mineral water, breweries, food processing etc.

As well as the high value use to which water abstracted for potable supply is put, there are a number of other practical reasons why the principal emphasis for groundwater protection zones has been, and will continue to be, on such sources:

- most available data on aquifer geometry and hydraulic characteristics are concentrated at and around major public supplies
- the yield from individual sources, or wellfields, can be high, sometimes in excess of 10,000 m^3/d, and such abstractions often exert a major influence on the flow regime of the aquifer unit
- where a particular aquifer is heavily exploited, as occurs for example with the Chalk, the Permo-Triassic sandstones or the Lower Greensand, the zones around public supplies may interdigitate and coalesce; where this occurs it provides a *prima facie* case for resource rather than individual source protection and may point to the need for particular vigilance or special protective measures.

The NRA estimates that there are in excess of 3,300 public water supply, major private potable and sensitive commercial supplies in England and Wales for which protection zones are required. This is a major undertaking and the programme to 1997 will aim to provide zones for just under 40% of the most important of these sources.

In comparison, it is estimated that there are upwards of 76,000 small sources, with a relatively large proportion in minor aquifers in rural areas where complex fissure flow may occur or whose hydrogeology is not well documented. It will not be practicable or efficient to define zones around such sources, other than on a reactive basis, where a specific need arises, not least because the lack of available data will preclude the application of all but the most simple techniques of zonation[15].

In Section 2.1, reference was made to the effects on groundwater flow of natural inhomogeneity and anisotropy in rocks. This can give rise to complex hydrogeological systems, whose intricacy can sometimes be compounded by structural or solution processes. The problems, for instance, of protecting sources in fissure-flow aquifers, and especially in limestones with extensive karstification, are great, and so far the tools to meaningfully simulate such systems and delineate protection zones on a routine basis have not yet been developed. Even in those systems where darcian flow predominates, extensive field data are required to model such systems precisely, and as such information is often lacking, it may need to be interpolated or approximated from other sites.

While this does place a practical constraint on the ability of models to represent the flow regime, it must be remembered that the zoning process, like the groundwater system it operates on, is dynamic. No zone is immutable, because groundwater conditions may change, or because further information may come to light which enables the aquifer to be more accurately represented. Equally, whilst accepting that many hydrogeological flow systems show complex behaviour in detail, especially very close to the well, such local inhomogeneities are less critical at the scale at which protection zoning is carried out. In most situations, existing simulation techniques, applied through a sound conceptual model, can provide acceptable results.

Finally, it may be helpful to restate the non-prescriptive theme of the GPP, following from its consultative and non-statutory nature. This is reflected in the stance of the NRA with respect to updating and refinement of zones as new information becomes available. The NRA welcomes further information which would help to refine the zones around sources, and could be incorporated for future updates. This could come, for instance, from the acquisition by developers of further field data, during a site investigation or environmental impact study prior to a development application, whose incorporation after validation would lead to an improvement in the conceptual model on which a particular simulation was based. Similarly, an operator may be able to provide water quality data from pollution incidents, or from the distribution and behaviour of natural tracers, or from commissioned artificial tracer work, which sheds light on flow patterns through an aquifer unit or near a particular source.

15 National Rivers Authority 1995: Small Source Protection Zone Delineation.

3 APPLICATION OF PROTECTION ZONES

3.1 INTRODUCTION

The Groundwater Protection Policy provides a framework for making decisions about the acceptability of proposals to develop and manage land developments that may pose a threat to the underlying groundwater. Protection of groundwater is only one of the many factors to be taken into account in such decisions. It has not historically been given due attention, partly because the technical issues are difficult to understand and the decisions are made by non-specialists (largely in the land-use planning arena). The concept of groundwater vulnerability has been introduced to improve comprehension. The conceptualisation of groundwater vulnerability is through the development and use of maps, in respect of the overall groundwater resource, and the defining and application of protection zones for individual and groups of abstractions.

3.2 POTENTIAL USES

The primary use of Groundwater Protection Zones is to signal that within specified areas there *are likely to be* particular risks associated with the quality and possibly the quantity of water abstracted from the related pumping stations, should certain activities take place on or within the land surface. They are, first and foremost, a screening tool to be used with caution when assessing specific activities.

Pollution prevention

To achieve the greatest efficiency in the use of available resources, pollution prevention advice should be aimed at those activities considered to be most threatening and in those locations where there could be the greatest impact. Groundwater Protection Zones fulfil this need. Pollution Control staff can carry out inventories of potential pollution sources within the defined zones and assess the risks using specified procedures or professional judgement. Preventative action can therefore be encouraged where the risks of impact on the groundwater user are greatest.

Planning

Regulatory bodies, other than the NRA, also have a significant influence over land use practices. It is important that they are aware not only of the issues of concern which could influence groundwater quality but also of the areas which are at greatest risk. The publication of the groundwater vulnerability map series achieves this in a general way for groundwater, but the definition of zones around boreholes expands the process in relation to the immediate concerns surrounding abstracted water. Since the policy statements in the GPP are linked to zones in many instances, it is important that they have been defined to reinforce the stance made by the NRA over individual developments.

Risk assessment

There is a need to explain to developers and others the likely or actual stance to new development in any given situation. The Policy document is only part of the picture for without the maps and zones the policy statements are difficult to implement. Groundwater Protection Zones in a published form will also be a useful aid to those industries who take a proactive stance to their existing facilities and assess the risks from on-going operations. Some companies who have widespread national operations will wish to prioritise according to the greatest need (risk). This has already happened to some extent with the use of the national groundwater vulnerability maps, however assessing risks on a more local scale requires finer detail.

