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Groundwater Source Protection Zones – Review of Methods

Integrated catchment science programme
Science report: SC070004/SR1

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Steve Killeen

Head of Science

Executive Summary

Source protection zones (SPZs) form a key part of the Environment Agency's policy and approach to controlling the risk to groundwater supplies from potentially polluting activities and accidental releases of pollutants.

Although the Environment Agency has defined SPZs for over 2,000 public potable supplies, major non-public potable and sensitive commercial supplies in England and Wales, there remains a need to update SPZs as circumstances change and to define them for new sources. This report updates the methodology for defining groundwater source protection zones.

A manual published by the Environment Agency in 1996 described the methodology to be followed to define SPZs. The subsequent 12 years have seen advances in available delineation techniques and in the use of geographical information systems (GIS). This is linked to increased availability of spatial data in electronic formats and the development of national databases such as the Water Resources GIS, Catchment Abstraction Management Strategy (CAMS) and the Environment Agency/British Geological Survey (BGS) aquifer properties manuals. The policy framework has also changed with GP3 (*Groundwater protection: policy and practice. Part 3 – tools*) replacing PPPG (*Policy and Practice for the Protection of Groundwater*), and the advent of the Water Framework Directive.

This report is a comprehensive revision of the 1996 original. It draws on advances in groundwater research over the period and changes in groundwater protection policy. It provides detailed guidance to Environment Agency staff, its contractors and other organisations and their consultants on the procedures and methods to be adopted in the definition of SPZs.

With over 10 years' experience in zone delineation and groundwater protection, the Environment Agency has reviewed the SPZs used and made some modifications to their definition. The revised definition of the zones is:

- **SPZ1 – Inner Protection Zone** is defined as the 50 day travel time from any point below the water table to the source. This zone has a minimum radius of 50 metres.
- **SPZ2 – Outer Protection Zone** is defined by a 400 day travel time from a point below the water table. The previous methodology gave an option to define SPZ2 as the minimum recharge area required to support 25 per cent of the protected yield. This option is no longer available in defining new SPZs and instead this zone has a minimum radius of 250 or 500 metres around the source, depending on the size of the abstraction.
- **SPZ3 – Source Catchment Protection Zone** is defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source. In confined aquifers, the source catchment may be displaced some distance from the source. For heavily exploited aquifers, the final Source Catchment Protection Zone can be defined as the whole aquifer recharge area where the ratio of groundwater abstraction to aquifer recharge (average recharge multiplied by outcrop area) is >0.75 . There is still the need to define individual source protection areas to assist operators in catchment management.

A fourth zone SPZ4 or 'Zone of Special Interest' was previously defined for some sources. SPZ4 usually represented a surface water catchment which drains into the aquifer feeding the groundwater supply (i.e. catchment draining to a disappearing

stream). In the future this zone will be incorporated into one of the other zones i.e. SPZ 1, 2 or 3, whichever is appropriate in the particular case, or become a safeguard zone.

Delineation of a protection zone is not simply a modelling approach but combines a number of stages as follows:

1. Data collation and conceptualisation
2. Calculations, modelling and hydraulic capture zone production
3. Technical review of hydraulic capture zones with modification, where appropriate, of the zone boundaries to produce the final SPZs
4. Documentation and publication of final SPZs.

The revised manual details the recommended approach for these four stages.

Contents

1	Introduction	1
1.1	Objectives	1
1.2	Definition of groundwater source protection zones	2
1.3	SPZ determination procedure	2
1.4	Environment Agency's role and responsibilities	4
2	Source protection zones	7
2.1	Background	7
2.2	SPZ1 – Inner Protection Zone	9
2.3	SPZ2 – Outer Protection Zone	9
2.4	SPZ3 – Source Catchment Protection Zone	12
2.5	Protected yield	13
3	Factors controlling the geometry of hydraulic capture zones	16
3.1	Hydrogeological factors	16
3.2	Field data factors	21
3.3	Assumptions and limitations of calculations and models	22
3.4	Model specific issues	23
4	Source protection in special cases	27
4.1	Karst sources	27
4.2	Kinematic porosity and sandstone sources	33
4.3	Small sources	35
4.4	Sources with limited data	36
4.5	Spring sources	37
4.6	Heavily abstracted aquifers	37
5	Data collection and the conceptual model	40
5.1	Data collection	40
5.2	Assessment of data	44
5.3	The conceptual model	45
6	Defining hydraulic capture zones	47
6.1	Previous modelling tools	47
6.2	Choice of technique	47
6.3	Translating conceptual models into hydraulic models	51
6.4	Manual methods	51
6.5	Simple manual methods and analytical solutions	52
6.6	Analytical element models	56
6.7	Recommendations for updating FLOWPATH models	60
6.8	More complex models	60

6.9	Adits and other elongate sources	61
6.10	Model procedures and guidance	63
6.11	Uncertainty	64
6.12	Transfer of calculation output to GIS	65
7	Definition of SPZs	66
7.1	Initial zone definition steps in GIS	66
7.2	Adits and other elongate sources	67
7.3	Minimum shape factors	67
7.4	Adjustment of boundaries	68
7.5	Final checks on SPZ compliance	71
7.6	Delivery of final SPZs	72
8	Quality assurance, reporting and publication	74
8.1	Quality assurance	74
8.2	Source evaluation reports	75
8.3	Review	76
	List of abbreviations	77
	References & Bibliography	78
	Appendix A: Outer zones and Permo-Triassic Sandstone	85
Table 2.1	Summary of protection zones in Europe, Australia and the USA	15
Table 3.1	Factors controlling the shape and area of hydraulic capture zones	18
Table 3.2	Influences on the geometry of hydraulic capture zones	18
Table 3.3	Possible problems when transferring field data to a model	21
Table 4.1	Recommended techniques to delineate small source protection zones	39
Table 6.1	Hierarchy of hydraulic capture zone delineation approaches	49
Table 6.2	Advantages and disadvantage of different methodologies for hydraulic capture zone delineation	50
Table 6.3	Assessed analytical element modelling packages	58
Table 6.4	Approaches for uncertainty analysis	65
Table A.1	Size of outer hydraulic zone	86
Figure 1.1	Overview of SPZ definition process	6
Figure 2.1	Influence of pumping rate, kinematic porosity and aquifer thickness on a 400-day time of travel zone	11
Figure 2.2	Equivalent travel time for minimum radius of 250 and 500 m	12
Figure 2.3	Schematic representation of Inner, Outer and Source Catchment Protection Zones	13
Figure 3.1	Source capture zone and the zone of influence around a pumped well	17
Figure 3.2	Example source catchment zone shapes	20
Figure 3.3	Influence of model grid spacing on zone definition	24
Figure 3.4	Influence of stream partial penetration on capture zones	25
Figure 3.5	Influence of calibration of groundwater levels on protection zone definition in a thin unconfined aquifer	26

Figure 4.1	Radius of 50 and 400 day travel time zone dependent on kinematic porosity	34
Figure 4.2	Application of the heavily exploited aquifer method	38
Figure 5.1	Example of a conceptual model prepared for SPZ delineation	41
Figure 6.1	Protection zone delineation using volumetric flow method	53
Figure 6.2	Capture zone to borehole located in uniform flow field	55
Figure 6.3	Example application of WHAEM to define hydraulic capture zones	59
Figure 6.4	Minimum dimensions of zones around wells with adits	62
Figure 7.1	Modifications of hydraulic zones using minimum shape factors	68
Figure 7.2	Final modification of hydraulic zones	69
Figure 7.3	Modifications of hydraulic zones to comply with minimum distance criteria	72
Figure A.6	Modification of 400-day hydraulic capture zone	91

1 Introduction

The Environment Agency originally published Version 1.1 of this manual in August 1996. The subsequent 13 years have seen advances in available delineation techniques and in the use of geographical information systems (GIS). This is linked to increased availability of spatial data in electronic formats and the development of national databases such as the Water Resources GIS, Catchment Abstraction Management Strategy (CAMS) and the Environment Agency/British Geological Survey (BGS) aquifer properties manuals. The policy framework has also changed with GP3 (*Groundwater protection: policy and practice. Part 3 – tools*)¹ replacing PPPG (*Policy and practice for the protection of groundwater*),² and the advent of the Water Framework Directive.³

This new review and manual is a comprehensive revision of the 1996 original. It draws on advances in groundwater research over the period and changes in groundwater protection policy to present up-to-date methodologies to aid source protection definition. With over 10 years' experience in the application of source protection zones (SPZs) to protect groundwater, the Environment Agency has reviewed the SPZs used previously and made some modifications.

1.1 Objectives

This manual provides the technical background to groundwater capture zone delineation. It has three objectives:

- To outline the Environment Agency's approach to the protection of groundwater sources as part of its national policy of groundwater protection as set out in *Groundwater Protection: Policy and Practice. Part 3 – tools* (GP3) (Environment Agency 2007a);
- To provide detailed guidance to Environment Agency staff, its contractors and other organisations and their consultants on the procedures and methods to be adopted in the definition of SPZs;
- To describe and update methods that can be used for SPZ delineation.

This manual is an output from an Environment Agency research project to:

- review the scientific, technical and policy basis for future protection and safeguard zones around groundwater abstraction sites;
- review and recommend cost-effective options for delineating such zones.

¹ Environment Agency 2007a

² NRA 1992

³ See <http://www.environment-agency.gov.uk/research/planning/33106.aspx> for information about the Water Framework Directive.

1.2 Definition of groundwater source protection zones

GP3 uses two methods for mapping the potential risk to aquifers from polluting activities:

- groundwater vulnerability mapping;
- determination of source protection zones (SPZs).

SPZs indicate those areas where groundwater supplies are at risk from potentially polluting activities and accidental releases of pollutants. SPZs are primarily a policy tool used to control activities close to water supplies intended for human consumption. The final SPZ is strongly based on model outputs, but may be modified to allow for uncertainty, information or local knowledge that cannot be modelled. This means that the production of most SPZs is a two-stage process. The first stage is the production of time of travel areas and total catchments using modelling or manual methods as appropriate. This is followed by technical review and, if necessary, boundary adjustment to produce the actual SPZ.

SPZs have been defined for nearly 2,000 groundwater sources. These are wells, boreholes and springs used for major potable uses, in particular public drinking water supply. Three zones have typically been defined:

- **SPZ1 – Inner Protection Zone** is defined as the 50-day travel time from any point below the water table to the source. This zone has a minimum radius of 50 metres (Section 2.2).
- **SPZ2 – Outer Protection Zone** is defined by a 400-day travel time from a point below the water table. The previous methodology gave an option to define SPZ2 as the minimum recharge area required to support 25 per cent of the protected yield. This option is no longer available in defining new SPZs (Section 2.3).
- **SPZ3 – Source Catchment Protection Zone** is defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source. In confined aquifers, the source catchment may be displaced some distance from the source (Section 2.4).

A fourth zone, SPZ4 or '**Zone of Special Interest**' was defined for some sources. This usually represents a surface water catchment which drains into the aquifer feeding the groundwater supply (i.e. catchment draining to a disappearing stream). In future, this zone either will be defined as a safeguard zone or it will be incorporated into one of the other zones ie. SPZ 1, 2 or 3, whichever is appropriate in the particular case (Section 2.1).

The **protected yield** is the rate of groundwater pumping from a source used to delineate each SPZ around that source. It is defined as the maximum authorised and sustainable rate of groundwater pumping that can take place from the source in question (Section 2.5).

1.3 SPZ determination procedure

The Environment Agency estimates that there are over 2,000 public potable supplies, major non-public potable and sensitive commercial supplies in England and Wales. It has defined SPZs for the majority of these, but there will remain a need to update SPZs as circumstances change and to define them for new sources.

There are also upwards of 70,000 small potable sources, of which a relatively large proportion are in secondary aquifers in rural areas where complex fissure flow may occur or where the local hydrogeology is not well documented. It will not be practicable or efficient to formally publish zones (using models or manual methods) around such sources. Nevertheless, a potable source is always assumed to have a default minimum Inner Protection Zone with a radius of 50 metres and a default minimum SPZ2 with a radius of 250m. The protection of small sources is discussed in Section 4.3.

This manual provides an update of the procedure for defining SPZs. The main changes to the previous manual are:

- changes in the procedure for definition of the SPZ2 (i.e. dropping the 25 per cent rule) and use of a default minimum radius of 250 or 500 m around the source;
- merging of SPZ3s where these cover a significant part of the aquifer outcrop;
- modifications in the shape of modelled SPZs to take account of other hydrogeological information that cannot be readily incorporated within many of the models;
- changes in the procedure for assessment of the uncertainty in SPZ boundaries;
- updating of the tools used to model hydraulic capture zones.

These changes have been introduced to provide a more pragmatic approach to SPZ delineation, reflecting an improved understanding of groundwater protection and its implementation. But they are also important to achieving zones that are robust in planning terms and which can be linked more firmly to the policies set out in GP3.

The Environment Agency does not intend to immediately revise previously defined SPZs. For the foreseeable future, it will only define new SPZs for new sources, or after significant licence amendments or where it receives credible information concerning the accuracy of existing SPZs. We may revise a SPZ if it is to be used for the basis of a Water Protection Zone or safeguard zone and we are not sufficiently confident of the existing delineation for that further use.

The determination of a SPZ refers to the overall process (Figure 1.1) that covers:

- data collation and conceptualisation;
- calculations, modelling and hydraulic capture zone production;
- definition of final SPZs, documentation/report, maps, review and publication.

The main phases are described in subsequent sections. Relevant Environment Agency Area and Regional staff should liaise closely throughout the SPZ determination process to ensure local knowledge/data are included.

It is worth emphasising at the outset that delineation of SPZs is not simply a modelling exercise. In fact, for many sources, modelling may not be the most appropriate method of SPZ definition. In these cases, the use of manual methods or default zone shapes is recommended.

Furthermore, it must be remembered that the SPZ process, like the groundwater system it operates on, is dynamic. No SPZ is immutable. Not only do groundwater conditions change, especially in extensively exploited aquifers, but also further information comes to light which enables the aquifer to be more accurately

represented. A point will eventually be reached, however, when the simulation of the natural system is sufficiently accurate that further effort on data collection and modelling will not significantly improve the accuracy of the delineated hydraulic capture zone. It is difficult to define objectively when this point has been reached. It is usually a subjective decision based on the perceived accuracy of a hydraulic capture zone and the costs of further data collection/modelling to improve the accuracy. Further alterations may be required when defining the formal SPZ from the hydraulic capture zone.

SPZ3 (sometimes called 'Capture zone') delineation is a good example of the iterative process inherent in all good modelling practice. Data are gathered, a conceptualisation of the system is derived and a model is set up, calibrated and results provided. Comparison with real conditions may prompt the collection of further data, which may amend the way the system is conceived to function, generating a need for further modelling, and so on.

It is also vital that a system of quality assurance is an integral feature of the SPZ determination process. This enables any existing SPZ to be scrutinised by a third party or provides an easy means to assess the methods used. We can then, if necessary, employ improved techniques as they become available and appropriate. The quality assurance system needs to extend beyond the actual SPZ determination stages to include accessibility to the input data available at the time, to the model codes used and the simulation runs, and to the output map/SPZ files.

1.4 Environment Agency's role and responsibilities

The Environment Agency has a statutory duty to monitor and protect the quality of groundwater in England and Wales, and to conserve its use for water resources. The Environment Agency's statutory powers and policy objectives in respect of groundwater are set out in the GP3 (Environment Agency 2007a). This document explains the Environment Agency's policy in relation to the control of activities that could give rise to pollution in SPZs.

The SPZ maps produced by the Environment Agency are a key resource to:

- help prioritise regulatory action on existing threats to groundwater;
- filter new (proposed) activities in applying policy for new development.

The Environment Agency has introduced a second stage to SPZ definition by allowing adjustments to account for uncertainty. In so doing the Environment Agency is demonstrating greater confidence in the application of GP3 policies in the SPZ. Activities or developments will be considered strictly as being either one side of the zone boundary or the other. If they straddle the line, the activity will also be considered inside.

The Environment Agency plans to only update SPZs in response to particular needs or programmes. Such updates may be in response to the availability of new data or a change in the authorised abstraction.

Where hydrogeological investigations associated with a proposed development cast doubt on the validity of existing SPZs, the Environment Agency may consider revision based on any relevant new evidence provided as time and resources allow. It may also consider revisions put forward by a third party provided they are fully compliant with the SPZ methodology. But given that the methodology aims to account for uncertainty and sets a basis for policy, this should not be done lightly. The Environment Agency will

only enter into such discussion where there is clear evidence that the basis for the existing zone is flawed.

The Environment Agency may also use SPZs as the basis for safeguard zones (European Commission 2007) or water protection zones. These will be used at sources at risk of groundwater pollution resulting in a deterioration in the quality of water abstracted leading to a likely increase in treatment needed to supply good quality water used for human consumption.

SPZs are also likely to underpin the development of Drinking Water Safety Plans (DWI 2005). These will require water companies to undertake a catchment risk assessment to identify activities which may pose a risk to abstracted groundwater quality and for which it may be appropriate to implement measures.

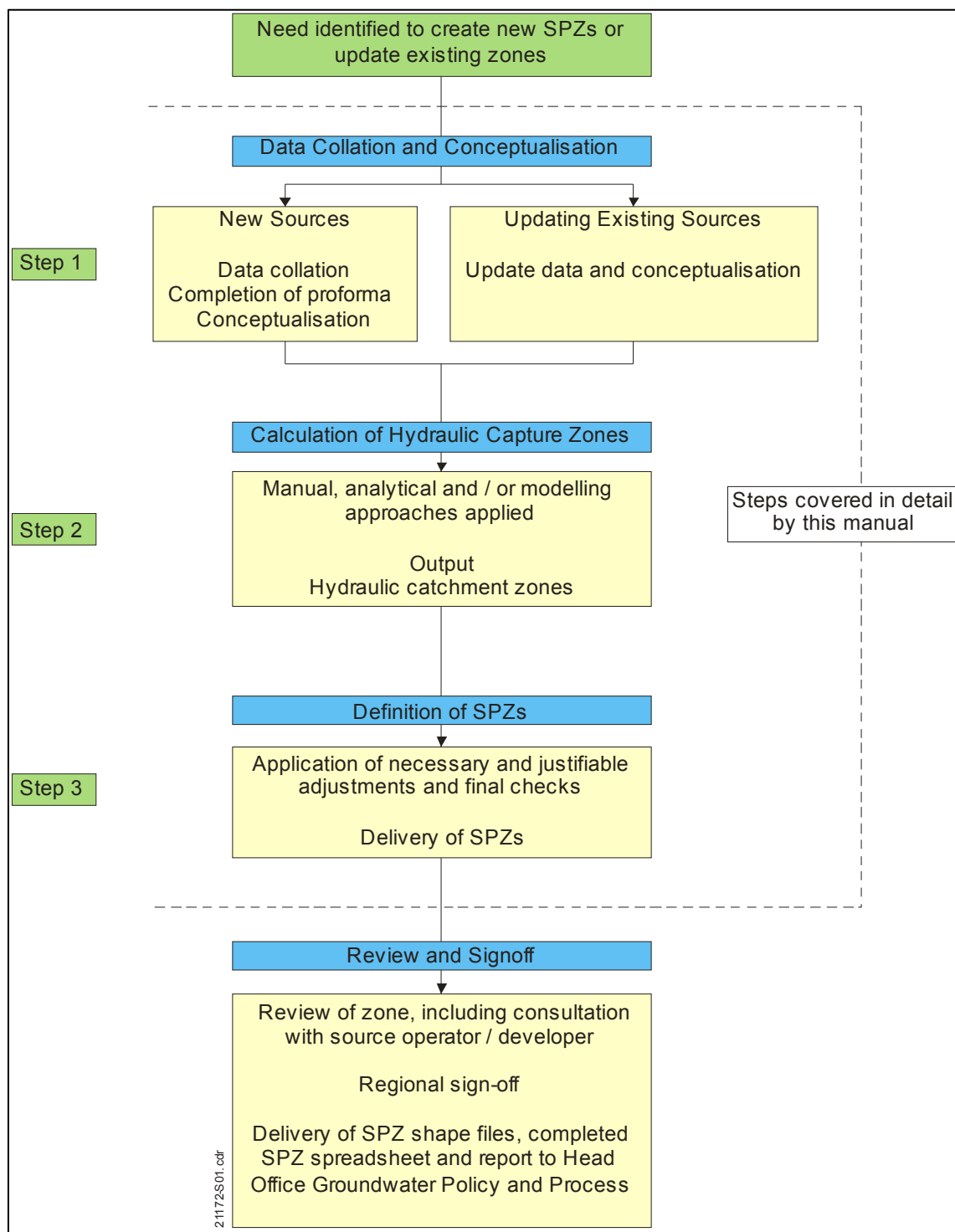


Figure 1.1 Overview of SPZ definition process

2 Source protection zones

This chapter describes the basis for defining inner, outer and catchment zones, and how and why they are defined. Note that some adjustments have been made to the definitions from the previous manual (PPPG; NRA 1992).

The Environment Agency's groundwater protection policy (GP3; Environment Agency 2007a) deals with the management and protection of groundwater from pollution. It includes the definition of groundwater source protection zones (SPZs) around individual sources to provide a means for assessing the risk of contamination by human activities. GP3 sets out policy statements linked to the acceptability of activities within SPZs.

2.1 Background

Below is a description of the zones as they were defined in the previous manual and the changes that are made later in this document :

- **SPZ1 – Inner Protection Zone** is defined by a 50-day travel time from any point below the water table to the source or a minimum 50-metre radius from the source, whichever is larger. It is located immediately adjacent to the well. It is designed to protect against the transmission of rapidly degrading toxic chemicals and some water-borne disease (Section 2.2). The Environment Agency's groundwater protection policy sets the tightest controls on human activity in this zone.

The SPZ1 boundaries are adjusted where the aquifer is confined beneath substantially low permeability material or where deep unsaturated zones or patchy drift cover are present (Section 7.4). This is a precautionary measure to guard against the case where rapid pathways for contaminant transport are present such as deep structures. The 50-metre radius inner protection zone is assumed by default for any potable source (licensed or not) in the absence of an SPZ defined formally and published by the Environment Agency.

- **SPZ2 – Outer Protection Zone** is defined as a 400-day travel time or, for existing SPZ2s, 25 per cent of the source catchment area, whichever is the larger. For future SPZ delineation the 25 per cent rule will be dropped as discussed in Section 2.3, though a minimum radius of 250 or 500 m will be defined around the source depending on the size of the abstraction. The 400-day travel time is based loosely on consideration of the minimum time required to provide delay, dilution and attenuation of slowly degrading pollutants (BGS 1991). The zone is generally not defined for confined aquifers (Section 2.3).
- **SPZ3 – Source Catchment Protection Zone⁴** is defined as the area needed to support the protected yield from long-term groundwater recharge. In areas where the aquifer is confined beneath impermeable strata, this source catchment may be located some distance from the actual abstraction.

⁴ Also referred to as the 'total catchment', Total Capture Zone or Catchment Protection Zone.

- **SPZ4 – Zone of Special Interest.** We will no longer define or use SPZ 4 – ‘Zones of Special Interest’. Where protection is needed we will define a Safeguard Zone or assign the appropriate SPZ 1, SPZ 2 or SPZ 3 to the area in question. The procedure for defining these zones is as set out in the Karst section in Section 4 below. We must use suitable justification in assigning the appropriate SPZ status to these areas.

The first two zones are based on the travel time of potential pollutants through the saturated zone. SPZ3 represents the recharge area.

SPZs were defined in the previous manual based on the recommendations of a project undertaken by the British Geological Survey (BGS) in 1991 to research the scientific background for groundwater protection in the recharge capture areas to critical sources. The only exception was that the introduction of the 25 per cent rule by the Environment Agency in the definition of SPZ2 because the use of a 400-day travel time zone in thick high porosity aquifers (e.g. Permo-Triassic Sandstone) resulted in relatively small zones that were considered to provide insufficient protection to sources (Section 2.3).

The Environment Agency subsequently defined SPZ4 or ‘**Zones of Special Interest**’ where local conditions required additional protection. These zones typically represent the surface water catchments to streams or areas of land draining into the aquifer from outside of the outcrop area. They must contribute a significant proportion of a groundwater source yield. This pathway, particularly for karst aquifers, can provide a rapid pathway for contaminants to migrate to the groundwater sources (travel times from the point of entry into the aquifer to the source can be of the order of hours or days)..

The **hydraulic capture zone** is defined as the 50-day, 400-day or catchment zone derived through the modelling process. The revised SPZ methodology introduces a formal step between the definition of the hydraulic capture zones and the SPZs. This process allows for pragmatic adjustments and is described in more detail in Section 7. These SPZs will influence the management of activities within the catchment to the source.

2.1.1 SPZ delineation in other countries

Other countries use protection zones to protect abstractions from human activities that could give rise to pollution. Table 2.1 (at the end of the chapter) provides a summary of the zones defined by 12 countries and international context for the zones defined by the Environment Agency. The approaches include:

- setting zones based on travel time and/or minimum distance;
- whole catchment.

There are some similarities in approach (e.g. use of ‘50 days’ and catchment protection zones). The majority of countries define the equivalent of an inner protection zone used principally to protect from pathogens. The travel time for this zone varies from 10 to 100 days, although is more commonly 50–60 days. The use of a 400-day travel zone or 25 per cent zone is unique to the Environment Agency.

The following sections provide the rationale for defining SPZs and set out the basis for the changes described in this document.

2.2 SPZ1 – Inner Protection Zone

The Inner Protection Zone is used to control a wide range of activities that could pose a significant risk to groundwater such as landfill, major developments and septic tanks (GP3; Environment Agency 2007a). The main purpose of this zone is to reduce the risk of pollution from rapidly degrading chemicals and some pathogens. While this is reasonable for some cases, there is evidence that some pathogens (particularly encysted protozoa and viruses) may persist for longer than the 50-day travel time below the water table (Taylor et al. 2004).

Groundwater quality monitoring for a large number of sources shows that contamination incidents continue to occur. Such incidents may indicate:

- the presence of rapid pathways;
- the persistence of pathogens – not only bacteria but spores, oocysts and viruses (greater than 50 days); and/or
- that activities giving rise to pollution within the Inner Protection Zone are not effectively controlled.

The definition of the Inner Protection Zone therefore incorporates some protective measures. These are:

- the use of maximum daily abstraction (see Section 2.5);
- a minimum radius of 50 metres;
- no allowance for any attenuation (e.g. decay, retardation etc) within the unsaturated zone.

The determination of the 50-day travel time zone relies on adequate definition of aquifer properties, in particular intergranular kinematic porosity. For example, in drawing the Inner Protection Zone for a groundwater source in the Permo-Triassic Sandstone, an intergranular kinematic porosity (typically 10–15 per cent) is often assumed, whereas tracer tests and water quality monitoring may indicate that contaminant movement is via fissures and a lower porosity (<2 per cent) may be more appropriate (see Section 4.2).

No changes to the criteria for defining the Inner Protection Zone are proposed here. However, the size of SPZ1 should be modified where tracer tests or water quality monitoring provide strong evidence of rapid movement of contaminants (including pathogens) such that the zone should be determined using:

- an appropriate intergranular kinematic porosity (e.g. fissure rather than intergranular porosity as discussed in Section 4.2); and/or
- manually adjusted to include the identified source and pathway (Section 7).

2.3 SPZ2 – Outer Protection Zone

SPZ2 is defined by the 400-day travel time or, for SPZs delineated under the previous methodology, by 25 per cent of the source catchment area, whichever is the larger. The 25 per cent rule tends to apply in thick high porosity aquifers such as the Permo-Triassic Sandstone where the 400-day travel time zone can be relatively small (several hundred metres across). This area of the travel time zone can be underestimated for one or both of the following reasons:

- Contaminant movement may be via fissures rather than by intergranular flow and, therefore, a lower kinematic porosity should apply. Tracer tests have provided evidence that fissure flow can occur over hundreds of metres in the Permo-Triassic Sandstone (Section 4.2) (Ward et al. 1998, Tellam and Barker 2006).
- The full aquifer thickness may have been assumed in defining the zone (based on borehole depth) whereas flow to the borehole may be drawn largely from specific horizons. As a result, the Darcy velocity and travel time zone will be underestimated.

These assumptions may result in insufficient protection to the groundwater source.

However, the travel time from the edge of the 25 per cent SPZ can be very large with travel times in the range of tens to hundreds of years. They are therefore inappropriate for the activities currently requiring control under GP3 such as pipelines and large industrial sites.

The continued use of the 25 per cent rule is, therefore, not recommended and the following modifications to the procedure for defining SPZ2 should be adopted:

- modification of the size of SPZ2 where tracer tests or other monitoring data provide strong evidence of a rapid pathway to the groundwater source (<400 days) (see Section 7.4);
- use of lower kinematic porosity or saturated aquifer thickness where available data indicate this is appropriate, i.e. contaminant movement is via fissure rather than intergranular flow (see Section 4.2);
- minimum radius of 250 m, though this should not extend outside the source capture zone for sources with a protected yield of <2,000 m³/day;
- minimum radius of 500 m for sources with a protected yield of >2,000 m³/day but not extending beyond the source capture zone.

In most cases, the 400-day hydraulic zone is likely to exceed the minimum radius; its purpose is to afford a minimum level of protection to the source and to provide a default zone where hydrogeological data are limited.

The influence of pumping rate, kinematic porosity and aquifer thickness is examined in Appendix A. Figure 2.1 illustrates the influence of these factors on the radius of a 400-day hydraulic zone (assuming a flat water table) and Figure 2.2 shows the equivalent travel times for default radii of 250 and 500 m.

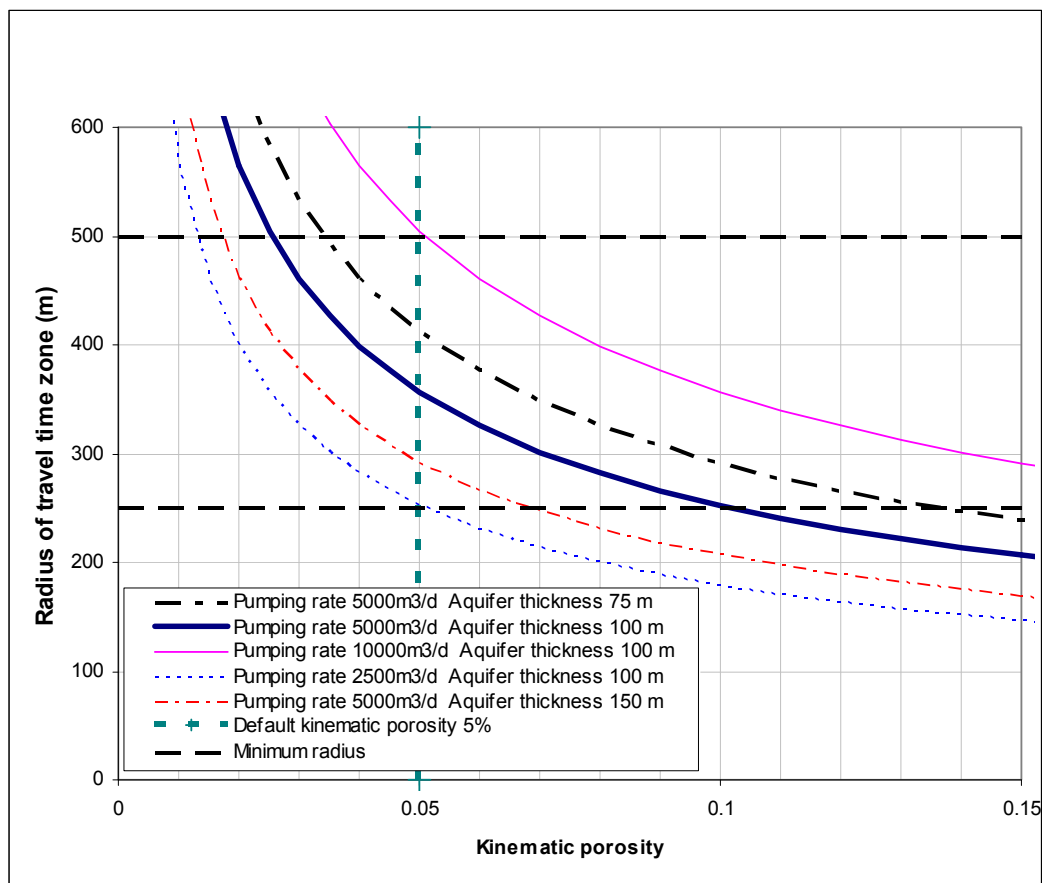


Figure 2.1 Influence of pumping rate, kinematic porosity and aquifer thickness on a 400-day time of travel zone

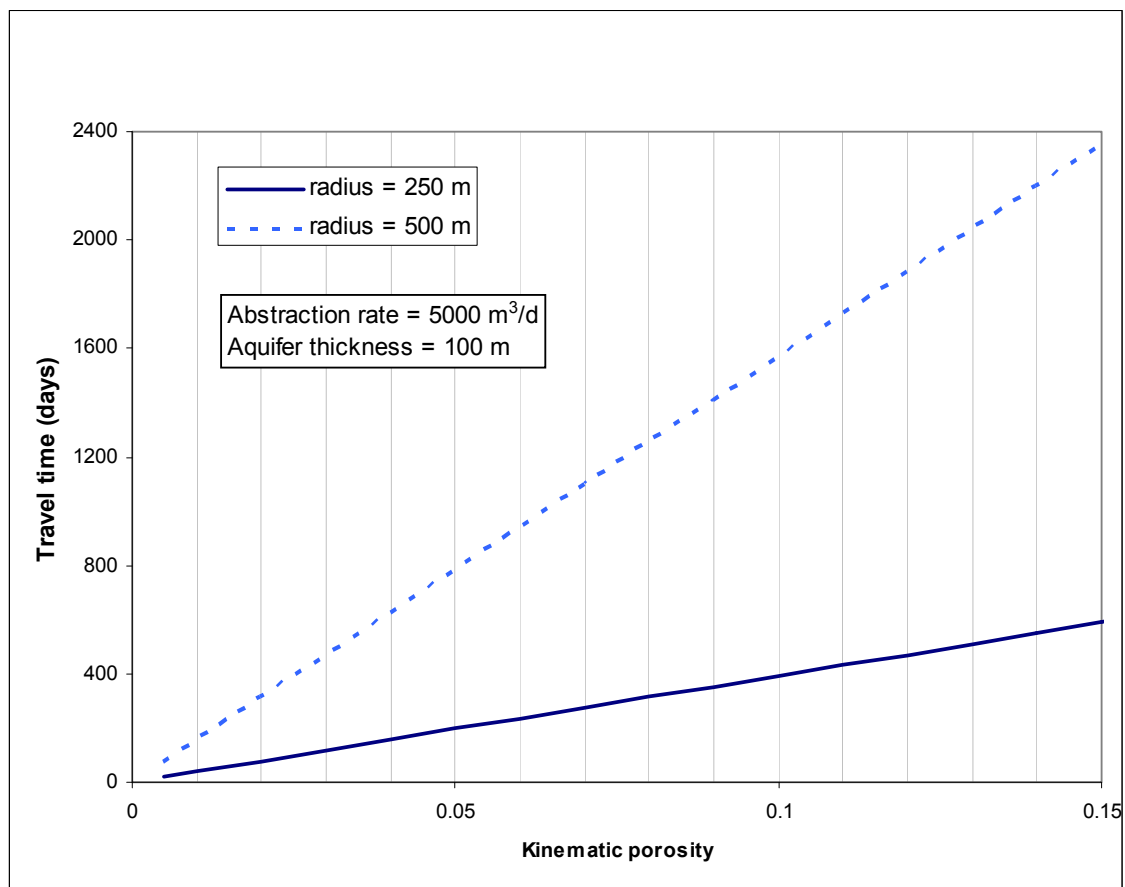


Figure 2.2 Equivalent travel time for minimum radius of 250 and 500 m

2.4 SPZ3 – Source Catchment Protection Zone

SPZ3 is defined as the area needed to support the protected yield from long-term groundwater recharge. For heavily exploited aquifers (i.e. groundwater abstraction represents a significant percentage of aquifer recharge), much of the recharge area will be covered by SPZs.

Due to the interference between abstraction boreholes and seasonal variations in groundwater flow, it is difficult to define individual Catchment Protection Zones with certainty. Existing SPZs can show gaps between them that can present problems in applying aquifer protection policies.

Under GP3, the main policy statements that apply to the SPZ relate to landfill location and diffuse pollution. These are similar to those applied to the aquifer as a whole. As a result, there can be limited benefit in defining individual Catchment Protection Zones.

To provide a more pragmatic approach to zone delineation, the Environment Agency has therefore taken the decision to define the entire outcrop area of a heavily exploited aquifer as the Catchment Protection Zone when the ratio of licenced abstraction to recharge is >0.75 . This ratio has been determined empirically based on a review of the existing SPZ cover in heavily exploited aquifers (there is no apparent benefit in providing a higher level of accuracy for Catchment Protection Zones). The scale of this assessment should be at Catchment Abstraction Management Strategy (CAMS) groundwater management units or groundwater body scale.

The Environment Agency will only produce SPZ 3 zones for sources, where it is necessary for the needs of other users of SPZs. This applies particularly to Water Companies and their statutory duties to produce Drinking Water Safety Plans that include assessment of risks to raw water quality and require knowledge of catchments (DWI, 2005).

The production, by the Environment Agency, where necessary of SPZ 3s for sources in heavily exploited aquifers with a ratio greater than 0.75, is aimed at preventing abstractors and regulators deriving and working with different zones.

SPZ3s may also play a future role in Safeguard Zones designated under the Water Framework Directive or Water Protection Zones.

Figure 2.3 gives a schematic representation of the three SPZ zones defined in this manual.

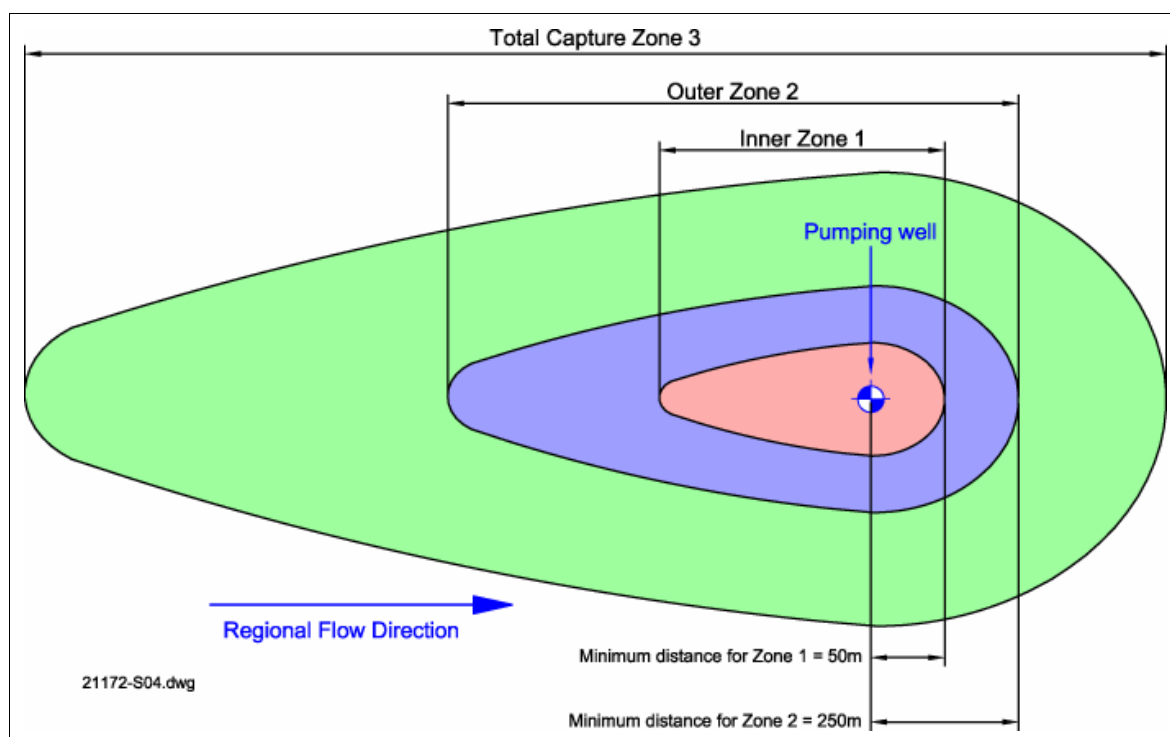


Figure 2.3 Schematic representation of Inner, Outer and Source Catchment Protection Zones

2.5 Protected yield

The protected yield of a source is the groundwater pumping rate used to delineate each SPZ around that source.

Ideally, it should be based on the following rates taken from the abstraction licence for the source:

- licensed maximum daily quantity regarded as the protected yield and used to derive the SPZ1 for the source;
- licensed annual quantity divided by 365 to give the protected yield and used to derive the SPZ2 and SPZ3 for the source.

The protected yields associated with the SPZs of each source should be established as early in the delineation process as possible and when considering the conceptual model.

Protected yields can be less than the licensed quantities in the following circumstances:

- **Licensed quantity unobtainable.** This is usually when the maximum licensed daily quantity exceeds the hydraulic capacity of the borehole or aquifer. In this case, the protected yield should be regarded as the maximum quantity that can be physically obtained from the source works described within the licence. This may be obtained by reference to test pumping results or the source reliable output.
- **Licence quantity unsustainable.** This is usually when the annual licensed quantity, when taken with other nearby licences, exceeds the available groundwater resources. In such cases, the Environment Agency licensing staff for the catchment should be consulted to agree a sustainable abstraction rate.
- **Licence quantity unreasonable as it far exceeds the current or predicted rate of abstraction.** In this case the protected yield should be agreed with the operator based on the recent abstraction rates together with any reasonable forecasted increases. Again, Environment Agency licensing staff should be consulted.

The protected yield for spring sources is discussed in Section 4.5.

Table 2.1 Summary of protection zones in Europe, Australia and the USA

Country	Size	Inner zone	Outer zone	Relation to catchment	Comment
England and Wales		50 days and 50 m minimum	400 days or minimum 25% of recharge catchment	Whole catchment	In karst aquifers, the aquifer source protection area may be also be mapped as the Inner Protection area. Zones of Special Interest (i.e. surface water catchments located outside of aquifer outcrop area).
Ireland		100 days or 300 m		Whole catchment or 1,000 m	Karst – whole aquifer source protection area
Austria	<10 m	60 days		Whole catchment (sub-divided for large catchment areas, based on radius of 2 km)	
Denmark	10 m	60 days or 300 m		10–20 years	
France	<1 hectare	50 days		Whole catchment	
Holland		60 days (replaced by risk assessment)		100 years	
Germany	10–30 m (Zone I)	50 days (Zone II)		Whole catchment (subdivided for large catchment areas based on radius of 2 km) (Zone III)	
Hungary		20 days	182.5 days	5–50 years (hydrogeological protective zone)	
Italy	Minimum 10 m (absolute guardianship zone)	180–365 days depending on vulnerability and hazard (respect zone)		Whole catchment (protection zone)	
Portugal		20–60 m (inner)	50 days or 40–280 m depending on aquifer type (intermediate)	3,500 days or 350–2,400 m depending on aquifer type (outer)	Protection zone defined as larger of distance or travel time zone.
Switzerland	10 m	Individually defined		Double size of middle zone	
Australia		50 m	10 years	Whole catchment	
USA		100–400 feet		Whole catchment (Well Head Protection Plan)	

3 Factors controlling the geometry of hydraulic capture zones

This chapter provides an overview of the factors that control the size and shape of time-of-travel and capture zones around boreholes. No account is taken of other criteria used in drawing zones such as the minimum 50 m radius for the Inner Protection Zone.