The operator/owner of a groundwater abstraction should be aware of the provenance of the water that he uses or puts into supply. The water supply industry must be one of the few consumer supply businesses that does not know precisely where his raw material comes from and therefore has little influence on quality control. This is also true of other sensitive groundwater users such as brewers and mineral water suppliers. Knowledge of the catchment and subsequently the influences on it should be important to the water user. It in no way relinquishes the NRA's duties in groundwater protection, but rather assists them in ensuring that potentially polluting activities are noticed and assessed.

3.3 CHANGES TO GROUNDWATER PROTECTION ZONES

Groundwater Protection Zones may be subject to change as additional data become available or when the hydrogeological regime changes. In both cases the existing model will need to be refined and the zones redrawn where necessary. It must be noted that for areas of aquifer which are extensively abstracted, changes to one borehole catchment may have knock-on affects on adjacent sources. Where such conditions exist it is sensible for aquifer blocks to be modelled rather than individual abstractions.

The modelled zones will be issued into the public arena according to the standardised format as they become available. The trigger for changes to these zones could come from:-

- *within the NRA* : in response to changes in abstraction patterns or licensed quantities initiated by Water Companies or other abstractors. In this case judgements will be needed to assess whether the changes are sufficient to warrant remodelling. In some cases situations may occur where additional data is obtained from external bodies (for example as a result of site investigations). NRA staff should be alert to such data sources and set up systems to enable information gathering to take place between internal departments. A secondary situation could arise with the increasing development of regional models covering blocks of aquifer within which there may be many sources. These models are likely to have been developed and tested more rigorously and should be used, either to directly delineate protection zones, or to define the boundaries for smaller models with particle tracking capability.
- *bodies external to the NRA* who wish to independently validate or challenge the validity of zones since the application of policies related to them may have an influence on their interests. This Guide and associated Manual provides the methodology for delineating protection zones. It is open to anyone to rework all NRA data which is non-confidential, and is freely available in individual source evaluation reports, with additional data obtained from local investigations.
- *a joint initiative from NRA and developer* in cases where the modelled zone is recognised to be deficient because of the lack of data and/or resources put into the modelling. Zones which have an element of doubt about them are nevertheless valuable in that they flag possible risks to abstracted water quality which could impinge on the planning of new developments. Therefore any zone is better than no zone, providing the limitations are recognised. Where new development is proposed in such uncertain situations a more rigorous remodelling should be part of a risk/impact assessment

which must include the collection of new data through site investigation. The NRA would normally work with developers in such situations with the aim of producing better defined zones.

However any outside body who seeks to further investigate or construct an alternative GPZ should do so in the knowledge that:

- all investigations will be carried out at the outside bodies expense.
- the NRA will require a full explanation of any proposed changes to GPZ supported by any new field or scientific evidence.
- the NRA will reserve the right to reject any proposed GPZ changes on the grounds that they are not technically or scientifically proven.

Ultimately any differences of opinion between the NRA and outside bodies would have to be aired on appeal.

3.4 APPROPRIATE USE OF ZONE MAPS

Once each groundwater protection zone has been agreed and completed, it is the intention of the NRA to make it freely available to all interested bodies.

It must be re-emphasised that protection zones have no statutory status and are simply produced in order to advise NRA staff, other regulators and developers about the likely NRA attitude on a geographic basis. Because of the ephemeral nature of the zones, for the reasons given above, they are not being published as printed maps.

However, the maps must be considered in conjunction with the relevant groundwater vulnerability maps in order to obtain an overall representation of groundwater vulnerability over an area.

The zone maps and the policy statements must also be interpreted with caution. The policy is necessarily generic and local circumstances may warrant a more restrictive or relaxed approach. For example the presence and nature of Drift deposits can be a significant influence over the vulnerability of the underlying groundwater, but due to its variability the effect can only be determined by local site investigation. Similarly the depth to water table is an important factor, but again can only be determined locally. Thus differences in attitude to similar developments, in similar topographic locations, could arise due to these variable factors.

Care is also needed with regard to the scale of the published maps. There are inherent inaccuracies in interpreting geological and hydrogeological boundaries from published maps, which, when compounded with the inaccuracies of the modelling process, makes decision making based on the lines and policy statements alone a potentially dangerous matter.

Detailed interpretation of the mapped zones is best left to specialists who can take into account information, (or lack of it), which may mitigate the particular risks, and therefore make professional judgements. They will need to consider the information in the source evaluation reports together with any additional data submitted during a site investigation.

4 FACTORS CONTROLLING THE SHAPE OF ZONES

4.1 HYDROGEOLOGICAL FACTORS

The geometry of capture zones is dependent on the following hydrogeological factors :

- abstraction rate
- recharge (direct and indirect)
- permeability (hydraulic conductivity)
- effective porosity (specific yield)
- aquifer thickness
- hydraulic gradient and direction of groundwater flow.

and their influence in the delineation of steady-state protection zones is summarised in Tables 4.1 and 4.2 below.

The shape of a protection zone is largely a function of the form of the groundwater level surface and this is controlled by hydraulic conductivity, aquifer thickness, local aquifer boundary conditions, abstraction rates and recharge from rainfall and watercourses etc.

Inner protection zones are generally fairly simple in geometry and tend to be circular in form reflecting the cone of depression around an abstraction borehole. The areal extent of these zones is very sensitive to the assumed values of aquifer thickness and effective porosity, while the shape is sensitive to permeability.

The key factors in defining the geometry of Source Catchment Zones are recharge, the form of the groundwater surface and the catchment boundary conditions and the shape can vary from the simple to the complex as illustrated by Figure 4.1. Complex shapes can generally be attributed to :

- interference effects between groundwater abstractions
- groundwater/river interactions
- lateral variations in hydraulic properties
- model imprecision

of which, perhaps, interference between groundwater abstractions is the main cause of complex shapes. Long narrow protection zones can occur where the source is located at distance from the aquifer boundary and/or where the abstraction is small, the hydraulic gradient is relatively steep or the transmissivity is relatively high.

Outer protection zones are generally intermediate in shape between Inner and Source

TABLE 4.1
Factors Controlling the Shape and Area of Protection Zones

	Area	Shape
Inner and Outer Protection Zones	Abstraction rate Effective porosity Aquifer thickness Hydraulic conductivity (hydraulic gradient) Recharge	As for Area plus boundary conditions
Source Catchment Zone	Abstraction rate Recharge (direct and indirect)	As for Area plus hydraulic conductivity aquifer thickness boundaries (hydraulic gradient)

(The term hydraulic gradient is given in brackets as this factor is dependent on groundwater flow, aquifer thickness and hydraulic conductivity).

FIGURE 4.1
Examples of shapes of source catchment zones

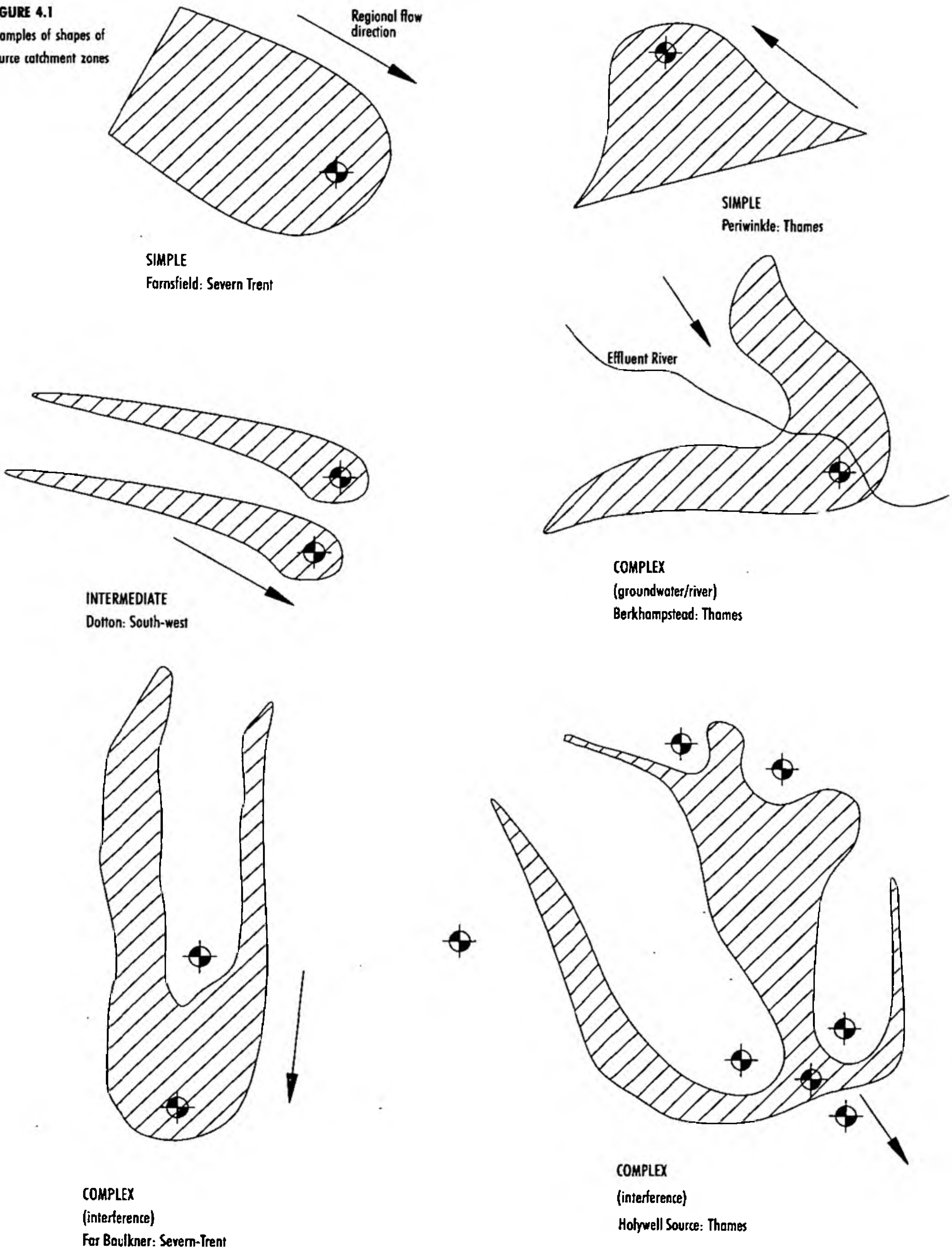


TABLE 4.2
Summary of Influences of Factors on the Geometry of Protection Zones

Parameters	Influences
Aquifer thickness	The aquifer thickness will determine the transmissivity of the aquifer and the volume of water in the aquifer and hence will directly affect the *area* of Inner and Outer Protection Zones and the *shape* of Protection Zones. A 50% decrease in aquifer thickness results in approximately doubling of the zone area and an increase in the width of the zone.
Effective porosity	Effective porosity has a direct affect on the *area* of the Inner and Outer Protection Zones. A 50% decrease in porosity results in approximately a doubling of the zone area.
Hydraulic conductivity	The hydraulic conductivity will mainly affect the *shape* of protection zones in terms of the width and the downgradient extent of the zone. An increase in hydraulic conductivity will decrease the width of the capture zone to a borehole.
Hydraulic gradient	The hydraulic gradient will affect the *width* and *downgradient extent* of the protection zone. The steeper the gradient the narrower the zone.
Abstraction rate	The abstraction rate will directly affect the *area* of protection zones. *Interference* between abstraction boreholes can significantly affect the *shape* of protection zones, producing 'tails' and 'holes'
Recharge (annual)	The rate of groundwater recharge will directly affect the *area* of the *Source Catchment Zone*, relatively small affect on Inner and Outer Zones.
Boundaries – no flow	No flow boundaries, faults and groundwater divides will constrain the *shape* of protection zones.
– recharge	Recharge boundaries will affect the *shape* and reduce the *area* of groundwater protection zones, particularly the Source Catchment Zone.

catchment zones and long narrow tails are rarely produced; when present however, they are generally the result of interference effects or marked lateral variations in transmissivity.