3.1 Hydrogeological factors

3.1.1 Principal components

The capture zone to a borehole is the area within which all aquifer recharge whether derived from precipitation or leakage from surface water courses may flow to that source.

It is important to distinguish the capture zone from the area of influence. The latter can be defined as the limit of the cone of depression to an abstraction borehole.

In the case of a horizontal groundwater surface, the capture zone and the area of influence to a borehole are coincident. For the case of a regional hydraulic gradient, the two zones will not coincide as shown by Figure 3.1.

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

- abstraction rate;
- recharge;
- hydraulic boundaries (edge of aquifer, stream, lake, etc.);
- hydraulic conductivity and its spatial variation (both vertically and horizontally);
- kinematic porosity and its spatial variation (both vertically and horizontally);
- aquifer thickness;
- hydraulic gradient;
- direction of groundwater flow.

Many of these factors are interdependent. Their influence in the delineation of steady-state protection zones is summarised in Tables 3.1 and 3.2.

The ability to simulate accurate hydraulic capture zones is limited by data. The main deficiency is the lack of data on the variability of aquifer properties due to aquifer heterogeneity. Most current models use average aquifer properties to generate hydraulic capture zones. The catchment scale zones tend to be least affected as model aquifer properties are often more representative of the regional scale.

Inaccuracies will tend to be greater for zones of a length-scale less than a couple of kilometres and/or for those aquifers with heterogeneities that affect flow and transport at a km scale or greater, in particular aquifers with dominantly fracture flow and/or karst such as the Chalk and the Carboniferous Limestone.

Manual modifications to hydraulic capture zone boundaries should be made where source-specific knowledge/data show that the hydraulic capture zone is incorrect (Section 7).

The geometry of protection zones will also vary with time as the groundwater head changes in response to variations in aquifer inflows and outflows such as recharge and abstraction. In most cases, however, these variations are not taken into account in defining hydraulic capture zones due to the models used and/or absence of data to define these changes. This does not preclude taking time-variant factors into account through manual modifications to zone boundaries (Section 7) or the use of models such as MODFLOW (Section 6).

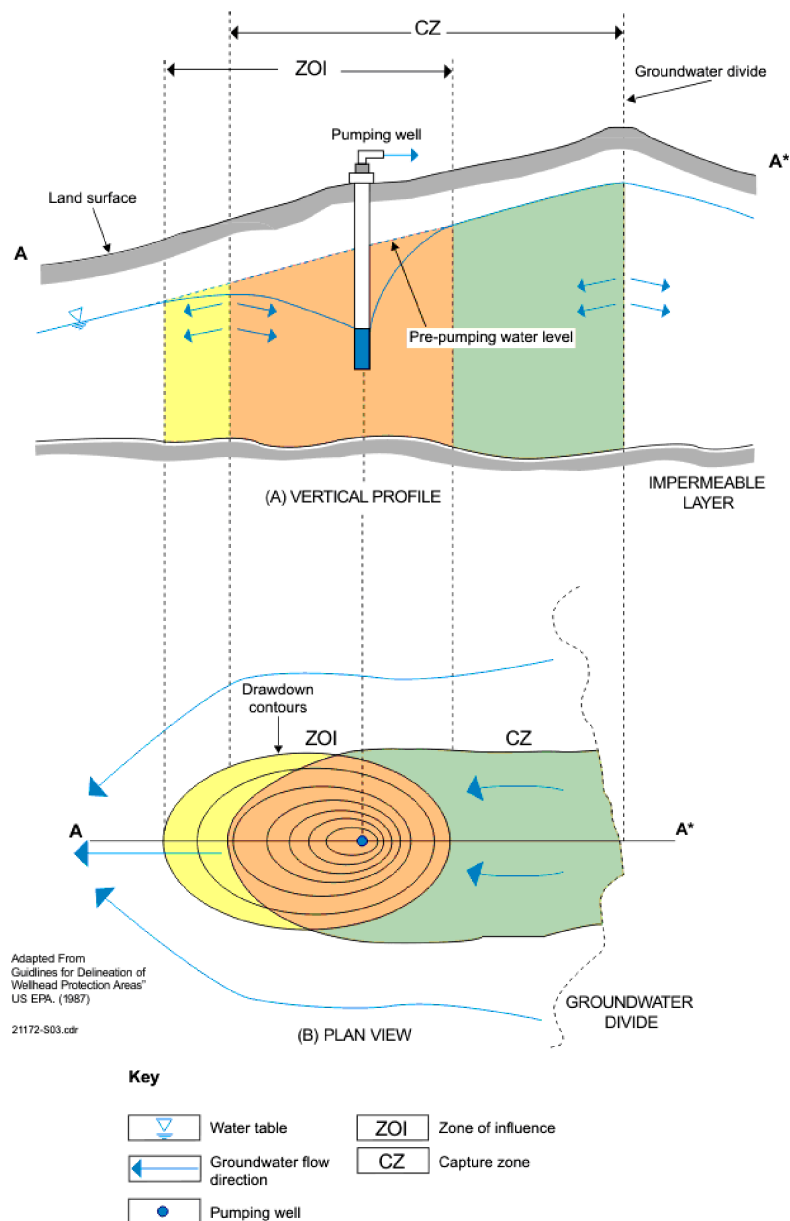


Figure 3.1 Source capture zone and the zone of influence around a pumped well

Table 3.1 Factors controlling the shape and area of hydraulic capture zones

Type of zone	Area	Shape
50 and 400 days	<ul style="list-style-type: none"> • Abstraction rate • Kinematic porosity • Aquifer thickness • Hydraulic conductivity • Recharge (direct and indirect) • (Hydraulic gradient and direction)¹ 	As for factors in area column plus: <ul style="list-style-type: none"> • boundary conditions
Catchment Protection Zones	<ul style="list-style-type: none"> • Abstraction rate • Recharge (direct and indirect) 	As for factors in area column plus: <ul style="list-style-type: none"> • Hydraulic conductivity • Aquifer thickness • Boundaries • (Hydraulic gradient and direction)¹

Notes: ¹The term hydraulic gradient is given in brackets as this factor is dependent on groundwater flow, aquifer thickness and hydraulic conductivity.

Table 3.2 Influences on the geometry of hydraulic capture zones

Parameters	Influences
Aquifer thickness	Aquifer thickness determines the transmissivity of the aquifer and the volume of water in the aquifer, and hence directly affects the area of 50 and 400 day zones and the shape of hydraulic capture zones. A 50 per cent decrease in aquifer thickness results in an approximate doubling of the zone area and an increase in the width of the zone.
Kinematic porosity	Kinematic porosity has a direct affect on the area of the 50 and 400 day zones. A 50 per cent decrease in porosity results in a 2–4 fold increase in the zone area.
Hydraulic conductivity	The horizontal and vertical hydraulic conductivity mainly affect the shape of protection zones in terms of the width and the downgradient extent of the zone. An increase in the horizontal hydraulic conductivity will decrease the width of the capture zone to a borehole. In practice, the vertical horizontal conductivity is rarely considered due to lack of data/information.
Hydraulic gradient	The hydraulic gradient affects the width and downgradient extent of the hydraulic catchment zone – the steeper the gradient the narrower the zone.
Abstraction rate	The abstraction rate directly affects the area of hydraulic protection zones. Interference between abstraction boreholes can greatly affect the shape of zones, producing ‘tails’ and ‘holes’.
Recharge (annual)	The rate of groundwater recharge directly affects the area of the catchment zone. The areas of 50 and 400 day zones are less sensitive to recharge rates. Recharge from surface run-off from adjacent drift or karstic areas can distort the catchment zone.
Boundaries – no flow	No flow boundaries, faults and groundwater divides constrain the shape of hydraulic protection zones.
Boundaries – recharge head dependent	Head-dependent boundaries affect the shape and possibly reduce the area of hydraulic capture zones (particularly the catchment zone).

3.1.2 Shapes of source protection zones

SPZ1 – Inner Protection Zone

Inner Protection Zones generally have a fairly simple geometry as they are normally based on modelling using uniform aquifer properties. They tend to be circular or ellipsoid in form reflecting the cone of depression around the abstraction borehole.

The areal extent of an Inner Protection Zone is dependent on aquifer thickness, hydraulic conductivity and kinematic porosity.

These zones can greatly over-simplify the actual shape of the 50-day zone due to the lack of information on the variability of aquifer properties around the source. For example, Robinson and Barker (2000) explore how the shape of a 50-day zone changes in relation to variations in fracture hydraulic properties, orientation and densities.

SPZ3 – Catchment Protection Zones

The shape of Catchment Protection Zones can vary from the simple to the complex as illustrated by Figure 3.2.

Complex shapes can generally be attributed to:

- interference effects between groundwater abstractions;
- groundwater/river interactions;
- lateral variations in hydraulic properties;
- natural pattern of diverging and converging groundwater flow.

Aquifer heterogeneity and interference between groundwater abstractions are the main causes of complex shapes. Modelled hydraulic capture zones do not tend to show the effects of the former because of the uniform aquifer properties used (related to the lack of information on their variability).

Long narrow capture zones can occur where the source is located some distance from the aquifer boundary and/or where the abstraction is small; the hydraulic gradient is relatively steep or the transmissivity is relatively high.

The modification of modelled complex and long shapes is discussed in Section 7.3.

SPZ2 – Outer Protection Zones

Outer Protection Zones are generally intermediate in shape between Inner and Catchment Protection Zones, with complex shapes arising through interference, heterogeneous aquifer characteristics or the characteristics of the source (e.g. the presence of adits).

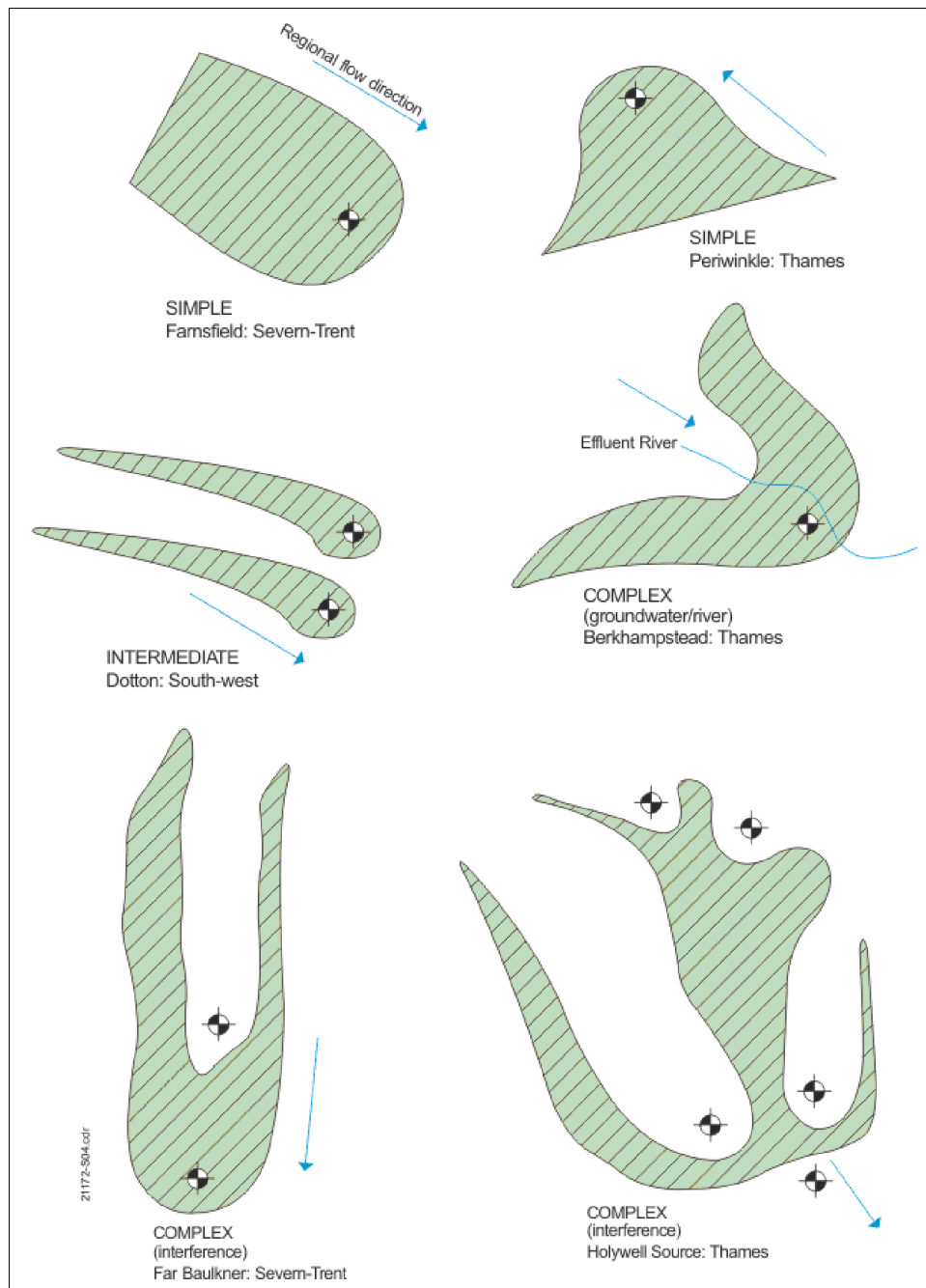


Figure 3.2 Example source catchment zone shapes

3.2 Field data factors

The calculation of hydraulic capture zones is dependent on the accuracy and detail of the field information describing the aquifer system. There is always uncertainty associated with these data because:

- field data are sparse but parameter values are required for the whole of the aquifer unit;
- the data may be based on estimates of average or regional conditions which may not be representative of local conditions in the vicinity of the source;
- aquifer parameters may be derived from tests carried out on sources which may not be typical of the regional aquifer;
- estimates of parameters derived from pumping tests may be dependent on the method of analysis used and/or duration of the test;
- field values may be functions of scale or of local conditions (e.g. estimates of effective rainfall may be based on data from one site but rainfall may vary significantly over the catchment).

Errors can also arise when using field data in calculations and models, for example:

- the assumption of conditions requiring estimates of average flows, recharge and groundwater levels for calibration (such estimates may be derived from sparse, and possibly unrepresentative, time series data);
- extrapolation of point measured field values and parameter estimates over the model domain.

Examples of the problems that can be associated with data used to construct predictive groundwater flow models are given in Table 3.3.

Table 3.3 Possible problems when transferring field data to a model

Parameter	Field	Implication for model
Hydraulic conductivity	<p>Pumping test data may only be available for larger groundwater abstractions which were probably located in areas of higher permeability.</p> <p>Pumping tests may have been carried at different rates or duration, and the values derived may be representative of different volumes of the aquifer.</p> <p>A range of permeability values may be quoted based on different methods of analysis of a pumping test.</p> <p>Transmissivity values only may have been quoted with no information on aquifer thickness.</p>	Model values may be overestimated and will have uncertainty.
Kinematic porosity	<p>Limited data may be available.</p> <p>Tracer or laboratory testing is required to measure kinematic porosity but is rarely undertaken.</p>	Model values may be estimates or based on expert opinion.
Groundwater levels	Groundwater level contours are often drawn	Model takes no account of

Parameter	Field	Implication for model
	based on an interpretation of limited water level data and may not fully account for lateral and horizontal variations in aquifer properties. The water levels measured in a borehole may be more representative of local conditions (e.g. the borehole may only partially penetrate the aquifer). Groundwater levels vary with time whereas a single average value is often used in a model.	seasonal or long-term changes. Model calibration dependent on interpreted groundwater levels.
Aquifer base	There may be limited data (borehole records, flow logging, permeability testing) on the effective base of the aquifer (e.g. the effective thickness of the Chalk is typically less than the total thickness of this formation).	Usually only estimates of the effective thickness are available and the model base of the aquifer is defined by subtracting this value from the groundwater surface. This approach involves a large amount of interpolation of the field data.
Recharge	Recharge values may be estimates, particularly where drift cover is present. No account may have been taken of variation in rainfall over the model area.	SPZ3 may be in error, particularly for catchments with a drift cover or in karstic areas.
Groundwater/river interaction	Stream gauging data may be limited in providing a measure of the gain or loss in river flow due to groundwater interaction. Little or no data on valley bottom/alluvial deposits separating river from aquifer.	Modelled groundwater/river interaction cannot be checked and hence hydraulic capture zones may be in error.

3.3 Assumptions and limitations of calculations and models

The geometry of capture zones can also be influenced by the methods used to delineate them. For example, manual or analytical methods (Section 6.5) generally produce simple shaped SPZs. Numerical models (Sections 6.7–6.10) can enable more accurate hydraulic capture zones to be drawn because they are based on a more detailed representation of the hydrogeological environment.

Whatever the chosen method for delineation, assumptions are made to simplify complex real world hydrogeological systems. Typical assumptions made during capture zone delineation, with examples of possible implications, include:

- **Particular conditions prevail.** In reality, groundwater flow varies with time. The orientation and geometry of predicted capture zones, delineated assuming particular conditions, should be interpreted in relation to actual field data to ensure the approximation is reasonably valid. The impact of model assumptions has been explored by Rock and Kupfersberger (2002).
- **Groundwater flow is horizontal.** This assumption may lead to anomalous zones, for example around partially penetrating boreholes where vertical flow in the vicinity of the borehole may be significant. In this case, the actual borehole capture zone may be very different to that delineated with a two dimensional model. In most cases, however, there will be insufficient

data/information on the vertical hydraulic conductivity and its spatial variation to justify modelling in three dimensions.

- **Flow in the aquifer is by intergranular or by diffuse fracture flow.** In karstic aquifers, groundwater flow is non-Darcian, i.e. conduit flow occurs through discrete open fracture zones and cave systems. In such aquifers, flow velocities are high (up to several km/day). Travel times from the edge of the catchment to the source can be of the order of days or even hours such that the Inner Protection Zone (50-day travel time) may coincide with the Catchment Protection Zone. Catchment zones in such environments can not be adequately resolved using methods assuming Darcian flow. More detail on source protection in karst systems is given in Section 4.1.
- **Poor resolution** of the model (e.g. grid density) relative to the areal extent of the hydraulic capture zone;
- **Relative accuracy** of the model when simulating observed conditions such as groundwater levels;
- **Assumptions** made in assembling the model, including transfer of field data to the flow model;
- **Bias in interpretation** during the construction and calibration of the model or during zone delineation.

Some sources such as springs and adit systems, which can be several hundred metres in length and exert controls on flows to the borehole over a wide area, present particular problems for modelling. A series of rules has been developed for delineating the associated capture zones (Section 6.9).

3.4 Model specific issues

A number of issues may influence the accuracy of hydraulic capture zones delineated with numerical models, particularly those methods that rely on discretisation of the flow domain. These issues include:

- **Model mesh spacing** (Figure 3.3). Insufficient resolution around pumped wells results in a poor approximation of the cone of depression. When particle tracking this leads to inadequate divergence of particles and narrow capture zones.
- **Weak sinks.** These occur where an abstraction does not account for all the flow into a model cell element. In this instance, particle tracking algorithms can struggle to determine the pathway for individual particles (to the abstraction or out of the cell).
- **Partial penetration** (Figure 3.4). Single layer models can not adequately represent boundary conditions (e.g. a river or a well) that only partially penetrates the thickness of the aquifer.

These issues apply to the finite difference model MODFLOW. Other models, particularly finite element models, permit larger changes in mesh scale. Weak sinks and mesh spacing problems are less of an issue with these models.