4.2 MODELLING AND SOURCE FACTORS

The accurate delineation of protection zones drawn is dependent on the quantity and accuracy of the data describing the aquifer system and the reliability of the conceptual model adopted. The geometry of the protection zone may also be influenced by the method used in its delineation. For example, manual or analytical methods generally produce simple shapes as these methods tend to simplify the hydrogeological system. In contrast, numerical groundwater models potentially allow relatively accurate protection zones to be drawn because they provide the closest approximation to the real system.

5 METHODS OF DELINEATION

Prior to the implementation of the GPP, a number of protection zone delineation methods were in use within the various NRA regions and by the Water Services Companies but, in general, there was a lack of consistency in approach, and many of the methods lacked a sound technical basis. One of the aims of this Guide is to review the general principles of capture zone delineation and to describe the currently recommended methodologies for defining source protection zones. A brief description of the available methodologies is given in this section, while the interested reader is referred to the associated manual for a more technical discussion of the subject.

The methods available for delineating source capture zones vary in complexity, from the declaration of simple arbitrary fixed radii circular zones, through empirical methods based on water balance calculations to three – dimensional computer modelling studies, although usage depends upon the availability of data and resources, and ultimately the acceptability of the method in the public domain.

Arbitrary fixed radii protection zones, although used extensively in the past, are not technically sound nor considered defensible in public.

Where aquifer data are poor or nonexistent, circular protection zones based on the recharge area required to support the abstraction under average conditions may be delineated. If estimates of the saturated aquifer thickness are also available, then circular time of travel zones may also be defined based on aquifer blocks with a volume equal to that pumped out during the required period.

If estimates of aquifer permeability, saturated thickness and hydraulic gradient are available, then analytical formula, based on the assumptions of an infinite, isotropic and homogeneous aquifer may be used to derive the capture zones.

The empirical and analytical methods do not allow for interference effects between neighbouring sources nor for variability in aquifer characteristics to be considered, and for these situations numerical modelling techniques are more appropriate. However, the additional data requirements must not be ignored.

The following mathematical models have been used, within the GPZ programme, to delineate protection zones :

- WHPA: semi-analytical model
- FLOWPATH: two-dimensional steady-state numerical groundwater flow model
- MODFLOW/MODPATH: two/three dimensional steady-state/time-variant groundwater flow and particle tracking models

and worked examples, illustrating their usage are given in the associated Manual.

The WHPA and FLOWPATH models were prescribed for use in phases I & II of the GPZ project following a review by BGS of the available model codes, while the MODFLOW/MODPATH combination has been used in a number of specific cases where a more sophisticated numerical model was considered necessary. The use of time variant models is likely to become more widespread in the future when upgrading existing protection zones or for delineating new zones as more relevant data becomes available or as conceptual models of specific aquifers become better developed.

Recommended procedures for delineating protection zones around small sources and springs, situations where numerical modelling techniques are unlikely to be appropriate because of their restricted resolution, are available from the NRA[16].

The delineation of protection zones around sources is often complicated by the existence of adits because they can distort the flow field by providing preferential pathways for groundwater movement. However, models of adit hydraulics, or data on individual adit performance are not readily available, and to date empirical adjustments to maps generated using the methods discussed above have been utilized, (see Chapter 7).

The delineation of protection zones is complicated if a source abstracts groundwater from more than one aquifer or from a multi-layered aquifer. Groundwater flow may vary between horizons or a vertical hydraulic gradient may exist thereby inducing leakage between the aquifer units. In such cases, it is not considered practicable to give a set of procedures but rather to note that each multi-layered aquifer situation will need to be examined on a site-by-site basis.

Sources in Karstic aquifers also need to be looked at on a site – by – site basis. In such aquifers groundwater moves through systems of well developed underground conduits and caves formed by dissolution of the rock. But the unpredictability and heterogeneity of the aquifer means that the assumption of regional darcian flow is unlikely to be valid and computer simulation of groundwater flow based on the standard models inappropriate. In these circumstances, the interpretation of field data coupled with the use of tracer tests is often a more appropriate methodology, particularly for determining travel times. In the absence of tracer tests, however, recourse to empirical models, with suitable factors of safety to allow for the unpredictability of the fissure distribution may be necessary.

Where limestones are not karstified they may be more amenable to theoretical analysis of groundwater movement, although they too will invariably be influenced by topography (dry valleys), jointing and fissuring and careful consideration of these will need to be taken in GPZ definition.

However, this does not totally invalidate the use of such models when considering Chalk aquifers, although in such circumstances additional care should be taken. The results can produce a 'first pass estimate GPZ' for further discussion and validation. Model use should really be viewed as another available tool, and together with other information can be used towards producing the best estimate GPZs for a karstic source. In karstic environments the results from empirical models should not be considered as the only available answer.

16 National Rivers Authority 1995: Small Source protection Zone Delineation.

6 SENSITIVITY ANALYSIS

The size, shape and location of Inner, Outer and Source catchment zones are largely controlled by hydrogeological parameters which, in general, are poorly defined. From this it follows that confidence in the predicted zones is limited by the uncertainties in the parameters concerned.

The groundwater model developed using the most likely combination of hydrogeological parameters will, by definition, produce the best estimate of the required zones. However, a model with a less plausible, but nevertheless realistic, set of parameter values may also produce an acceptable calibration, but result in zones which differ substantially from the best estimate. The non – uniqueness of groundwater model solutions has been acknowledged within the GPZ programme and a methodology, based on a systematic sensitivity analysis of the imprecisely known model parameters, developed to delineate what have been termed the 'zone of confidence' and the 'zone of uncertainty' associated with the best estimates of each zone.

These two zones are constructed graphically, usually in a CAD environment, and are defined as:

a) *zone of confidence*: the region which is common to all the capture zones derived using a specified combination of hydrogeological parameters which maintains the model calibration within acceptable limits,

b) *zone of uncertainty*: the area lying within the boundaries of all the capture zones derived using the same set of model parameters.

Examples of the best estimate catchment and zones of confidence and uncertainty around the Edgmond Bridge and Bearstone sources in the West Midlands are illustrated in Appendix 1.

The parameters which are usually varied to allow the construction of the two zones are recharge and hydraulic conductivity. The acceptable ranges of the two parameters are established by varying them systematically around the best estimate value, running the model and noting the bounds within which the calibration targets are satisfied. Sensitivity runs, using parameter values from within the acceptable range are subsequently carried out to compile the data used in zonal delineation.

In a typically well calibrated model, recharge multipliers in the range 0.8 – 1.2, and hydraulic conductivity multipliers within the range 0.5 – 2.0, (where a multiplier of unity represents the best estimate), and applied universally across the model, have been found to give satisfactory results, but the actual multiplier range needed to ensure the acceptable calibration of each specific model must be established before zonal delineation is carried out.

Zones of confidence and uncertainty around the Inner and Outer protection zones are constructed using the same method once the best estimate solution has been developed, with an additional set of model runs obtained using multipliers for the effective porosity. Multipliers between 0.5 and 1.5 are typical, but the resulting time of travel zones are correspondingly more uncertain than the source catchment zone because of the influence of the additional unknown parameter.

Parameter uncertainty is a major consideration when delineating Inner, Outer and Source capture zones, and the identification of those areas which are a) definitely or b) possibly contributing to a zone has been found to be a useful tool in the development of groundwater protection strategies. However, it must be noted that the method does not take account of errors arising from the use of inappropriate or incorrectly set up models and therefore expert judgement remains central to the overall modelling and uncertainty assessment.

7 ADJUSTMENTS TO MODELLED ZONES AND MAP PRODUCTION

The final stage in the GPZ process is the translation of the output from the modelling or manual delineation process into final protection zone maps. This stage involves a sequence of modifications to the computed outputs which experience has shown is probably best carried out in a CAD environment. The general sequence is as follows:

- transfer of the computed zones into a CAD environment;
- final checks that the Inner and Outer zones meet the minimum criteria noted in the definitions of these zones;
- adjustment of boundaries;
- adjustments to deal with the problems of scale (minimum shape factors);
- map production and reproduction.

The Inner and Outer zone definitions require that certain minimum criteria are met in terms of zone size. The minimum radius of the Inner Zone must be 50 m, but in thick, high porosity aquifers for example, or for sources with small protected yields, the calculated or modelled Inner Zone radius may be less than this value in which case the mapped zone should be increased to satisfy the standard. If the source consists of multiple boreholes then the 50 m criterion should apply to them all. If the source has associated adits then a 100 m wide zone should extend along their length whilst within Zone II, increasing to 250 m if the adit extends beyond Zone II into Zone III.

For some sources located in thick, high porosity aquifers, the area of the calculated Outer (400 day) zone may be less than the recharge area required to support 25% of the protected yield. In these cases the models need to be rerun with increasing travel times in order to derive, by interpolation, the zone which satisfies the minimum area rule. The computed 400 day zones should then be replaced by the 25% zone and mapped.

When drawing the boundaries to the protection zones, actual geological and hydrogeological features should be used rather than model boundaries wherever possible, although the difficulties in doing so, particularly where the boundaries are vague or variable is recognized. A good general convention is to draw and label actual boundaries where these are known and firm and indicate model boundaries where the boundary is indistinct, again with suitable labelling to make this clear to the map user.

A further degree of judgement is often required when dealing with **confining layers**. Where there is a substantial and proved confining layer around a source, the Inner protection zone (with the exception of the minimum 50 m radius) is not normally shown. However, on occasions, where there are known or planned major man-made subsurface structures such as tunnels or access shafts the Inner zone should be shown.

The Outer zone is only shown where the relevant recharge area is within the 400 day travel time or is part of the minimum 25% equivalent recharge area for this zone. The Source Catchment zone outside the confined zone is shown by definition. Where a possible confining layer or low permeability cover occurs around the source, this area is identified on the protection zone maps using hatched shading. This is to indicate an element of doubt regarding the degree of protection afforded by the cover; it may or may not have been represented in the modelling process, though normally a low recharge zone would be incorporated around the source. The NRA reserves the right to take account of the effectiveness of the cover on a site-by-site basis, based on local knowledge.

Due to interference effects and the precision with which computer models delineate capture zone boundaries, zones with relatively thin tails or holes within or between adjacent zones can be produced. Wherever such tails arise, they should be truncated at a minimum radius of 50 m. This is an arbitrary measure but is consistent with the minimum 50 m radius for Inner zones and prevents the maps from appearing impossibly precise.