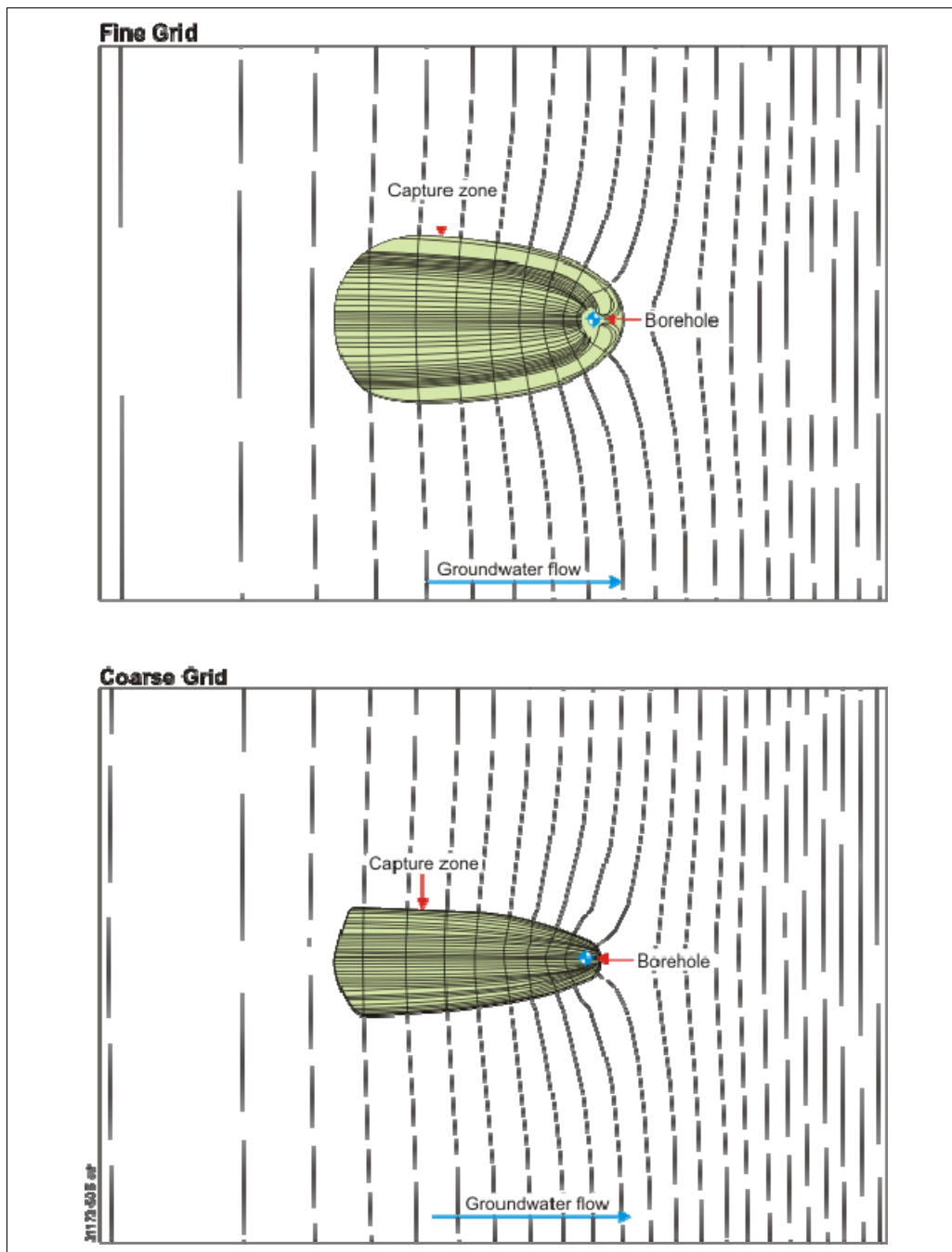


Figure 3.3 Influence of model grid spacing on zone definition

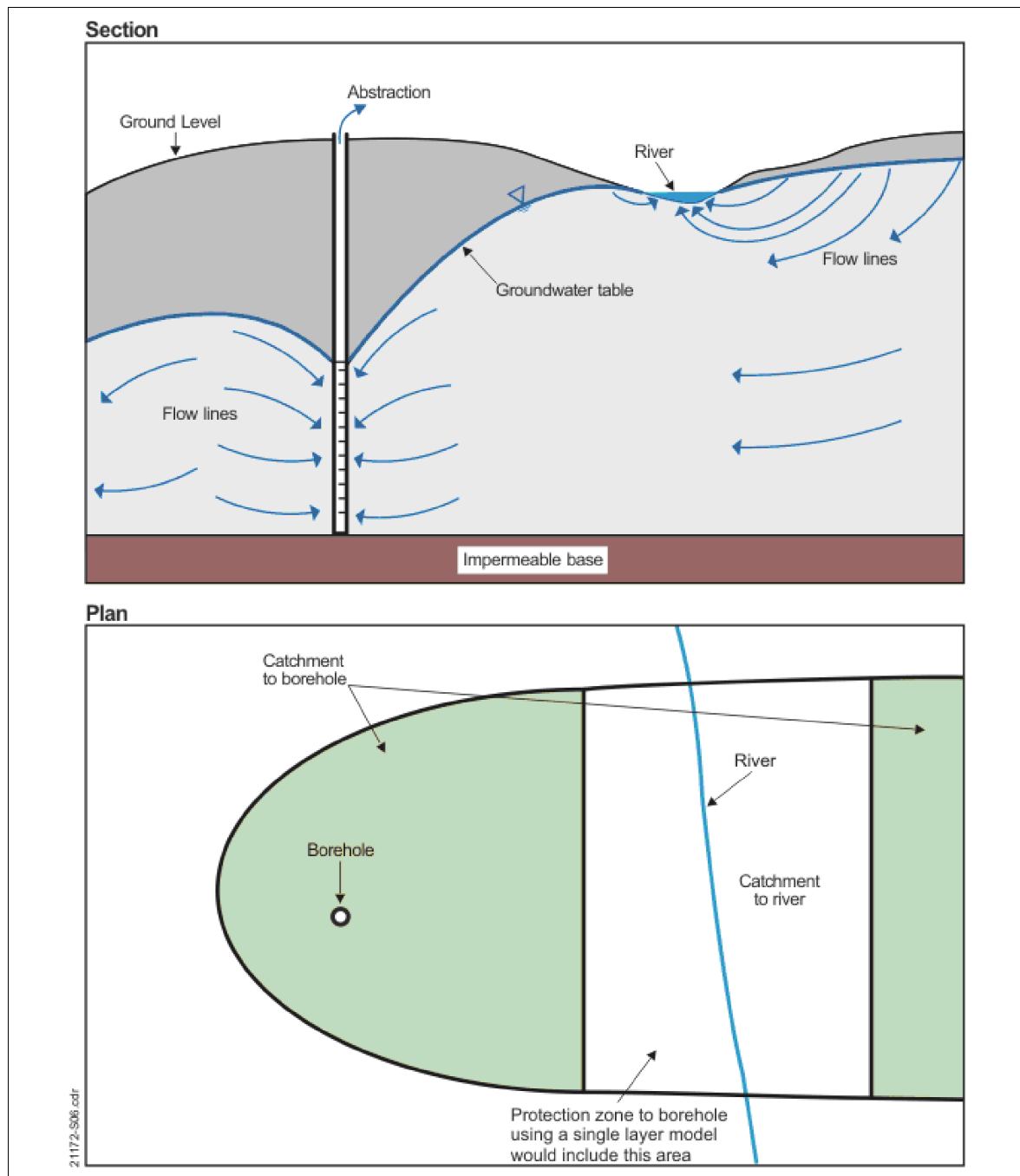


Figure 3.4 Influence of stream partial penetration on capture zones

3.4.1 Model calibration

The accuracy of modelled capture zones depends on the satisfactory calibration of the model. Figure 3.5 illustrates the effect of poor calibration to groundwater levels on protection zone definition in a thin unconfined aquifer.

Calibration refers to the process of varying initial parameter estimates to more accurately model observed field conditions. It is important to decide the acceptable range of parameter variation in advance of model calibration.

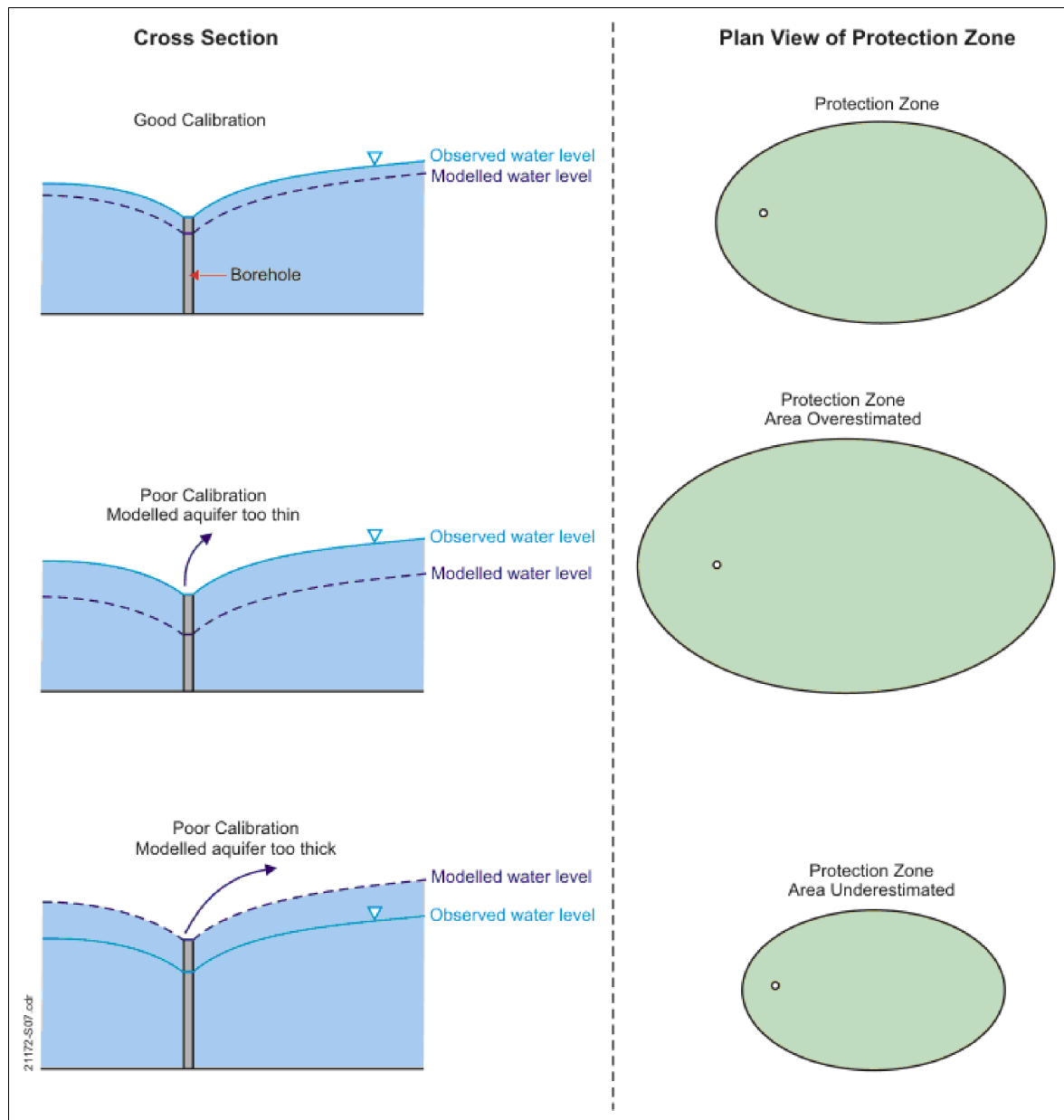


Figure 3.5 Influence of calibration of groundwater levels on protection zone definition in a thin unconfined aquifer

4 Source protection in special cases

The aim of this chapter is to draw together issues related to SPZ definition in particular hydrogeological environments and aquifers. It deals with:

- karst sources;
- kinematic porosity and sandstone sources;
- small sources;
- sources with limited data;
- spring sources;
- heavily abstracted aquifers.

4.1 Karst sources

This section provides an overview of karst hydrogeology and sets out a proposed methodology for delineation of SPZs in karst aquifers. It also describes karst in different aquifers and how this might influence the delineation of SPZs.

4.1.1 Karst

Those of our aquifers that may be regarded as karst (e.g. Carboniferous Limestone) or that exhibit at least some karstic (e.g. Chalk) features present some significant problems in defining SPZs that are adequately protective without being over protective or covering very large areas of land.

Karst features include:

- conduit flow/solution enlarged features;
- caves;
- swallow holes – also known as sinkholes, dolines and swallets;
- epikarst – the interface zone between soil and rock in karst landscapes;
- rapid groundwater flow (tracer tests showing flow velocities of km/day);
- springs;
- dry valleys.

In such areas a large component of flow may well be rapid and non-Darcian. There may be substantial seasonal variation and the importance of swallow hole and other solution features may also vary over time.

An abstraction source may be fed by streams which drain to the aquifer via swallow holes. Such streams may drain large areas of impermeable or low permeability strata above or adjacent to the karstic aquifer. Travel times from the swallow hole to the discharge point (groundwater source) may be very rapid (hours, days) such that in

order to protect the abstraction it is necessary for the SPZ to incorporate the surface water catchment feeding the karst system.

The source SPZ may therefore comprise two components:

- a surface water catchment area on the impermeable drift non-karstic strata concentrating recharge through swallow holes
- a more conventional saturated groundwater flow capture zone.

Equally, there may be areas of land where such run-off or perched groundwater does not provide flow to the source in the relevant timescale. For these areas inclusion in the SPZ would be overprotective.

In short karst presents major challenges to delineation and an assessment will need to be made on the most appropriate method for SPZ determination based on the data availability, resources and the complexity of the system.

For the majority of sources in karst areas, SPZs are best delineated using field mapping and manual methods rather than analytical or numerical techniques which assume Darcian flow since these latter are unsuitable. Numerical models have been developed to represent karstic systems however, for SPZ delineation they are impractical.

4.1.2 Methodology for delineation of SPZs in Karst

Delineation of SPZs in karst dominated aquifers will largely be based on manual methods supported by field investigations (e.g. tracer tests) and appropriate calculations.

There are some basic principles that should be followed :

- where areas of land can be clearly recognised as not contributing water to the abstraction source they should not be included within the SPZ; and
- where areas of land beyond the edge of the recognised aquifer do contribute water to the source they should be included in the SPZ as described below.

The latter are best recognised as a surface flow area that provides run-off to a rapid flow aquifer such as karst limestones. Hence:

1. SPZs should be based on a conceptual understanding of the water flow in that location. A defensible conceptual model is required for all SPZs produced.
2. SPZs should be delineated on horizontal flow times of water to the receptor (source).

This would normally refer to water that is groundwater (i.e. in the saturated zone), but could also include perched shallow interflow/overland flow from an aquitard that runs off into a high porosity or fracture flow aquifer. This case is inadequately covered in current policy documents and led to different interpretations in different Regions.

3. Areas of land that do not provide water to the source within the relevant timescale should not be included in an Inner or Outer Protection Zone.

Where this relies on an impermeable covering layer the nature of the layer must be sufficient to protect the source from all activities including those below ground or that require excavation. The covering layer must not provide a rapid

pathway, via shallow interflow/overland flow, to the source. Lias mudstones and other regional aquitards are a good example of a low permeability layer that could provide such protection. Other strata may provide suitable protection, but the Environment Agency would need additional and extensive evidence that this is the case before this area could be excluded from the SPZ.

In summary the method involves the following stages:

1. Data collection including tracer tests (Section 4.1.3).
2. Field inspection of each source and its possible catchment area to assess the importance of:
 - active or dry springs and watercourses;
 - topographic and geological features.
3. Develop a conceptual understanding of the source catchment based on spring/borehole behaviour, karst features, dry valleys, interfluvies, etc.
4. Calculate the hydraulic capture zone (recharge area) using water balance calculations. This should be regarded as the minimum area for the following reasons.
 - Tracer tests may also demonstrate that recharge is drawn from a larger area than that calculated using water balance calculations.
 - The catchment area may vary seasonally and the capture area should allow for this variation. In mature karst areas, for example, the catchment areas of perennial low-level springs can expand to include the catchments of seasonal high-level springs as the latter dry up.

It is recommended that the total catchment area should represent late summer conditions in an average year (not 'worst case' but worse than average).

5. Define the boundaries of the hydraulic capture zone based on:
 - calculated recharge area – for some karst sources, the recharge area should be treated as a minimum area (see point 4 above);
 - geological and hydrogeological boundaries;
 - tracer tests (see Section 4.1.3);
 - pollution incidents;
 - mapping of underground cave systems.
6. Define SPZ 1 based on:
 - tracer tests (where available);
 - other information such as pollution incidents;
 - understanding of the behaviour of the the surface water catchment and its interaction with the groundwater, such as the location of sinking streams that support the potable source;
 - manual calculations (see Section 6.5) assuming low fissure porosity.

7. Define the 400 day zone and catchment zone. In most cases the boundaries of the 50 and 400 and catchment zones will be drawn as co-incident (i.e. tracer tests have indicated travel times of less than 50 days within the catchment). Given the physical dimensions of karstic aquifers in England and Wales, breakthrough travel times of greater than 50 days will not be common in the conduit system. The delineation of separate Outer and Catchment Protection Zones would normally only be considered where it is possible to map with confidence a geology type which itself does not have a conduit flow system, but that does discharge groundwater to a potable source via a karstic aquifer with an active conduit system. The definition of Outer and Catchment Protection Zones would then be based on the assessment of the 400 travel time isochron in this geology type prior to discharge to the karstic aquifer where the potable source is located
8. Define the 'allochthonous' part of the catchment. Many karstic sources capture surface water through sinking streams that have all or part of their catchment underlain by low-permeability bedrock. Although the surface water from the allochthonous catchment pose a risk to karstic sources, groundwater discharge from this allochthonous area to the karstic aquifer is considered insignificant. The hydraulic capture zone boundaries may need to be modified to include the surface water catchment to streams draining to swallow holes and which support the groundwater source. Review information from tracer tests or pollution incident data to determine whether to include this catchment in the Inner Protection Zone based on travel times.
9. Identify areas which can be excluded from SPZs (e.g. areas with an impermeable layer that affords protection to the source). Justification will need to be provided to support the exclusion of such an area.
10. Define proposed SPZ boundaries and review these based on conceptual understanding of local and regional groundwater flow.
11. Finalise SPZ boundaries.
12. Record the basis for SPZ determination (see Section 7).

4.1.3 Data sources, data reliability and records of methodology

The main sources of data are likely to be:

- licence files;
- geological and hydrogeological maps;
- local knowledge;
- historical records (e.g. cave group memoirs and local archives);
- tracer tests.

Local knowledge should be validated using independent sources where possible to avoid conflict, while historical records should be checked at source to ensure reliability.

Key data will be information on:

- karst features;
- spring flows;

- variations in groundwater level and flow direction.

These data may need to be supported by discussions with quarry operators and local groups (nature trusts, cavers, etc.).

Tracer tests

Water tracing tests provide the most positive evidence in defining Inner Protection Zones.

When using the results from tracer tests, it is essential to assess whether the results are appropriate to the catchment and the level of confidence that can be attached to them. The following should be considered:

- how the test was undertaken (e.g. sample points, tracer used, sample method and analysis);
- what information was collected (e.g. groundwater levels, flows, tracer recovery);
- reliability of the test;
- at what time of year were the tests carried out? Experience suggests that measurements made late in the summer when groundwater is at its normal lowest level are the most representative. Karst hydrogeologists find it useful to define the 'standard travel time' of a particular underground connection as the travel time when the resurgence is at its long-term average yield.
- whether the tracer test was appropriate for the specific environment tested.

Information on tracer tests may be available from universities, local archives, cave groups, the British Geological Survey (BGS), WRc, quarry operators and the Environment Agency.

4.1.4 Aquifer types

Palaeozoic limestones (Carboniferous limestones)

The Carboniferous and other limestones, including limestone conglomerates, of the Mendips, the Pennines, north and south Wales and elsewhere are characterised by mature karst landscapes and very extensive cave development. Caves and major conduits systems are generally determined by cave exploration and/or groundwater tracing.

Most Palaeozoic limestone water supplies are obtained from springs or resurgences. Some borehole sources do exist, though both these and spring sources draw water from a karstic drainage network. Spring sources can be large with mean outputs sometimes exceeding 1,000 litres/second [86 million litres/day (Ml/d)] and represent the outlets for integrated underground cave drainage systems.

In most well-karstified Palaeozoic limestone catchments, the underground streams flow at rates comparable with those of surface streams. The areas between the main underground conduits are drained by minor tributary conduits with similarly rapid flow. Standard travel times of a few days are common, so the greater part of such catchments usually require levels of protection typical of an Inner Protection Zone.

The methodology described in Section 4.1.2 is likely to be the most appropriate for Palaeozoic limestone sources.

Jurassic limestones

In general, the Jurassic limestones are less hard and compact than their Palaeozoic equivalents, retaining some primary porosity and permeability. The main limestones in southern England are the Great Oolite, the Inferior Oolite (Lincolnshire Limestone) and the Portland and Purbeck limestones. Many thin but extensive limestones are also known and these include the Blue and White Lias, the Junction Bed, the Fuller's Earth Rock, the Forest Marble, the Cornbrash and the Osmington Oolite. In northern England, there is the Corallian of Yorkshire and northern extensions of the Lincolnshire Limestone.

Most of the large abstraction boreholes in the Great and Inferior Oolites of the Cotswolds draw water from deep within the confined zone, remote from any large natural springs. In such areas with no long established groundwater flow routes, karstic development is likely to be immature. Nevertheless, preferred flow routes to the boreholes will already be in process of establishment and enlargement. A few large springs do exist in the confined zone and must be fed by channels that are karstified to some degree.

Where groundwater is abstracted from the unconfined Great and Inferior Oolite aquifers, flow is typically controlled by fractures and structure (e.g. faults, etc.). These enhanced flow zones lead to karstic recharge.

The zoning procedure described in Section 4.1.2 can be applied to the Lincolnshire Limestone where karstification is known or suspected. In areas where there is no evidence of karstification, methods of hydraulic capture zone delineation based on analytical or numerical modelling assuming Darcian flow may be used supplemented, where appropriate, by local hydrogeological knowledge.

Chalk

The Chalk aquifer can show the development of the following karst features:

- solution-enlarged fissures characterised by rapid travel times and high borehole yields;
- solution features such as swallow holes that may provide the focus for groundwater recharge;
- high flow systems characterised by travel times of km per day;
- large springs that are likely to be supplied by an integrated drainage system of karstic conduits.

In general, karst development in the chalk is immature.

The zoning procedure described in Section 4.1.2 can be applied to Chalk areas where karstification is known or suspected. In areas where there is no evidence of karstification, methods of hydraulic capture zone delineation based on analytical or numerical modelling assuming Darcian flow may be used supplemented, where appropriate, by local hydrogeological knowledge.

The delineation of capture zones around sources in winterbourne catchments may cause problems. Winterbournes are streams that typically flow in winter but dry up in

summer, and characterise the Chalk country of southern England. The problem is that the total catchment area of a large borehole beside a winterbourne is likely to flip from one configuration to another in step with changes in the winterbourne itself. Typically, at high flows and groundwater levels, with the stream gaining along its length, the source catchment will be an area on the borehole side of the valley. As flows and levels diminish, the stream loses water to the borehole and the source catchment expands to include the relevant stream catchment. When the winterbourne dries, the source catchment takes in both sides of the valley but may lose remote parts of the stream catchment. Time of travel zones show equal variability.

In determining SPZs for catchments including winterbournes, a good conceptual model is required and should involve discussion with local hydrogeologists to determine which parts of the catchment should be included in the protection zones. This may involve manual modification of hydraulic capture zones which have been drawn using models to represent seasonal variations in catchment areas.

4.2 Kinematic porosity and sandstone sources

The Permo-Triassic and Devonian Sandstones are characterised by relatively high total porosity (typically 10–30 per cent). The aquifer can be tens to hundreds of metres in thickness and boreholes are often drilled to depths of over 100 metres below the water table.