Groundwater protection maps available for public inspection should be produced to a format consistent with published OS and BGS maps and the scale should be appropriate for its intended usage. Thus, typically maps showing inner and outer zones could be produced at a scale of 1:25,000; source catchment zone maps for individual and small groups of sources could be produced at the 1:50,000 scale, and synoptic maps for larger sources, groups of sources and resource protection zones could be produced at the 1:100,000 scale, although other scales should be used if appropriate.

The increasing availability of digital data from the Ordnance Survey and elsewhere allows the production of accurate base maps showing relevant information upon which the delineated protection zones may be superimposed. This process is readily carried out using CAD facilities, and indeed was used to assist in the derivation of the 'hard' field boundaries from the 'soft' model boundaries as part of the NVZ studies. However, published map data is likely to be covered by copyright and the use of such material should only carried out with the permission of the owner of the copyright.

APPENDIX 1

GLOSSARY OF TERMS

Abstraction
removal of water from groundwater, usually by pumping

Aquifer
permeable strata that can transmit and store water in significant quantities

Artesian flow
overflow of groundwater where water rises under pressure above the top of the aquifer

CAD
Computer Aided Design

Capture zone
area around a source which contributes water to the discharge

Conceptual Model
a description of the factors and processes governing groundwater flow in a clearly defined block of aquifer

Confined
where permeable strata are covered by a substantial depth of impermeable strata such that the cover prevents infiltration

Darcy's Law
an empirical equation which relates the flow of water in an aquifer to the area through which flow can occur, the permeability of the rock and the hydraulic gradient

Darcian flow
groundwater flow which obeys Darcy's Law eg intergranular flow

Drift deposits
term used to include all unconsolidated superficial deposits (eg, fluvioglacial, alluvium etc) overlying solid rocks

Effective Porosity
that part of the total porosity which can transmit water

Effective Rainfall
proportion of rainfall that can infiltrate to an aquifer after evapotranspiration and run-off

Evapotranspiration
loss of water from the land surface through the transpiration of plants and evaporation from the soil

Fractures/fissures
natural cracks in rocks that enhance rapid water movement

Head
groundwater height above a reference level

Hydrogeological characteristics
properties relating to flow of water through rocks, eg permeability, transmissivity, porosity etc

Hydraulic gradient
rate of change of groundwater potential or head per unit distance in the direction of flow

Impermeable
having texture that does not permit water to move through it under the head differences ordinarily found in subsurface waters

Intergranular flow
groundwater flow between individual rock grains which obeys Darcy's Law

Outcrop
where strata are at the surface, even though they may be obscured by soil cover

Particle tracking
mathematical technique employed in groundwater models to determine flow paths

Permeability
measure of a rock's capacity to transmit water

Porosity
ratio of the void space to the total volume of the rock

Protected Yield
The abstracted quantity used in deriving each GPZ.

Protection Zone
an area of land which the water regulatory authority has determined should be delineated around a source or over a catchment in order to provide a degree of protection against a range of activities

Radial Flow
radially symmetrical groundwater flow centred on a pumped borehole

Recharge
water which percolates downwards from the surface into groundwater

Source
point of abstraction of water eg well, spring, borehole

Specific yield
the amount of water in storage released from a column of aquifer of unit cross section under unit decline in groundwater level

Unconfined
an aquifer in which the water surface is formed by the water table which is free to fluctuate under atmospheric pressure and can thus reflect changes in storage in response to abstraction & recharge.

Spring
natural emergence of groundwater at the surface

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APPENDIX 2

EXAMPLES OF PROTECTION ZONES – Edgmond Bridge

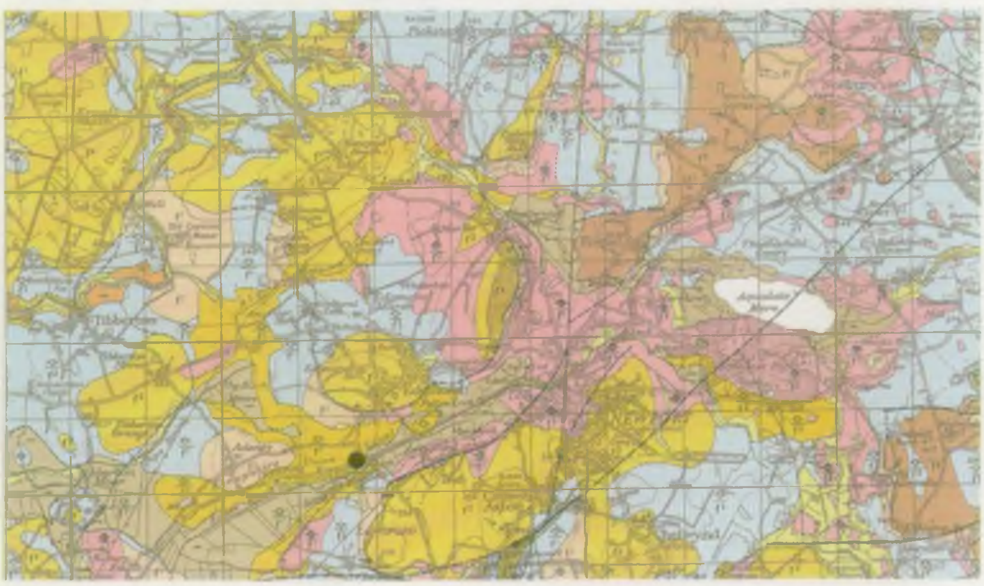
Conceptual Model/Hydrogeological Setting

In this area up to 150 m of Sherwood Sandstone strata dip gently east and beneath Keuper Marl. At outcrop a mixed glacial sequence, comprising glacial sands and gravels, peat and boulder clay covering the valley floor areas may be locally extensive and consequently recharge is subject to areal variation.

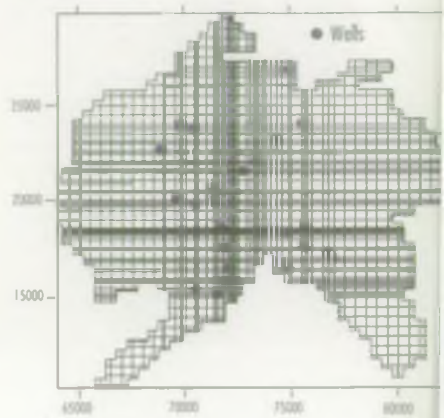
To the west the sandstones extend many kilometres towards Shrewsbury. To the south they are bounded by carboniferous strata and to the north a groundwater divide is assumed where the catchment definition is unclear.

Site map (extract from OS sheet 127)

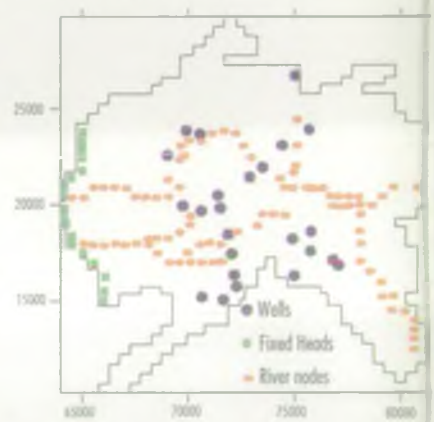
Geological map (extract from BGS map 139)



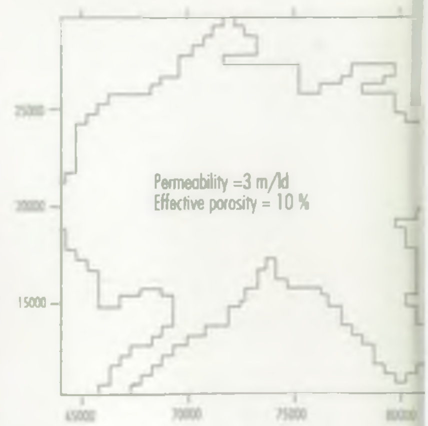
Model grid



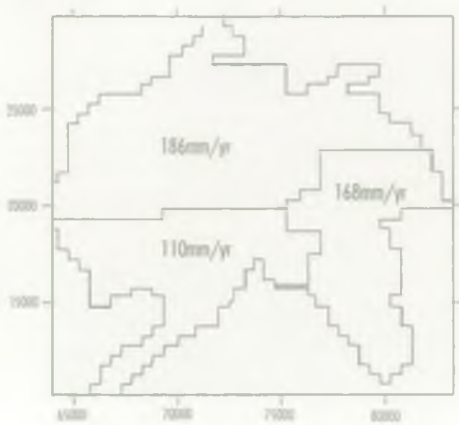
Internal boundaries



Aquifer characteristics

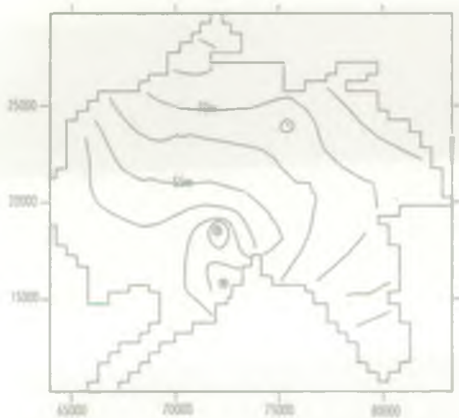


Recharge

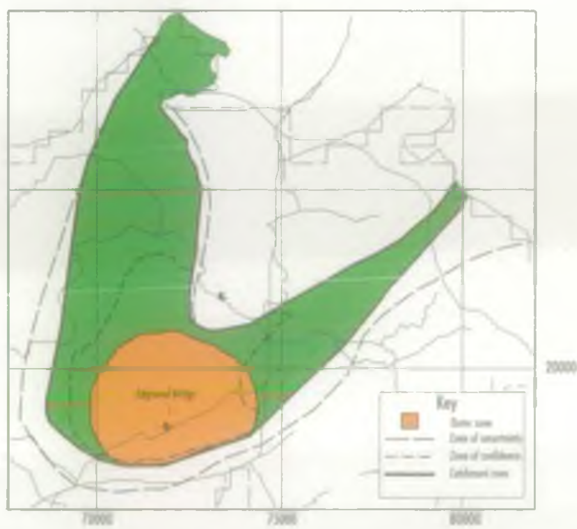


Inner Zone

Groundwater contours



Source Catchment Zone



Pathlines

Assessment of Uncertainties
The main uncertainty in this model relates to the relative paucity of hydrogeological detail particularly with respect to calibration against known or realistic groundwater heads and the vertical and lateral variation in permeability.

Assessment of Confidence
The zones have been graded : Inner C, Outer C, Source C. The outer zone was calculated as 25% of the total zone. The source catchment zone is considered to be the best estimate given the limitations of the current field data, but may not be defensible if further data becomes available.