The conventional model for these sandstone aquifers is that:

- contaminant movement is mainly via intergranular flow;
- kinematic porosities of 10–15 per cent are appropriate.

However, the use of these values in thick aquifers can result in relatively small Inner (50 day) and Outer (400 day) Protection Zones as illustrated by Figure 4.1.

Tracer tests provide the most reliable source of information on rates of contaminant movement, though there is only limited published data (Ward et al. 1998) and the majority of these tests were undertaken over relatively short distances (metres to tens of metres). The tests indicate that flow was mainly intergranular, with kinematic porosities in the range 12–14 per cent, but in one case flow was by fissure flow over a distance of at least 280 m.

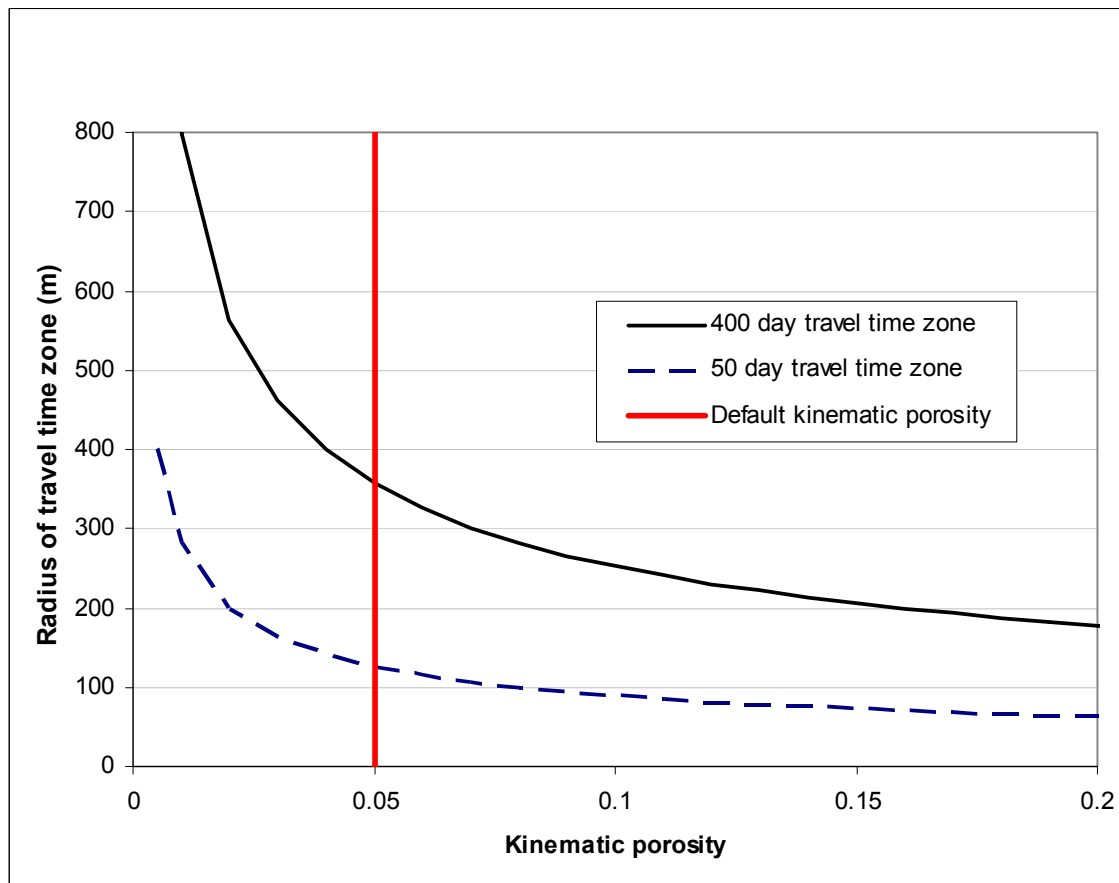


Figure 4.1 Radius of 50 and 400 day travel time zone dependent on kinematic porosity

The most recent review of contaminant movement in the Permo-Triassic Sandstone was by Tellam and Barker (2006) who noted that an important consideration was whether fractures are interconnected over distance. They tentatively concluded:

- fissure flow dominates for distances <10 m;
- both fissure and intergranular flow are present for distances of 10–100 m;
- intergranular flow dominates for distances >100 m.

Investigations from some of the main groundwater pollution plumes in the Permo-Triassic Sandstone (Four Ashes and Mansfield) indicate that plume migration is largely controlled by intergranular porosity. However, groundwater flow and contaminant transport may be via fissures and higher borehole yields are typically associated with fracture systems. The use of a kinematic intergranular porosity could result in an underestimate of the time of travel zone.

Figure 4.1 presents calculations of travel times and the size of 50 and 400 day zones for a range of fissure and intergranular kinematic porosities. It is likely that:

- contaminant migration to an abstraction source is a combination of fissure and intergranular flow;
- the significance of fissure flow will be greater over shorter distances and most relevant to the 50-day zone.

The approach to be followed for sources in the Permo-Triassic and Devonian Sandstones is as follows.

- Collate and review available hydrogeological information for the source borehole(s) including data from tracer tests, groundwater pollution, water quality monitoring, geophysical logs, CCTV and borehole yield.
- If information on kinematic porosity is available from tracer tests or other reliable sources (e.g. groundwater investigations of contaminant migration), use to define the time of travel time zones as follows:
 - Use a default kinematic porosity of 5 per cent to determine SPZ1 (50 day) and SPZ2 (400 day) time of travel zones. This assumes that groundwater flow to the abstraction is due to a combination of fissure and intergranular flow. The relative contribution of fissure and intergranular flow is rarely known and this default value is considered to be a reasonable assumption based on scoping calculations (see Appendix A).
 - Use a lower kinematic porosity value of 1–2 per cent if field evidence (pollution event, turbidity data, bacteriological monitoring) provides strong evidence for rapid flow to the abstraction borehole.
 - Use a higher kinematic porosity value such as 10 per cent if available data (e.g. tracer test) provide strong evidence that flow is by intergranular flow only. In most cases, however, the use of a default radius will result in a larger protection zone.
 - Record the justification for the selection of kinematic porosity.
 - Determine Inner and Outer Protection Zones;
 - Check if protection zones are consistent with known pollution problems.

In the absence of any evidence for the importance fracture flow in the vicinity of the source boreholes then distance rules may be used as follows:

- SPZ1 (Inner Protection Zone). Apply the 50 m default rule.
- SPZ2 (Outer Protection Zone). A minimum radius of 250 m for sources with a protected yield of $<2,000 \text{ m}^3/\text{day}$ or a minimum radius of 500 metres for sources with a protected yield of $>2,000 \text{ m}^3/\text{day}$. In either case, the radius should not extend outside the Catchment Protection Zone.

4.3 Small sources

Small sources (typically abstraction rates of $<100 \text{ m}^3/\text{day}$) can present the following problems for hydraulic capture zone delineation.

- Data are often limited or of poor quality.
- The width of the catchment zone can be very narrow. Where there is no or limited data on the direction and gradient of groundwater flow, there will be significant uncertainty on the location of the zone.
- The use of numerical methods (e.g. MODFLOW) is usually impractical as relevant data are unlikely to be available and there will be difficulties in setting up a model grid of sufficient accuracy to represent the flow field around a small source. In these cases, analytical methods are more suitable for hydraulic capture zone definition.

An example of limited data on defining hydraulic capture zones for small zones is uncertainty in the hydraulic gradient. If the hydraulic gradient is unknown, for example, the model assumes a flat water table and the resulting zones are circles. This will underestimate the extent of the SPZ in the upgradient direction. This problem can be overcome to some extent by using estimates of hydraulic gradient based on the surface topography, although sensitivity analysis is required to assess the effects of parameter uncertainty.

Table 6.2 summarises techniques used in England and Wales to delineate hydraulic capture zones. Recommendations on their use for small sources are given in Table 4.1. In summary the methods are:

- Manual supported by hydrogeological mapping techniques where data are limited;
- Analytical solutions or analytical element methods (Sections 6.5 and 6.6) where:
 - Darcian flow;
 - direction and gradient of groundwater flow are known with reasonable certainty;
 - estimates of permeability and kinematic porosity are available.
- Use of pre-defined zonal shapes, based on a representative selection of regional parameters, may be used to produce credible but rapidly applied SPZs for the many private supplies which have a low SPZ programme priority, but a high public health significance. A compendium of such standard simple shapes, together with instructions on their use, is given in Volume 3 of *Groundwater protection for small sources* (Environment Agency 1995). These represent the Environment Agency recommended technique for pre-defined zonal shapes.

In all cases, SPZ boundaries should take account of:

- geological and hydrogeological boundaries (Section 7);
- any additional local information such as tracer tests and pollution incidents.

For sources with an abstraction of $<20 \text{ m}^3/\text{day}$, a minimum abstraction rate of $20 \text{ m}^3/\text{day}$ should be used. This should provide additional protection. In addition, our policy is that each site should have a minimum protection of a default SPZ1 radius of 50 m and a default SPZ2 of 250m radius.

4.4 Sources with limited data

Sources with limited data should be defined using manual methods (Section 6).

The absolute minimum information that should be obtained is the licensed yield. For spring sources, the total discharge of the source should be estimated.

Every effort should be made to:

- measure or estimate the spring or borehole water level elevation (This may assist in defining the area of the catchment that could contribute to the source based on elevation.);

- obtain information on geological and hydrogeological boundaries that could be used to define SPZ boundaries;
- conduct a site visit to obtain details of the catchment, including a survey of geological and other features within the immediate environs of the source.

4.5 Spring sources

For spring sources, the licensed groundwater abstraction is typically less than the total spring discharge. However, the total spring discharge should be used for SPZ delineation rather than the licensed abstraction.

Spring SPZs are typically drawn using manual mapping methods (Section 6.4) as information on the source is often limited to the elevation of the spring. The spring source can also be complicated; for example the source may comprise a number of springs and significant engineering works may have been undertaken to allow collection of the water for supply purposes.

A site visit should normally be undertaken to determine details of the spring source.

4.6 Heavily abstracted aquifers

In heavily abstracted aquifers, the source protection area will cover a significant proportion of the recharge zone. As a result, SPZs are likely to be adjacent or will be separated by relatively thin slivers. The certainty that can be attached to the boundaries of individual SPZs is likely to be low as these will be sensitive to:

- changes in abstraction;
- seasonal variations in groundwater level;
- the ability of the definition tool (model) to delineate the hydraulic capture zone of the groundwater abstraction in such a complex system.

In addition, the same groundwater protection policies are likely to apply to the whole aquifer area rather than to individual SPZs. In heavily abstracted areas, therefore, the entire aquifer recharge area should be defined as a source protection area.

This principle is precautionary and would appear to ease the burden in defining SPZ3 source catchment protection zones. However, the statutory duty of water companies to produce Drinking Water Safety Plans requires them to know the source of their raw water supplies. If in heavily exploited aquifers the Environment Agency stopped defining the whole groundwater management unit as SPZ3, water companies would have to define catchments for their own sources. In areas where more than one water company abstracts from a groundwater management unit, it is desirable to have a consistent conceptualisation for zone definition.

Therefore there is a requirement in heavily exploited aquifers to:

- define the entire aquifer recharge area as a source protection area, SPZ3, making this the published zone;
- where necessary and in collaboration with water companies separate SPZ3 are defined, making these available to the public water supply (PWS) operators.

The Source Catchment Protection Zone (SPZ3) can be defined when the ratio of groundwater abstraction to recharge is >0.75 for a specified area of aquifer, normally considered to be at the scale of CAMS groundwater management units or larger.

Figure 4.2 illustrates the method. In summary, the procedure is as follows.

- Determine the aggregate protected yield for the aquifer area in question. This is the sum of the licensed annual quantities of potable/PWS abstractions abstracting from this area of aquifer divided by 365. Any restrictions placed on abstraction at individual sources by group licences should normally be ignored.
- Determine the long-term average groundwater recharge per day for the same area of aquifer.
- Calculate the ratio of abstraction to recharge.
- If ratio >0.75 , define aquifer area as SPZ3 for publication. Then define individual SPZs, if required for specific sources, to be provided to source operators only.
- If ratio <0.75 , define individual SPZ3s for publication.

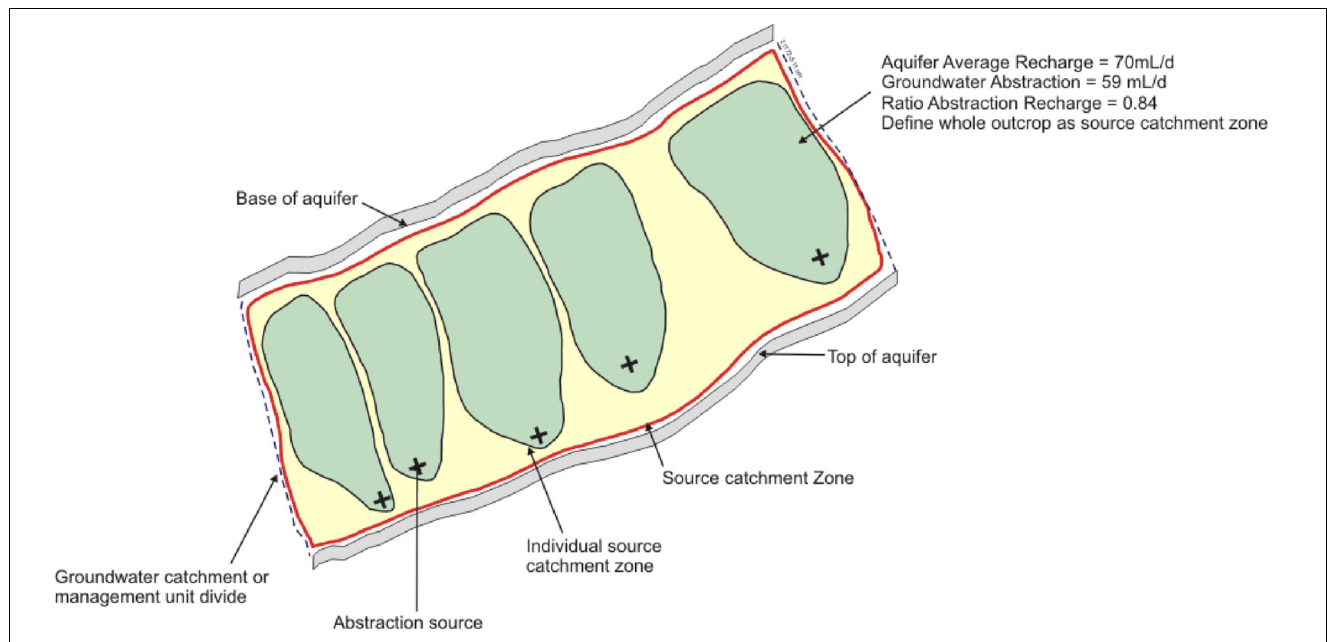


Figure 4.2 Application of the heavily exploited aquifer method

Table 4.1 Recommended techniques to delineate small source protection zones

Description	Comments
Hydrogeological mapping	Groups wells into hydrogeological domains/aquifer types enabling classification of behaviour. Must apply in all cases at paper map level and be used in conjunction with other methods to ensure results make geological sense.
Arbitrary fixed radius circles (AFRC)	A default 50-metre radius zone (AFRC) is possibly the only option for either very small sources or those for which further effort is not justified.
Calculated circular zones based on recharge and abstraction (plus kinematic porosity and thickness for Inner and Outer Protection Zones)	Easy to apply. Is clearer when applied to groups of similar abstraction and recharge. Where no aquifer parameters are available, this could be used with 50 m default AFRC. Problematic if actual daily rates are much greater than annual licensed quantity divided by 365. Only suitable for Inner and Outer Protection Zones if no hydraulic gradient available. Underlying concept easy for non-specialists to grasp.
Standard simple shapes based on idealised representation of local conditions	A previous compendium of standard shapes used analytical models based on parameter values typical of aquifers in England and Wales (Environment Agency 1995).
Analytical element modelling with WHAEM ¹	Analytical element models can be used to define zones where data are adequate. Otherwise use standard shape capture zones (see above).
Numerical modelling with MODFLOW	Generally only justified where numerous small sources occur across a small area or in vicinity of large sources already being modelled.
Notes	¹ Well Head Analytical Element Model

5 Data collection and the conceptual model

This chapter considers:

- the development of conceptual model(s) describing the hydrogeological system;
- the collection of information to form the conceptual model;
- the reliability of information and quality assurance procedures.

The delineation of useful source protection zones (SPZs) requires a sound understanding of the overall hydrogeological regime. A conceptual model is a very useful way to explain and record the hydrogeological understanding developed during the delineation process and is a requirement for Environment Agency SPZs.

Conceptual models are a quantitative description and/or a diagrammatic representation of the factors and processes governing groundwater flow in a clearly defined block of aquifer.

Conceptual models are the means of communicating and recording understanding. Ultimately the success of the model depends on its validity. Figure 5.1 shows the steps involved in developing a conceptual model.

More detailed guidance on the development of conceptual models can be found in:

- *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface* (Environment Agency 2001a);
- *Groundwater resources modelling: guidance notes and template project brief* (Environment Agency 2002).

5.1 Data collection

Historically, significant original data collection was required to enable SPZ delineation. The data collection process has now changed following the development of:

- regional models covering the majority of the principal aquifers;
- electronic datasets within the Environment Agency and other organisations.

In principal aquifers, the emphasis is now on collating reports and electronic datasets and building on existing interpretations rather than going back to original information. In secondary aquifers, it may still be necessary to go back to original data sources.

The availability of data, particularly for aquifer parameters and recharge, is extremely variable. Historically, information was derived from investigations oriented towards resource development and the testing of established sources, mainly in the principal aquifers. Where SPZs are to be derived in secondary aquifers or remote from the main areas of public supply in the principal aquifers, extrapolation from other areas may be inevitable.

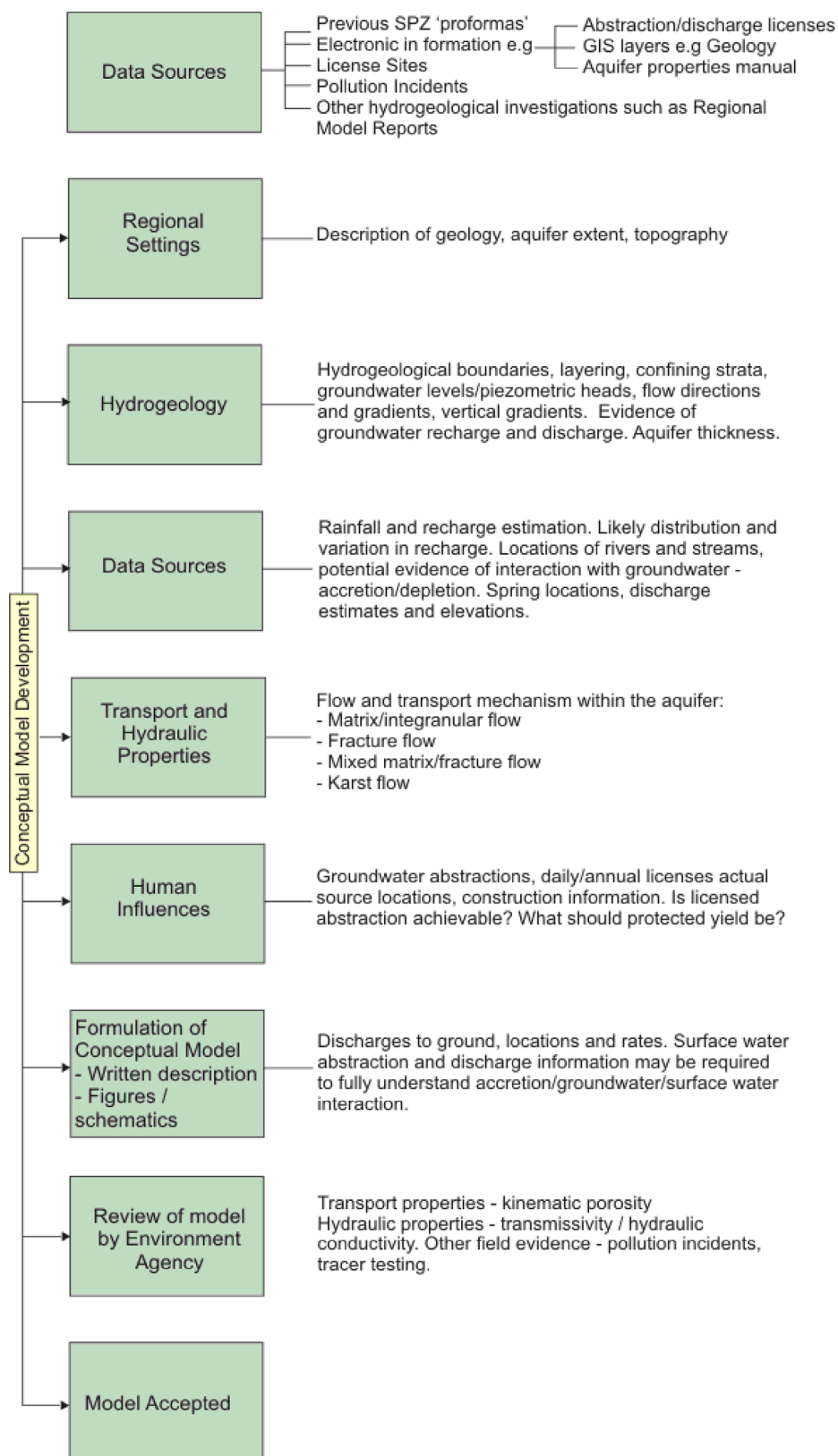


Figure 5.1 Example of a conceptual model prepared for SPZ delineation

The extent, accuracy and level of detail of data required to establish an adequate conceptual model needs to be balanced against resources and potentially the size, importance and vulnerability of the abstraction(s). Where resources are limited prioritisation of those factors that most affect the SPZ will be necessary. These are:

- recharge;
- aquifer hydraulic properties;
- boundaries;
- ground/surface water interaction.