APPENDIX 2

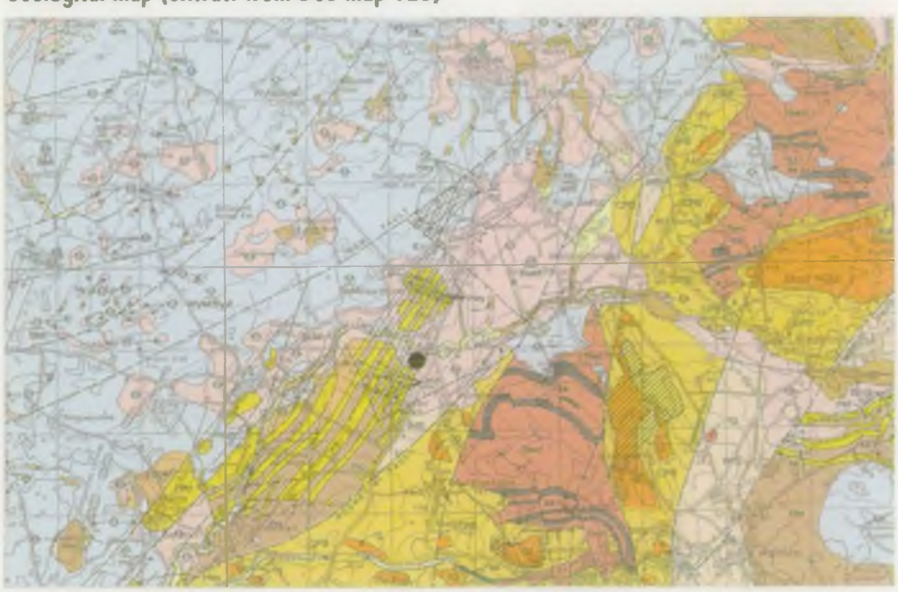
EXAMPLES OF PROTECTION ZONES – Bearstone

Conceptual Model/Hydrogeological Setting

The Sherwood Sandstone dips to the west with the main aquifer comprising the Wilmslow Sandstone and the lower part of the Helsby Sandstone. The aquifer is overlain to the west by the poorly permeable Upper Helsby Sandstone and the Tarporley Siltstone making it locally confined as far west as the Norton and Wem faults (c 1.5 km) which can be taken as the effective western boundary. The aquifer thins to the east and unconformably overlies the Keele Beds which are mainly Mudstone. The aquifer outcrop is a narrow band some 1 km wide and is overlain by permeable (sandy) drift. It is crossed by the River Tern which can be taken to be hydraulic continuity. Little hard information is available on aquifer characteristics but a value of 1.25 m/d for the permeability would seem reasonable. An effective porosity of 15% is typical for this aquifer, with a confined storage value of 10-4.

Site map (extract from OS sheet 127)

Geological map (extract from BGS map 123)



Manual metho

Available data

Abstraction Rate(m

Aquifer Thickness (

Effective porosity (

Annual Recharge (i

Hydraulic Gradient

Direction of flow

A) Source catchment zone

Area

The corresponding circular zone of equivalent area h
1000 m in the vicinity of the source. Therefore an int
has been used to construct the catchment zone assum
the outcrop geometry.
Zones of confidence and uncertainty, assuming a rec
methodology.

B) Time of travel zone

Area

Inner zone (time = 50 days)

Area

and radius of circular zone of equivalent area

Outer Zone (time = 400 days)

Area

This is less than 25% of the source catchment area
circular zone of area 1.78 km² (25% of 7.1 km²)
beyond the aquifer boundary and thus the interpola

af zone delineation

	4982
	160
	15
/yr)	256
	Unknown
	Unknown

$$\frac{\text{Annual abstraction}}{\text{Annual recharge}}$$

$4982 \times 365 / 0.256\ m^2$

$7.1\ km^2$

radius of 1500 m but the width of the outcrop is less than
olation procedure, carried out within a CAD environment,
it is circular and centred on the source, but truncated by

e variation of +/- 20% are deduced using the same

$$\frac{\text{Abstraction Rate} \times \text{Time}}{\text{Aquifer Thickness} \times \text{Effective porosity}}$$

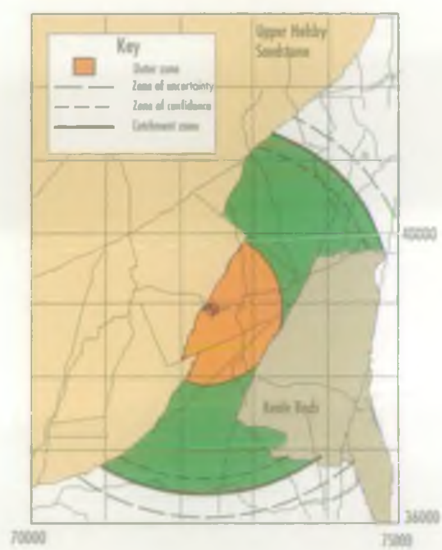
$4982 \times 50/(160 \times 0.15) m^2$
$10379 m^2$
57m

$4982 \times 400/(160 \times 0.15) m^2$
$83033\ m^2$

herefore must be increased to that value. The radius of the
D m, which, when centred on the source, again extends
procedure must be used to delineate the required zone

Inner Zone

Source Catchment Zone



Assessment of Uncertainties

The Inner, Outer and Source catchment zones have been calculated manually due to insufficient groundwater level data. The direction and gradient of the regional groundwater flow are both unknown.

Assessment of Confidence

The zones have been graded : Inner D, Outer D, Source D. The area of the Inner Zone should be good, providing the hydraulic gradient is not steep. The size of the Outer and Source catchment zones will also be good, but their location will depend on the actual direction of regional groundwater flow.

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GUIDE TO GROUNDWATER PROTECTION ZONES IN ENGLAND AND WALES

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In 1992 the National Rivers Authority published its Policy and Practice for the Protection of Groundwater. The implementation of the policy depends upon the definition of groundwater source protection zones and the preparation of vulnerability maps. This guide is one of two volumes which provide the background to the production and use of these two policy tools and complement the original policy document.

The companion volume to this guide is the *Guide to Groundwater Vulnerability Mapping in England and Wales.*

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