5.1.1 Licence and source information

Information related to the abstraction licence and the construction of the source should be compiled on either a 'by source' or 'by lead source' basis. This information should include:

- licence number(s) and locations of source(s);
- maximum daily and annual license quantities;
- depth of borehole, open intervals and geological formations.

This information will come mainly from Environment Agency Area or Regional offices.

If the SPZ is being redefined, paper proformas from the previous SPZ delineation should be available. However, it is still necessary in such cases to enter the source and licence data in the data collation spreadsheets.

Other sources of information include the source operator/water company. The British Geological Survey holds extensive water well records at Wallingford, the majority of which are now available digitally to the Environment Agency in the Wellmaster database. The BGS also hold other information such as geological and hydrogeological maps, thematic maps, memoirs, regional guides, reports and borehole records, etc. at its National Geosciences Data Centre at Keyworth.

The abstraction licence data are crucial when setting:

- source protected yield;
- actual abstraction rates to be protected and to be used in of the definition of SPZs.

The definitions of protected yield are given in Section 2.5.

5.1.2 Electronic data sources

The following electronic datasets and sources are useful during conceptual model development and in the calculation of SPZs:

- groundwater levels from the Environment Agency WISKI database and/or contoured during other projects;
- surface water flow information from the Environment Agency WISKI database including spot gauging information indicating accretion or losses from surface water;

- Environment Agency nationally available GIS layers including:
 - solid and drift geology;
 - rivers and lakes;
 - digital elevation information (DTM/DEM);
 - OS basemaps for geo-referencing.
- BGS major and secondary aquifer properties manuals (Allen et al. 1997, Jones et al. 2000).⁵

5.1.3 Previous studies, reports and data

Where previous regional hydrogeological studies have been completed, the written reports and electronic data (where available) should be obtained.

Regional water resource modelling studies commissioned by the Environment Agency have large electronic deliverables including the reports, model data files, calibration information and probably spatial datasets in GIS format.

5.1.4 Spatial extent of data collation

The area to be covered by data collation depends on:

- size and number of abstractions;
- local geology;
- recharge;
- presence or absence of boundaries.

For sources that are being re-assessed, the original Source Evaluation Reports (SERs) should be used and updated. The reports and electronic deliverables from regional water resource modelling projects should be obtained where the source(s) are located within such models.

For sources that have not previously had SPZs defined, the spatial area for data collation should be determined as part of conceptual model development and in discussion with Environment Agency staff. This is particularly important in aquifers with complex recharge processes such as those where the outcrop is partially covered by drift deposits or karstic landforms. In such cases, surface catchments draining onto and recharging the aquifer may be extensive and lie in directions contrary to the regional groundwater flow direction.

⁵ Available from the hydrogeological reports section of the BGS Bookshop (<http://shop.bgs.ac.uk/Bookshop/>)

5.2 Assessment of data

5.2.1 Representativeness and precision of data

Appropriately qualified and experienced hydrogeologists should handle the assessment and interpretation of the data and information leading to the formation of a conceptual model. The involvement of Environment Agency staff with an experienced feel for the characteristics of a region or area is an especial advantage.

Among the factors to consider are:

- **Representativeness of the data:** critical consideration should be given to the validity and significance of point values from pumping tests or laboratory values against those representing bulk aquifer properties. Pumping tests, for example, may commonly yield aquifer characteristics influenced by fissuring in the vicinity of a borehole, which may not be as appropriate as regional values for use in a model. This process may be assisted by comparison with existing models in related or comparative areas where more appropriate model parameters have been derived;
- **Data precision:** accurate grid references are critical. Sources should be located to a minimum precision of 10 m. As a general rule, data such as grid references and boundaries derived from maps, photocopies, paper or film copies should be scrutinised with a view to the inherent inaccuracies or instabilities associated with those media. Inaccuracies of scale due to distortion or stretching of the media can be sufficient to cause error, which may be significant in terms of the size of the final modelled SPZ.

Digitised maps should be regarded with caution unless there is detailed information available on their origin, accuracy and original scale at which they were created.

Although many of the inputs to a model can reasonably be regarded as fixed, others such as source abstraction rates may vary with time. The modelling process necessarily represents either one moment in time or an approximation to an assumed average situation. Whatever the case, it should be clearly defined and justified prior to use in the model.

The use of models can conflict with the idea of using licensed abstraction rates in order to delineate the maximum possible SPZ size. It may be that this simply leads to destabilisation of the model in aquifers that are historically over-licensed. In reality, actual abstraction may fall short of what could legally be taken.

Logically, calibration can only be effectively carried out by using actual abstraction rates and then comparing model outputs against measured water levels and groundwater contours from the same period.

5.2.2 Quality assurance of collated data

The use of the data collation spreadsheets, databases and GIS is recommended to:

- assist in the compilation and cross-checking of basic information;
- become a source of reference.

Use of these software tools reduces, but does not eliminate, the possibility of error.

Grid references should be scrutinised carefully, especially those of sources for which SPZs are to be derived. A key check is to verify the location co-ordinates with the licence file map. Plotting of well locations within GIS and comparison with other mapping (e.g. within construction reports) can help to highlight inaccuracies.

Grid references derived from secondary databases (e.g. from regional modelling projects) should also be scrutinised.

If required, grid references should be verified by site visits.

For other data, normal quality assurance practices should be observed.

5.3 The conceptual model

The preparation of plans, contour maps, cross-sections and diagrams is essential in the development of a conceptual model. It often highlights data gaps and inconsistencies, and provides a method for checking that assumptions make sense in the light of existing data. Presentation of these figures also serves the reporting function and enables others to gain a rapid understanding of the system.

Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface (Environment Agency 2001a) and *Groundwater resources modelling: guidance notes and template project brief* (Environment Agency 2002) indicate the topics to be covered in conceptual models and include example figures.

As a minimum the conceptual model should include:

- a text description;
- sketch diagrams of the groundwater–surface water flow and transport system and processes;
- an integrated data map showing:
 - solid geology and, where appropriate, drift cover;
 - water table/piezometric surface for main aquifer units;
 - surface and groundwater abstractions and discharges;
 - direction of groundwater flow;
 - details of the source boreholes;
 - if applicable, details of any nearby large structures (constructions);
 - locations and details of any known pollution incidents;
 - other surface water features including river gauging stations, impoundments, transfers, spot measurements and catchments.

Depending on the complexity of the hydrogeological regime and the size and importance of the source(s) additional figures may be appropriate including:

- river profiles showing geology, water table and flow accretion for the main rivers;
- maps showing distributions of average recharge and aquifer properties;
- cross-sections showing groundwater levels and flows.

In areas with developed regional models, some of these figures may already be available from modelling study reports.

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6 Defining hydraulic capture zones

The main basis for source protection zones (SPZs) is the definition of hydraulic capture zones. This chapter considers the available methods for calculating hydraulic capture zones from simple manual calculations, through analytical solutions, to modelling techniques and software. Guidance is given as to the appropriate tools to use, but the final choice of methods is left for the user to determine.

This calculation phase is not the final step in the SPZ process. Further refinement and alteration of the hydraulic capture zones may be required to complete the delineation process (Section 7).

6.1 Previous modelling tools

The FLOWPATH modelling package was chosen as the main tool for SPZ calculations by the National Rivers Authority (predecessor to the Environment Agency) in the early 1990s. FLOWPATH is not a recommended option for future delineation because the developer no longer supports the software. The application of the FLOWPATH modelling package is described in the original SPZ manual and is not considered further. Guidance is provided on updating existing FLOWPATH models (Section 6.7).

The other commonly used modelling packages were WHPA (semi-analytical model) and MODFLOW/MODPATH. The WHPA package has been superseded by WHAEM (Well Head Analytical Element Model) and this updated package is described in Section 6.6.

6.2 Choice of technique

A wide range of techniques is available for calculating hydraulic capture zone areas around sources. Table 6.1 presents a hierarchy of approaches to delineation of hydraulic capture zones ranging from the simple to the complex.

In practice, the selection of a suitable approach will depend on factors such as:

- the availability of hydrogeological data for the source and surrounding aquifer environment;
- the perceived hydrogeological complexity of this environment, particularly in relation to the amount of data;
- the time and resources available and necessary to achieve an acceptable delineation.

Table 6.2 lists applicable methods and software groups, detailing the respective parameter requirements and their respective advantages and disadvantages.

The choice of model can be a complex decision and the temptation to use a more sophisticated (generally more rigorous but more resource intensive) model must be resisted if the existing data are inadequate or the use of the results does not demand it. The model is a working tool to achieve a specific objective – in this instance to enable the delineation of usable protection zones – and not an end in itself.

To illustrate the range of techniques, two extreme cases can be considered:

- **Where there is little existing site data, an area of complex hydrogeology and a need to establish SPZs quickly.** The use of any model in these circumstances would probably be inappropriate and, pending the acquisition of the additional data needed, the only reasonable and cost-effective course of action is to construct the zones using Best Professional Judgement. That is, taking best estimate meteorological and aquifer property data combined with topographic, drainage and other site information and defining the zones using manual techniques and hydrogeological interpretation. This process may be assisted by the use of simple analytical models to confirm that the intuitive choice of zone geometry is consistent with the likely range of aquifer properties. The minimum response is to define a circular area around the source; in many cases, this will be preferable than defining no zone at all. This will be a common response for small sources and is already defined within *The Water Code* (MAFF 1998),⁶ where a minimum 50 m protection zone is recommended. Where appropriate and depending on the information available, it is possible to use another simple shape such as an ellipse.
- **Where an existing and proven hydrogeological model is available from which the hydraulic capture zones can be obtained.** The boundaries of such a model are likely to encompass a number of sources for which SPZs are needed under GP3 (Environment Agency 2007a), some with a high priority for definition and others of lower priority. However, it would be normal practice to define all such zones within the modelled area as this can be done with only modest additional cost. Regional groundwater models exist for principal aquifer units where they are required to aid the management of groundwater resources. They are restricted to those aquifer units with large volumes of groundwater pumping or where there are large-scale developments such as groundwater river support or artificial aquifer recharge schemes.

Some groundwater SPZ definitions will fall between the two extremes described above, whereby modelling solutions will be appropriate but no regional models are available.

The general approach in using semi-analytical, analytical element and numerical models to define hydraulic capture zones is to:

- define the groundwater flow field;
- release particles close to the source;
- track the particles back through the flow field to define travel times zones.

⁶ Available from: <http://www.defra.gov.uk/farm/environment/cogap/>

Table 6.1 Hierarchy of hydraulic capture zone delineation approaches

Method of delineation	Comment on applicability
Best Professional Judgement (BPJ)	<p>The need for BPJ arises when there is a lack of data or the hydrogeological regime is highly heterogeneous, or there is an important need to define a SPZ quickly.</p> <p>BPJ arises at two levels. First to decide whether it is appropriate to define a SPZ at all. This is a valid judgement, though in most circumstances and providing all users of the SPZ understand the limitations, it is better to have a zone to flag up a need for caution in land management decisions rather than not have one and risk the issues being ignored.</p> <p>Secondly, if the decision is to have a SPZ, use BPJ to define one with the sparse data available using essentially manual techniques. This situation commonly arises, for example, with small sources; the various methods available are set out in more detail in Section 6.4.</p>
Manual methods/ analytical solutions, e.g. simple recharge circles and Bear and Jacob	<p>Applied when data are available on the source and there is limited aquifer information. Of use particularly for small sources as an aid to BPJ.</p>
Analytical element models e.g. WHAEM, Split, WinFlow	<p>A widely applicable method that can be rapidly developed to cover simple single sources to relatively complex aquifers with many tens of sources.</p> <p>Some software (e.g. WHAEM) include simple analytical solutions (recharge circles, etc.) within their tools. This enables the progression from simple analytical solution methods to more complex modelling within one package. This can help to provide additional checking of model solutions and to develop confidence in results.</p> <p>This is normally a robust and cost-effective method.</p>
Distributed numerical models e.g. MODFLOW/ MODPATH	<p>Where models already exist, there is the potential to use them for hydraulic capture zone delineation. Experience suggests that the adaptation of regional models for SPZ work is not necessarily a straightforward or inexpensive option.</p> <p>MODFLOW/MODPATH models can be developed specifically for hydraulic capture zone delineation. Although the data demands for such models are much less than for time variant regional models, they do require more information and time to develop than analytical element techniques. Due to the longer time involved in setting up MODFLOW/MODPATH, it is recommended that this method is only used after an analytical element model has been developed.</p>
Geostatistical methods	<p>Many geostatistical methods reported in the literature are applied to consider the spatial variations in aquifer properties and incorporate the potential influence of these on groundwater flow paths. However, the use of such methods is likely to be impractical in terms of time, cost and data availability.</p>

Table 6.2 Advantages and disadvantage of different methodologies for hydraulic capture zone delineation

Classification	Capture zone method	Parameters that can be represented	Advantages	Disadvantages
Best Professional Judgement	Hydrogeological mapping	System boundaries and approximated divides	Should be combined with all other methods Good for karst and fractured aquifers with strong geological control	Poor in areas with indistinct boundaries Not quantitative
Manual methods/ analytical solutions	Fixed radii circular zones	None	Low cost Easy and quick to implement Highlights lack of data	No technical basis Does not have regard to local hydrogeological conditions
	Calculated zones based on recharge and abstraction	Recharge Time of travel Abstraction rate Kinematic porosity	Low cost Easy and quick to implement with minimal data requirements Some technical basis	Simplistic, does not represent detailed local hydrogeological conditions
Manual methods/ analytical solutions	Standard shaped zones based on idealised representation of local conditions	Hydraulic gradient Hydraulic conductivity Aquifer thickness Kinematic porosity Recharge – but all as single value parameters	Can represent a very simple system Easy and quick to implement Semi-quantitative	Local conditions may differ significantly from those used in the initial delineation Data may not be available
Analytical element models	Analytical modelling – WHAEM, Split, WinFlow, QuickFlow	Hydraulic gradient Hydraulic conductivity Aquifer thickness Kinematic porosity Recharge Simple recharge/barrier boundaries – some limited parameter variability possible	Capture zones based on idealized representation of local aquifer conditions Can represent a simple system Quantitative Simple and uniform boundaries and recharge allowed for	Darcian flow assumed Modest data requirements Assumes infinite aquifer Does not allow complex boundary and recharge effects to be considered

6.3 Translating conceptual models into hydraulic models

Before starting to translate the conceptual model into a numerical representation, it is important to consider the capabilities and limitations of flow modelling techniques.

There are circumstances, for example, where the available software is inappropriate for the complexity of a particular problem and/or the available data provide a poor description of the aquifer, and where modelling may not actually assist in the zonal delineation process. It is important to recognise the limitation of modelling in this respect and a manually derived capture zone may be the only reasonably practicable option. When not to model is a subjective decision balancing justifiable cost against the likely validity and usefulness of the output. Such decisions need to be made before modelling begins and false accuracies implied.

The transfer of the conceptual model to a groundwater flow model requires a level of idealisation within the computer code adopted. The process of idealising actual values to modelled values should be well documented in order to make the model understandable, repeatable and hence defensible. In particular, there should be a reasoned justification of the values used within the model including the design of the model grid, boundary conditions, aquifer properties, river/aquifer interactions, abstractions and groundwater recharge.

Transferring a conceptual model to a groundwater flow model requires the accurate locating of geological and hydrogeological boundaries. This is assisted by directly transferring spatial map information into modelling software. All relevant abstractions must also be identified and accurately located in the model domain; direct transfer of co-ordinates using data files is the preferred method.

Areal variations of recharge, transmissivity, storativity and kinematic porosity need to be converted into a form that can be handled by the computer code. The distribution of these parameters in the model domain may require adjustment, within the constraints set by the conceptual model, to achieve the necessary degree of calibration.

Groundwater flow modelling is necessarily an iterative process, with revision of aquifer parameters, boundaries, etc., and even the re-formulation of the conceptual model possibly necessary to achieve the required accuracy and ultimately the defensible delineation of source capture zones.

Additional guidance on the construction of numerical models is given in:

- *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface* (Environment Agency 2001a);
- *Groundwater resources modelling: guidance notes and template project brief* (Environment Agency 2002).

6.4 Manual methods

Hydrogeological mapping techniques are an essential component of delineating SPZs (particularly Catchment Protection Zones) to ensure SPZ boundaries are consistent with geological and hydrogeological features (see also Section 7.4). In some cases, they may represent the best method for defining zones (e.g. in karstic aquifers, or where data are limited or do not justify the use of a numerical model; see Section 4).

Hydrogeological mapping should consist of:

- collation of geological and hydrogeological maps (geological boundaries, outcrop area, catchment divides, rivers, etc.);
- development of a conceptual model of the source catchment including supporting cross-sections;
- site visit (more relevant to karst or spring sources than borehole sources);
- recording basis for defining SPZ boundaries.

6.5 Simple manual methods and analytical solutions

This section describes:

- simple manual methods of delineating circular hydraulic capture zones;
- analytical solutions that produce ellipsoidal hydraulic capture zones.

These methods are only suitable:

- where field data are extremely limited;
- when rapid SPZ delineation is required;
- for comparison with, and checking of, more complex techniques.

6.5.1 Catchment protection areas

The area A_R (m^2) of a source catchment in a region subject to annual recharge R_e (m) may be calculated from the simple water balance relationship as:

$$A_R = \frac{\text{Protected yield}}{R_e} \quad \text{Equation 6.1}$$

where:

protected yield of the source = groundwater pumping rate (see Section 2.5).

This calculation can only be used as a guide because recharge over the catchment area may vary for reasons such as the presence of drift deposits, variable vegetation cover, etc.

If the piezometric surface is horizontal, the catchment to an abstraction source may be assumed to be circular and hence the catchment radius can be readily calculated (Figure 6.1). Although this situation does not normally occur in practice, it is a useful approximation where there are insufficient data to determine the hydraulic gradient and the direction of groundwater flow.

Equation 6.1 has been used to delineate catchment areas around those sources (within the national SPZ programme) for which there are insufficient data to justify the use of numerical models equation. However, the SPZs have generally been modified manually to have regard to local geological and topographical boundaries.

In some instances, the interference between adjacent or nearby abstraction boreholes may need to be taken into account. In such cases, semi-analytical or numerical models are more appropriate. The use of such models has shown that the geometry of

hydraulic capture zones can be complex and that zones drawn by manual methods may represent an oversimplification of the true geometry.

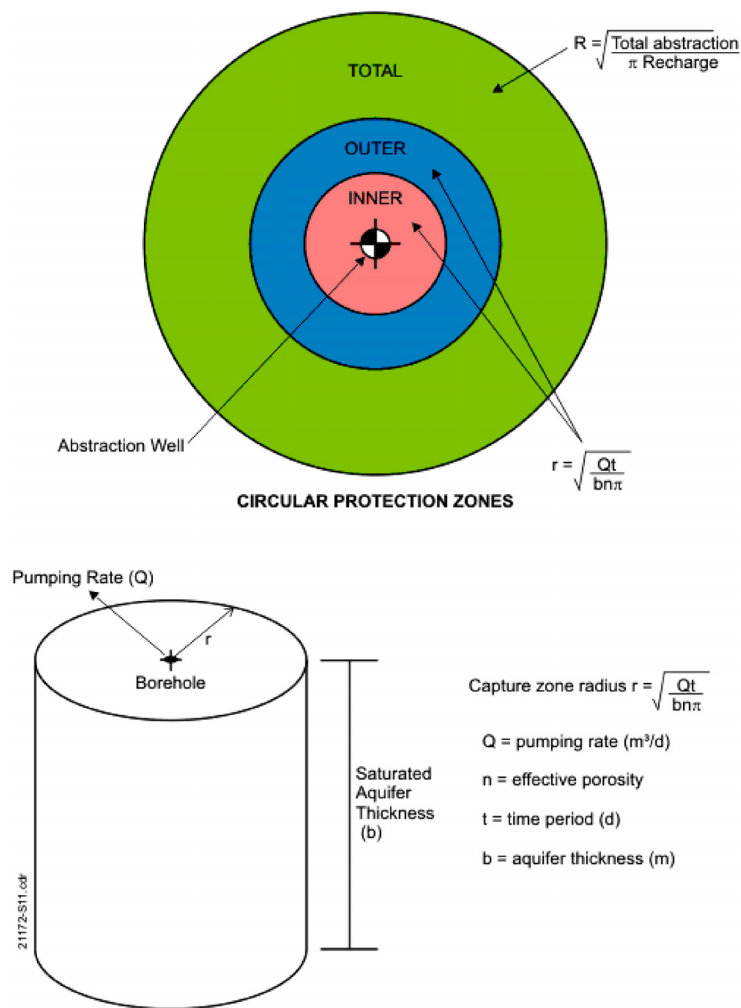


Figure 6.1 Protection zone delineation using volumetric flow method

6.5.2 50 and 400 day capture zones

An estimate of the area A_D (m^2) of a time of travel, t_d (days), capture zone can also be computed using a volumetric approach as:

$$A_d = \frac{qt_d}{bn} \quad \text{Equation 6.2}$$

where:

- q (m^3/d) = either the protected yield \div 365 or the licensed maximum daily quantity (depends on whether it is the 50 or 400 day capture zone that is being calculated for Inner or Outer Protection Zone)
- b = aquifer thickness (m)
- η = kinematic porosity.

This equation makes no allowance for recharge and assumes the aquifer thickness is constant.

Without information on the direction of groundwater flow, hydraulic capture zones may be assumed to be circular with radii calculated as illustrated in Figure 6.1. But where the zones intersect boundaries (faults, edge of outcrop, etc.), these are used to define the limits of the SPZ and the radius of the circle is increased to give the correct area.

These manual calculations make a number of gross simplifying assumptions regarding the nature of the aquifers. However, they have been found to be useful in giving a rapid indication of the size of SPZs in situations where more complex calculations are inappropriate.

6.5.3 Analytical solutions

The simple manual methods described above are normally used in situations where water level or hydraulic gradient data are absent. In the more general situation where the hydraulic gradient can be determined, theoretical methods are available to describe the flow field around a source and hence delineate time of travel zones.

The equation (Bear and Jacob 1965) describing the boundary line (Figure 6.2) of a hydraulic capture zone around a borehole in a confined aquifer of infinite extent with a uniform hydraulic gradient is given by:

$$\frac{y}{x} + \tan\left(\frac{2\pi k b i y}{q}\right) = 0 \quad \text{Equation 6.3}$$

where:

- q = abstraction rate (m³/d)
- k = hydraulic conductivity (m/d)
- i = hydraulic gradient (m/m)
- b = aquifer thickness (m)
- x and y = co-ordinate directions (m).

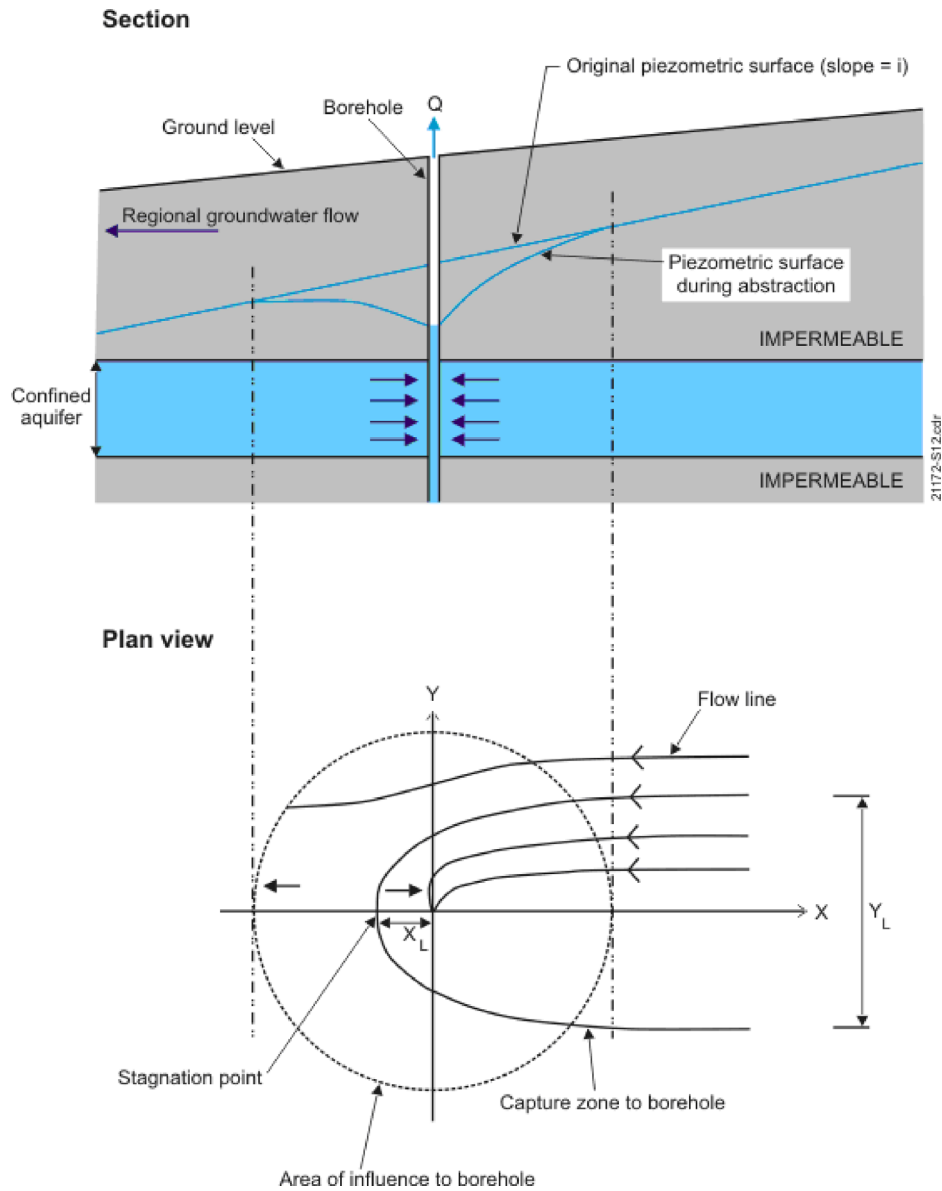


Figure 6.2 Capture zone to borehole located in uniform flow field

Equation 6.3 can be solved to give the maximum up-gradient width Y_L of the hydraulic capture zone as:

$$Y_L = \frac{q}{kbi} \quad \text{Equation 6.4}$$

and X_L , the maximum down hydraulic gradient extent as:

$$X_L = \frac{q}{2\pi kbi} \quad \text{Equation 6.5}$$

The co-ordinates of points (x,y) along the isochron, or line in the aquifer, from which the time of travel t_d to the abstraction borehole are identical can be described by the following equation:

$$e^{-t^*} = e^{-z} \left(\cos w + \frac{z \sin w}{w} \right) \quad \text{Equation 6.6}$$

where, to facilitate ease of use, z , w , and t^* are non-dimensional quantities defined by:

$$z = \frac{x}{X_L}, \quad w = \frac{y}{X_L}, \quad t^* = \frac{kit_d}{nX_L} \quad \text{Equations 6.7}$$

For points along the x-axis, the line passing through the borehole in the direction of regional groundwater flow, Equation 6.7, reduces to:

$$t^* = z - \log(1 + z) \quad \text{Equation 6.8}$$

The travel time from any point to the source can readily be calculated using Equation 6.8, but the inverse problem of determining (x,y) given t_d requires the use of numerical methods. Such methods are included within the Well Head Analytical Element Model (WHAEM) package developed by the US Environmental Protection Agency (US EPA) (Section 6.6).

6.6 Analytical element models

Analytical element models were first developed in the early 1990s, with examples including WHPA and QuickFlow. These have now been superseded, in part due to developments in the analytical element techniques, and also due to changes in computer power and operating systems.

The Analytic Element Community (<http://www.analyticelements.org>) defines the Analytical Element Method (AEM) as:

‘... a technique for solving problems in continuum mechanics that is based on the superposition of analytical functions and requires no discretization of the model space.’

The advantages of the AEM for calculating hydraulic capture zones are as follows:

- Only boundary conditions are discretised, not the domain of the model. The numerical solution is calculated continuously throughout the study area. There are no issues with grid size.
- AEM can model large areas yet retain great accuracy in small regions. This means cones of depression around pumped wells are represented accurately and particles backward tracked from pumped wells follow realistic paths. This is vital in SPZ calculations.
- AEM models have simple input, can be developed rapidly and generally solved quickly. Additional complexity can be added incrementally.
- Irregular boundaries can be represented.
- Rivers can be included – by defining river location, river level and a simple leakage term.
- Multiple abstraction sources can be represented and particle tracking can be performed for all of these sources.
- Simple variations in aquifer properties (thickness and hydraulic conductivity) and recharge can be represented, although the model may become unstable if this becomes too complex.

Analytical models can represent non-uniform flow fields and therefore provide a close match to observed conditions. As a result, they start to approach the complexity that can be achieved using a numerical flow model.

The disadvantages of the method are as follows:

- Very complex spatial changes in parameters cannot be represented.
- The range of boundary conditions is limited compared to distributed numerical models such as MODFLOW.
- The majority of AEM models are two-dimensional (2D) and cannot represent multiple layer aquifer systems. However, three-dimensional (3D) modelling for hydraulic capture zone definition is rarely considered because of lack of data/information on the vertical hydraulic conductivity and its spatial variation.

The application of early AEM models was limited by the low level of complexity that could be represented. Current AEM models and computing power now permit greater heterogeneity to be simulated, with many hundreds or thousands of boundary condition elements including abstraction wells and rivers/streams.

A review of currently available AEM modelling software was undertaken as part of the project to update this manual. The review identified a short list of AEM software for more detailed assessment. The aim of the review was to assess the applicability of each model and to highlight the software that may be most suitable for time of travel and hydraulic capture zone calculation. Table 6.3 lists the software considered.

From the list in Table 6.3, two software packages are highlighted as being particularly applicable to the calculation of hydraulic capture zones used for delineation of SPZ hydraulic capture zones. These are:

- WHAEM – the successor to WHPA with continuing development by US EPA;
- WinFlow – the AEM model developed by ESI Ltd (<http://www.esinternational.com/>) and sold with its pumping test software Aquifer Win32.

The recommendation of these two packages is not prescriptive. Any software that can perform calculations of hydraulic capture zones adequately can be used.

These two software packages are recommended ahead of the others in Table 6.3 for a variety of reasons including:

- they are actively developed and this is thought likely to continue;
- support is likely to be available in future years;
- they have intuitive user interfaces without additional complications;
- they work natively (without file conversion) with common data transfer file formats such as shapefiles (.shp) for both import and exporting;
- they can use and display a wide range of other files such as .tif images for OS basemaps;
- they are standalone, i.e. they are not tied to specific versions of other software packages that may be upgraded (e.g. ArcGIS).

Table 6.3 Assessed analytical element modelling packages

Modelling system	Computation engine (solver)	Version assessed	Graphical user interface	Licence	Comment
WHAEM2000	GFLOW1	Version 3.2.1 Sept 2007	Yes	Open Source Artist Licence, Free	Successor to WHPA Continued development funded by US EPA
WinFlow	Proprietary	Version 3	Yes	Proprietary	ESI Ltd is the developer and vendor. Now sold as part of Aquifer Win32
Visual BlueBird	SPLIT, BlueBird Cardinal and Ostrich	2.0 2005	Yes	Open Source Free	Open source project with flow transport and optimisation packages
ArcAEM	SPLIT	2.2 (beta) 2006	Uses ArcGIS	Open Source, Free	SPLIT AEM is driven using ArcGIS as a user interface Current version requires ArcGIS v9.1
TWODAN	Proprietary	5.0 1998	Yes	Proprietary	Fitts Geosolutions is the developer and vendor.
TimML	TimML	3.0 Feb 2007	No	Open Source, Lesser General Public Licence (free)	Simulates multi-layer s flow. No user interface

Figure 6.3 illustrates the use of WHAEM to define hydraulic capture zones.

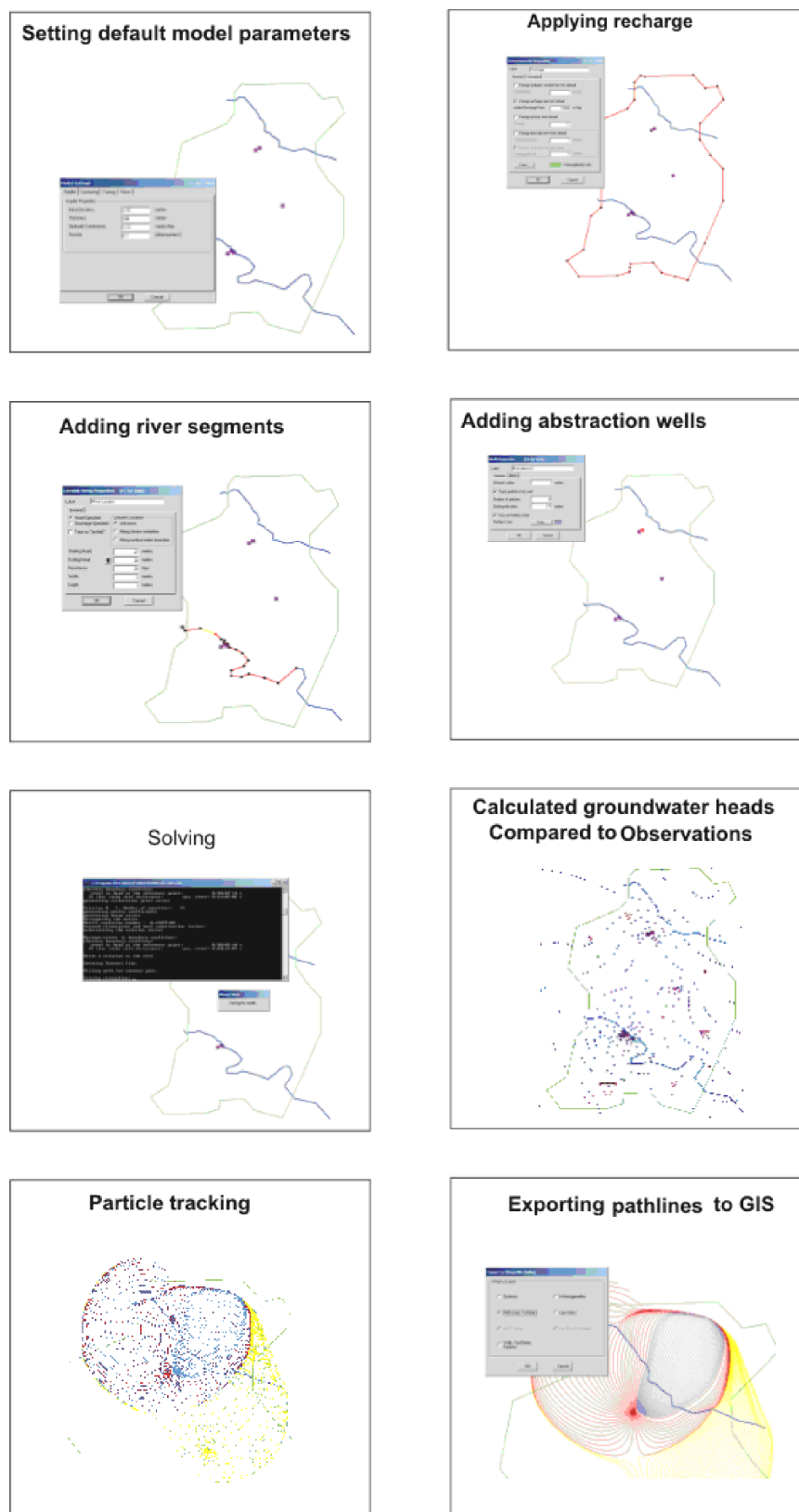


Figure 6.3 Example application of WHAEM to define hydraulic capture zones

6.7 Recommendations for updating FLOWPATH models

FLOWPATH was used for the bulk of SPZ delineation during the 1990s. As a consequence, a large number of FLOWPATH models exist. If these models are accepted as representations of the aquifer system then, following a relatively rapid assessment that no major changes have occurred in hydrogeological understanding or environment, it is acceptable to reuse the existing interpretation.

Where SPZs require updating and the electronic FLOWPATH files are available, there are three options:

1. Use the FLOWPATH model as the basis of an AEM model. This could include the use of Groundwater Vistas as an intermediate step to extract FLOWPATH model information. (Groundwater Vistas is capable of creating a MODFLOW model based on FLOWPATH files, from which data can be exported).
2. To convert the dataset to a MODFLOW finite difference model and complete the update using MODFLOW for the flow solution and MODPATH for particle tracking. Again this requires the use of Groundwater Vistas.
3. To find an old FLOWPATH executable and complete the update using FLOWPATH.

The first option is recommended. It is possible to re-create the majority of FLOWPATH models within AEM models, particularly WHAEM. By using Groundwater Vistas, it is possible to export data from the FLOWPATH model in geo-referenced files. This conversion to an AEM model should be a relatively rapid exercise.

The second option of conversion to MODFLOW/MODPATH is potentially more time-consuming. It can be problematic to achieve appropriate flow solutions in MODFLOW and, beyond this, setting up and running of MODPATH is required. As AEM models are rapid to set-up, it is recommended that the first option be tried before moving to MODFLOW/MODPATH. This approach of FLOWPATH to MODFLOW conversion has already been adopted by the Environment Agency's Southern Region to maintain usability.

The third option, to use FLOWPATH, is essentially a retrograde step as it does not address the fact that FLOWPATH is no longer sold or supported. At some point, with operating system changes, it will not be possible to run FLOWPATH on a normal PC. It is recommended that FLOWPATH datasets be converted to another format.

Where electronic files have been lost, it may be practical to re-create essentially the same model using AEM software based on paper records. If the FLOWPATH model was an accepted representation of the aquifer, this option is preferred. If not, re-conceptualisation and a new model are recommended.

6.8 More complex models

More complex modelling tools may be required in:

- aquifers with extensive heterogeneity –particularly in base elevation or hydraulic conductivity;
- larger regional aquifers that cannot be split practically into smaller units.

In these cases, AEM models may not be capable of simulating the degree of heterogeneity required to achieve an acceptable representation of the hydrogeological system.

The MODFLOW/MODPATH codes are discussed below in more detail because of their widespread use in the UK and elsewhere in the world.

The MODFLOW code developed by the US Geological Survey (USGS) has been the Environment Agency's preference for regional-scale water resources models since the late 1990s. As such there is a wide body of MODFLOW experience both within and outside the Environment Agency. MODFLOW is a fully distributed quasi-3D finite difference model capable of representing a wide variety of boundary conditions. MODPATH is a USGS-developed particle tracking program written for use with MODFLOW. Simulating groundwater flow using MODFLOW and then performing backwards particle tracking from around pumped wells is a viable option for SPZ calculations. There are, however, some drawbacks which are discussed below.

MODFLOW and MODPATH were applied in the mid-to-late 1990s for SPZ delineation in some areas of complex hydrogeological environments. An example is the Environment Agency's Southern Region SPZ model of the Itchen catchment. Such models typically have hundreds of rows and columns with widely variable spacing to provide a refined grid around abstractions to allow better definition of the flow field and to facilitate particle tracking accuracy. The mesh density is concentrated around pumped wells to enhance particle tracking accuracy.

A further option for SPZ delineation is to adapt regional water resources models based on MODFLOW. Over 20 regional models have been developed in England and Wales over the last 8–10 years. These models have uniform grid spacing. Typical grid sizes are 200, 250 or 500 m. The adaptation of a regional model for SPZ delineation was completed with the West Midlands Worfe model. However, conversion of a regional, time variant model to steady state with substantially increased mesh density around pumped wells is not a trivial exercise. As additional rows and columns are added, boundary conditions such as stream cells require re-defining.

The use of regional flow models is unattractive for SPZ delineation due to the complications of:

- converting time variant models to steady state;
- refining constantly spaced meshes;
- re-defining boundary conditions (particularly stream cells).

Until a clear and cost-effective methodology is developed to utilise the 'in built knowledge' of regional models, the conversion of regional water resources models for SPZ delineation is not recommended.

6.9 Adits and other elongate sources

Adits and similar elongated sources present additional difficulties in defining SPZs as they can distort the flow field and provide rapid pathways for contaminant movement. Typically information on the influence of the adit on the flow field can be limited.

Approaches to the delineation of SPZs around such sources include the following:

- Define default distances around the feature. The SPZ is defined by marking their location on a map and defining a minimum 50 m width strip around them where they extend beyond the Inner Protection Zone. Where the adit

extends beyond the Outer Protection Zone, both a minimum 50 m Inner Protection Zone and a minimum 250 m Outer Protection Zone are defined as illustrated in Figure 6.4.

- If numerical methods are used, the adit can be represented by a high permeability zone. Information on the relative flow contribution to the source from each adit, together with detailed local water level data, is required to calibrate the model. This is performed by adjusting the permeabilities representing the adit to simulate the observed water level data. A more rigorous numerical approach to representing adits is given in Environment Agency (2001a), which also shows that the approach of representing adits with high permeability zones is adequate in most cases.
- Divide up the adit into sections and represent each section as a discrete borehole in the model. The protected yield is divided between the boreholes according to the known or perceived contribution of each section to the adit yield.

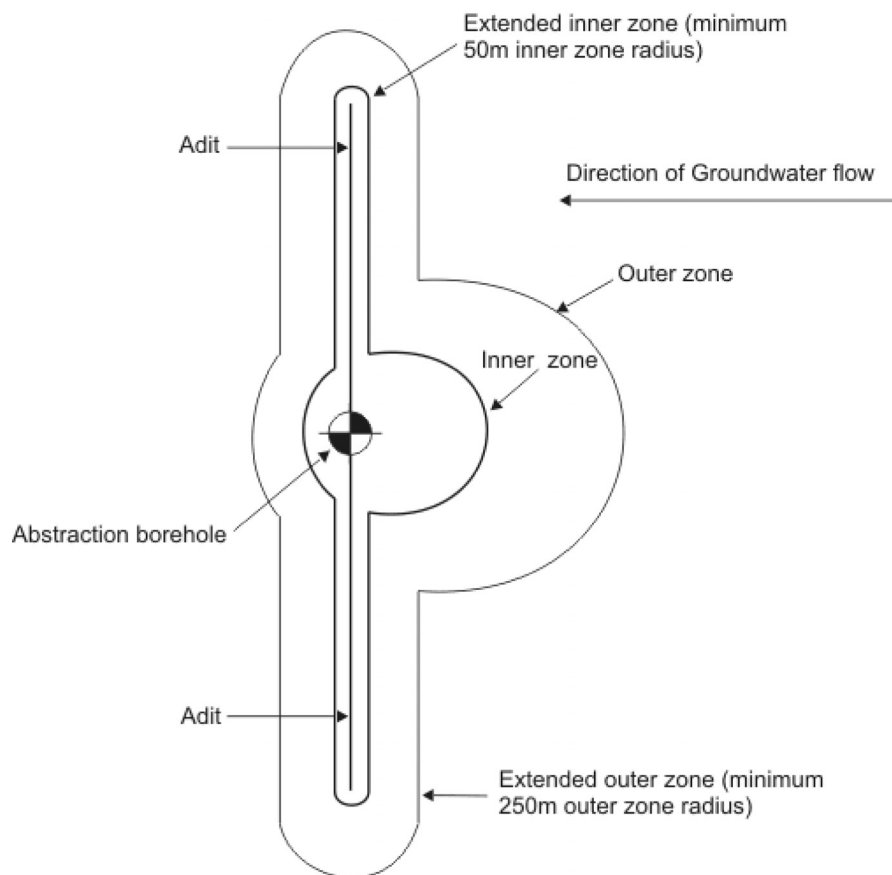


Figure 6.4 Minimum dimensions of zones around wells with adits

6.10 Model procedures and guidance

Sources of guidance relevant to SPZ modelling procedures include:

- *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface* (Environment Agency 2001a);
- *Groundwater resources modelling: guidance notes and template project brief* (Environment Agency 2002).

These documents give guidance on:

- the modelling process from data collation, processing and interpretation through to conceptual models;
- creating numerical models;
- their calibration and final use.

However, there are a number of issues specific to modelling for SPZ calculations which are described below.

6.10.1 SPZs and over-exploited aquifers

In the 1990s SPZ programme, some problems arose when developing steady state models for aquifer units which are overexploited, with licensed abstractions exceeding estimates of recharge.

Where this occurs, the recent actual abstraction quantities given normal operation of the source should as a minimum be modelled rather than the full licence. This is the preferred option, particularly if there is any doubt as to whether the full licence can be obtained.

Consultation with the licence holder and Environment Agency licensing staff regarding their future plans for the source and their view of the abstraction to protect yield is also recommended (Section 2.5).

6.10.2 Particle tracking

The following recommendations are made for completing particle tracking to estimate hydraulic capture zones:

- Set particles at a release radius of <20 m from the source;
- Release a minimum of 40 particles. Experience from zone calculation indicates that 40 particles typically yield sufficient resolution to define a catchment zone area. However, good practice is to check the resulting hydraulic capture zone shape to determine whether this is adequately defined and, if not, repeat process using additional particles.
- In WHAEM, reduce the tracing step size to ensure maximum resolution when completing particle tracking. If particle tracks appear to cross, then the tracing step size is too large.
- When calculating catchment zones, extend the tracking time sufficiently to enable particles to reach model boundaries or internal recharge sources.

The length of tracking time will vary depending on the model, but times in excess of 50,000 days may be required.

- For more complex numerical representations such as conducting particle tracking using MODPATH with MODFLOW, the depth of release of particles needs to be considered.
 - In single layer models, the depth of particle release should be guided by the depth of penetration and the well construction. This usually leads to the release of larger numbers of vertically distributed particles.
 - In multi-layer models, further consideration is required where wells represent abstraction from several horizons. The vertical distribution of particles should aim to reflect the relative contribution to well yield from the distinct horizons. Particle tracking in multi-layer models can lead to unexpected results including development of separate ‘tails’ and gaps between recharge areas. The vertical hydraulic conductivity and depth of particle release have a strong influence on the results of particle tracking in a multi-layer model. The definition of the SPZs from the hydraulic capture zones should be done with extreme care, given the relative lack of data/information on the vertical hydraulic conductivity and its spatial variation.

6.11 Uncertainty

The delineation of SPZs as set out in the previous version of this manual required a sensitivity analysis to determine zones of ‘confidence’, zones of ‘uncertainty’ and ‘best estimate zones’. This involved changes in the values of recharge, hydraulic conductivity and hydraulic gradient by specified amounts (typically 20 per cent), but necessitated 27 separate model runs. This process is time-consuming and the Environment Agency’s experience is that only one of these zones is used – often the best estimate zone for Chalk sources and the zone of uncertainty for the Permo-Triassic Sandstone sources.

A more pragmatic approach to determining SPZs is therefore required, but one which reflects uncertainty in the conceptual understanding of the flow regime around a source and uncertainty in parameter values.

A two-step approach should be used for the uncertainty analysis that aims to address both these aspects of uncertainty in a pragmatic manner:

- a limited sensitivity analysis on the best estimate hydraulic capture zones based on realistic variations in the main parameter values of the model;
- hydrogeological judgement to modify the best estimate hydraulic capture zones.

The two-step approach is summarised in Table 6.4. The second step is explicitly included in the process to define the SPZs from the hydraulic capture zones as described in Section 7.

Table 6.4 Approaches for uncertainty analysis

Step	Method	Requirements
1. Sensitivity analysis	<p>Three groundwater model runs based on best estimate model:</p> <ul style="list-style-type: none"> • decrease in recharge; • increase in hydraulic conductivity; • decrease in hydraulic conductivity. <p>One particle tracking run based on the best estimate model: decrease in kinematic porosity</p>	<p>Parameter ranges have to be specified and justified before the start of modelling.</p> <p>Recommended sensitivity variations are:</p> <ul style="list-style-type: none"> • recharge –15% • hydraulic conductivity $\pm 30\%$ • kinematic porosity –30%. <p>Any sensitivity variations should lie within the parameter ranges specified.</p> <p>Where hydraulic capture zones have been modelled using a numerical model and this provides an acceptable simulation of groundwater conditions, the sensitivity analysis may be limited to the kinematic porosity.</p>
2. Hydrogeological judgement to modify best estimate hydraulic capture zones	Part of the procedure for final SPZ delineation as set out in Section 7.	Reporting of changes is mandatory, together with any supporting information

6.12 Transfer of calculation output to GIS

Following satisfactory modelling and particle tracking, or analytical calculation of the hydraulic protection using one or more of the techniques described in this section, the results need to be transferred to a GIS environment. Transfer to GIS enables:

- further modifications to be made to zone boundaries as part of final SPZ definition (Section 7);
- storage of information in a standardised form;
- ease of SPZ publication.

Where particle tracking has been used, the following recommendations for transfer are made:

- Export the particle tracks as shapefiles (.shp) to provide maximum compatibility with current GIS software.
- Export 50 day, 400 day and catchment zones particle tracks separately.
- Export each source separately using a unique filename composed of the source name, licence number and the path line type (e.g. 50 day).

The export of other information such as the abstraction well locations is recommended for quality assurance purposes.

Where analytical calculations have been made, typically leading to circular or ellipsoidal areas, these areas should be transferred to the GIS environment – preferably using the shapefile (.shp) format.

7 Definition of SPZs

This chapter describes the process for the final definition of source protection zones (SPZs) following the process to define hydraulic capture zones (Section 6). The transition from calculations to definition of final SPZs is an important step. Calculated areas should be examined carefully, the conceptual model and spatial datasets such as geology re-considered, and the zone potentially altered prior to final SPZ definition.

Reasons for altering calculated areas when completing SPZ definition include:

- modifications to ensure that SPZ1 (Inner) and SPZ2 (Outer) meet the minimum criteria noted in their definitions in Section 2;
- adjustment of hydraulic capture zone boundaries where additional geological and/or hydrogeological information is available (e.g. geological boundaries, results from tracer tests, etc);
- practical changes (e.g. to remove overlaps after re-calculation of a single source) or, if required, extension to include all the area between two large abstractions. This also includes the removal of 'long tails', a common issue with modelled areas (Section 7.2).

This step also acknowledges that the model and calculation tools recommended in this manual cannot capture all aspects of real life hydrogeological systems – particularly the detailed spatial variability of aquifer properties associated with aquifer heterogeneity. Some of their shortcomings can be addressed, to an extent, by applying professional knowledge and judgement.

All adjustments to hydraulic capture zones require documenting. Decisions made during this stage should also be justified. Simple alterations such as an extension to reach a geological boundary due to its approximate representation within a model require only little justification. Where a hydraulic capture zone has been altered for more complex reasons (e.g. based on tracer test results), additional justification is required.

The examination of calculated areas and comparison with other spatial datasets is most easily completed within GIS. Therefore, it is recommended that all adjustments are completed within a GIS environment. The Environment Agency has developed GIS tools specifically to help in the adjustment and documentation process these will be detailed in a companion report to this volume.

7.1 Initial zone definition steps in GIS

This section gives recommendations regarding the transfer of hydraulic capture zones to the GIS environment (see also Section 6.12). Where particle tracking has been completed, it is recommended that the tracks be transferred in a geo-referenced electronic file such as the .shp shapefile format.

The first task within GIS is to import the hydraulic capture zone files containing 50 day, 400 day and catchment zone information. As a quality control step, the actual locations of source(s) should also be transferred to GIS. Additionally the loading of an OS basemap is recommended to ensure that geo-referencing is correct.

If particle tracks have been imported, the second step is to draw an envelope around the particle tracks to create an area as the basis of the zone. This step should be

repeated for 50 day, 400 day time-of-travel and total catchment areas. GIS tools developed by the Environment Agency are available to help automate this process.

In cases where the total aquifer area has been designated as a catchment protection area, boundaries are likely to be defined from existing GIS layers.

After production of initial zones, two further steps can be completed:

- calculation of the initial zone areas in m²;
- drawing of 50 m and 250/500 m circles centred on the abstraction source.

These feed into further steps detailed below.

7.2 Adits and other elongate sources

The models for SPZs for sources made up of adits or other elongate features (Section 6.9) need to be checked to ensure they meet the following default criteria.

- The Inner Protection Zone is defined by marking the location of the adits or other elongate features on a map and defining a minimum 50 m width strip around them if they extend beyond the 50-day capture zone.
- Where the adit extends beyond the 400-day capture zone, both a minimum 50 m Inner Protection Zone and a minimum 250 m Outer Protection Zone need to be defined (Figure 6.4).

7.3 Minimum shape factors

Modifications can be made to the boundaries of SPZs to deal with the situation where the modelling process may have resulted in hydraulic capture zone shapes characterised by long thin tails or where there are gaps/holes between zones (Figure 7.1).

In reality, these features are likely to be a function of the accuracy of the model (particularly in dealing with interference or small abstractions). A high level of uncertainty will be associated with the precise location of these features and, therefore, their relevance to aquifer protection.

In summary the following modifications can be made:

- **Truncating tails.** Remove the smaller and less significant odd shapes and holes by adopting a minimum shape factor of 50 m. This can be achieved by moving a 50 m radius circle around inside the zone in GIS. Elongated tails should be truncated at the point where the 50 m circle touches both sides.
- **Incorporation of larger holes into the adjacent SPZs.** The Environment Agency will need to consider the significance of this change to aquifer protection and catchment activities.

These modifications are pragmatic rationalisation of hydraulic capture zones, removing difficult to defend areas which have considerable uncertainty and applying the precautionary principle when infilling between zones.

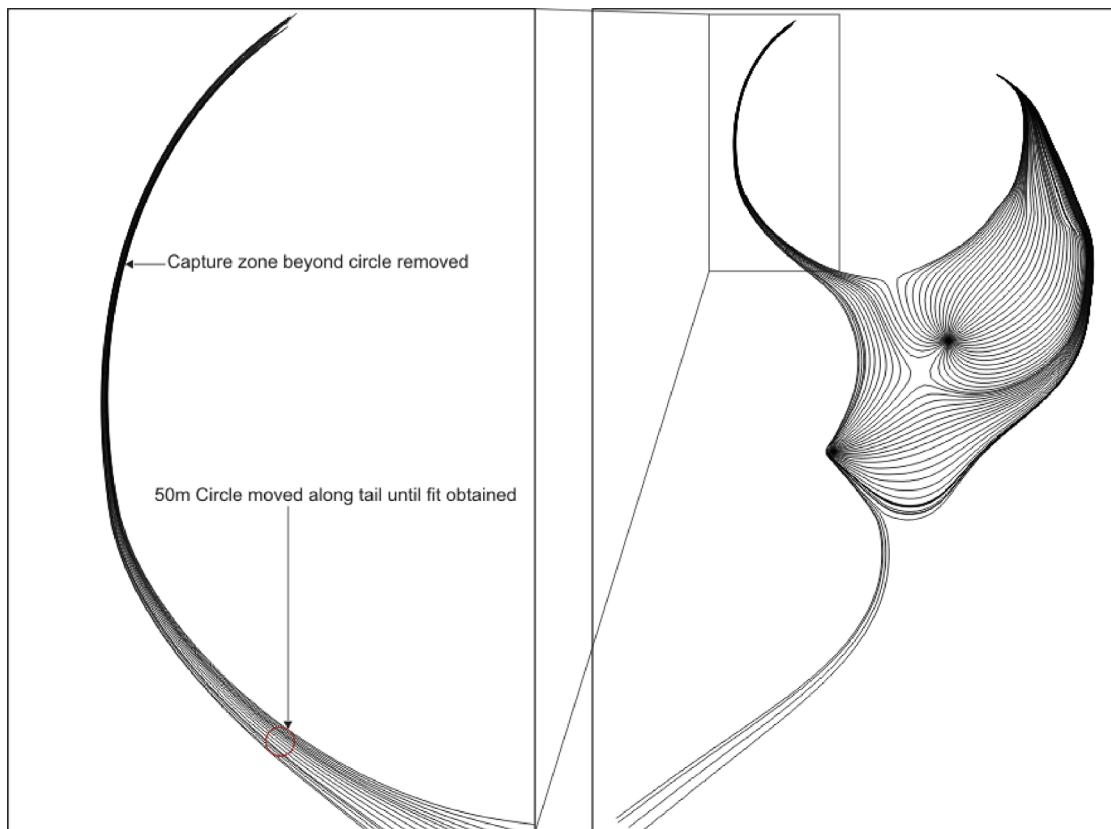


Figure 7.1 Modifications of hydraulic zones using minimum shape factors

7.4 Adjustment of boundaries

It may be necessary to modify the boundaries of hydraulic capture zones determined using analytical or numerical models to provide more reliability. Examples of cases where adjustments may be appropriate include:

- additional information may be available on groundwater flow (e.g. from tracer tests) that was not incorporated in the model;
- model boundaries may not precisely follow actual boundaries (e.g. geological boundaries), reflecting the precision of the model in representing these features.

Figure 7.2 provides an illustration of adjustments related to boundaries.

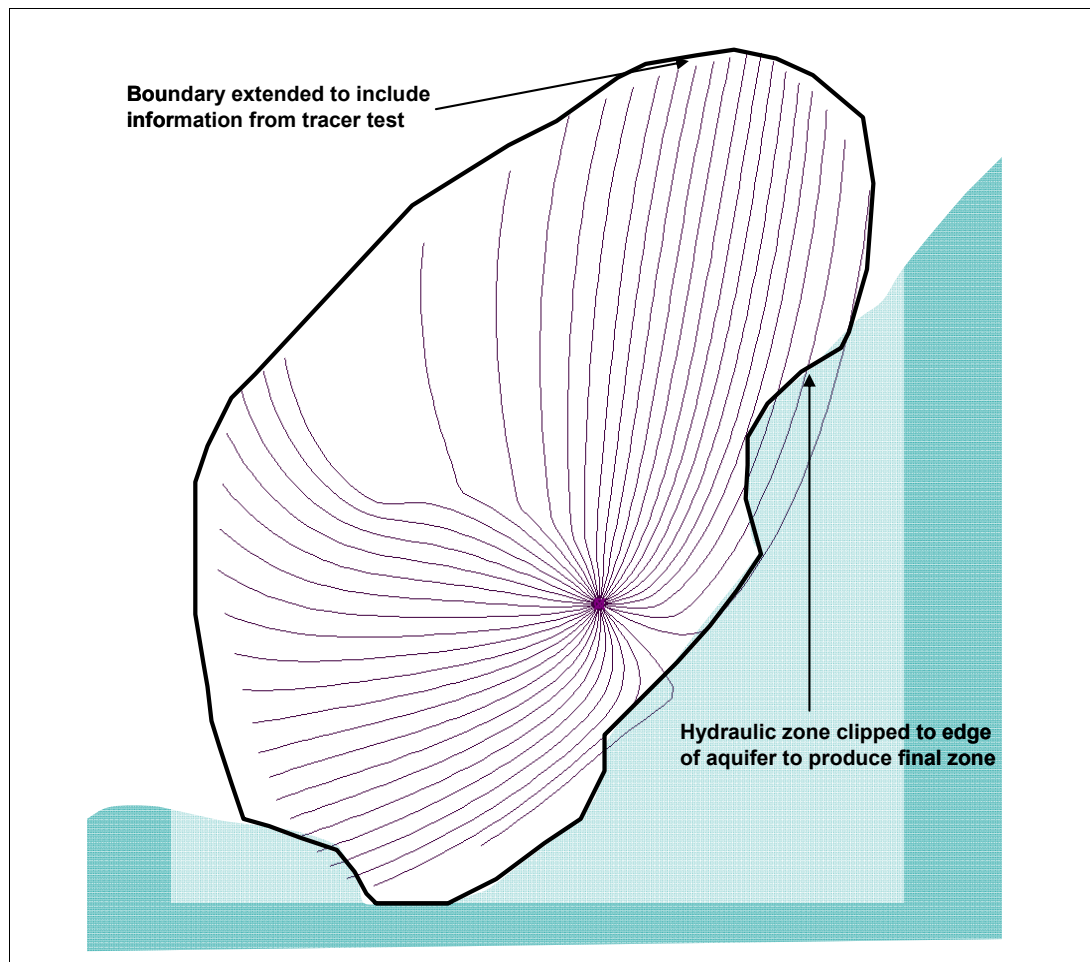


Figure 7.2 Final modification of hydraulic zones

Modifications can be undertaken on the basis of:

- geological boundaries (edge of outcrop, faults etc);
- hydrogeological boundaries (e.g. fully penetrating rivers, groundwater catchment divides), although there should be a reasonable level of certainty that these boundaries are accurate. For example, a detailed accretion profile may be available showing a reach of stream losing a significant quantity (e.g. >50 per cent of the protected yield) within the likely catchment of a source. If the model does not simulate this stream behaviour, this may justify truncating the SPZ at the stream if the particle tracks extended beyond it.
- tracer tests demonstrate that additional areas of the catchment should be included in the Inner, Outer or Catchment Protection Zone based on travel time and pathway;
- point pollution incidents demonstrate that additional areas of the catchment should be included in the Inner, Outer or Catchment Protection Zone based on travel time and pathway. There will need to be strong evidence that there is a pollutant linkage between the pollutant source and the abstraction.
- smoothing of model boundaries if these were influenced by a model grid.

Results from the sensitivity analysis (Section 6.11) should be used in conjunction with other information. For example, data on a pollution incident may suggest that there are

areas outside the hydraulic capture zone that might need to be included in the SPZ, but the exact pollution source is not known. The model sensitivity analysis in these cases may confirm which pollution sources are most likely to occur in the real capture zone of the source.

For catchments where sinking streams (swallow holes) are present close to the source(s), it may be appropriate to include the surface water catchment of the streams (see Section 4.1) within the appropriate SPZ. It may also be appropriate to include the catchment for areas from which surface water drainage feeds to an aquifer.

For each modification, the following should be recorded:

- details of the change;
- justification for modification (i.e. geological boundary, tracer test, etc.).

The use of GIS will facilitate this process by overlaying appropriate layers.

The level of justification should be appropriate; movement to a geological contact may require relatively little justification while modifications based on tracer test results would require additional information.

7.4.1 Confining layers

Modification to hydraulic capture zones can be made where there is a substantial and proved confining layer around a source as follows:

- **SPZ1 – Inner Protection Zone** should be shown as a minimum 50 m radius zone. But where there are known or planned major man-made subsurface structures such as tunnels or access shafts, the SPZ1 should be delineated and shown.
- **SPZ2 – Outer Protection Zone** is not normally shown where a confining layer is present (should be a minimum of 5 m thick). If part of the 400-day time of travel zone extends beyond the extent of the (>5 m thick) confining layer, this part of the Outer Zone should be displayed. Under the confining layer, the boundary of the Outer Protection Zone should be shown as a dashed line to provide a guide in understanding the groundwater flow path to the abstraction borehole and to assist in the assessment of activities (e.g. quarrying) that could involve removal of the confining layer.
- **SPZ3 – Catchment Protection Zone.** The Catchment Protection Zone outside the confined area must be shown. Where a possible confining layer or low permeability cover occurs around the source, this area should be identified on the SPZ maps using hatched shading. This indicates an element of doubt regarding the degree of protection afforded by the cover, which may or may not have been represented in the modelling process, though normally a low recharge area should have been incorporated into the model.

In the context of SPZ definition, major bedrock aquitards such as the Mercia Mudstone, Gault Clay and London Clay are classed automatically as a confining layer. The Environment Agency reserves the right to assess the importance of superficial deposits or minor, intra-formational bedrock aquitards on a site-by-site basis. Its occurrence should be included in the conceptual model and the Environment Agency must agree its importance at the onset of modelling. The agreement is important if the modelling is undertaken by a contractor.

7.5 Final checks on SPZ compliance

The final check on whether modifications are complete is to ensure that criteria related to definitions of the Inner Protection Zone (SPZ1), Outer Protection Zone (SPZ2) and Catchment Protection Zone (SPZ3) as set out in Section 2 are met.

7.5.1 SPZ1 – Inner Protection Zone

The minimum radius around the source (including adits) should be 50 m. This modification may be required for sources with small protected yields or for sources in thick, high porosity aquifers (i.e. the radius of the hydraulic capture zone may be <50 m). Figure 7.3 illustrates the modification of hydraulic zones to comply with minimum distance criteria.

A second possibility is that the hydraulic capture zone may not extend to 50 m, in which case the zone should be expanded to a minimum radius of 50 m around the source location. In all other cases, the 50-days travel time should be employed to define the zone (Figure 7.3). The mapped precision of the source is particularly significant when delineating such small zones.

Where the source consists of multiple boreholes, the 50 m criterion should apply to all the boreholes used for abstraction and any associated adits or satellite boreholes connected underground.

A problem can arise if, due to the scale of modelling, a multiple source has had to be considered as a single source. Such occurrences should be flagged and subsequently checked to ensure that all the constituent parts of the source are given the minimum protection required by GP3 (Environment Agency 2007a) and are located accurately on the final map.

7.5.2 SPZ2 – Outer Protection Zone

The minimum radius around the source should be 250 m (protected yield <2,000 m³/day) or 500 m (protected yield >2,000 m³/day (Section 2.3), but should not extend beyond the boundary of the Catchment Protection Zone. This modification may be required for:

- sources with small protected yields;
- sources in thick, high porosity aquifers (i.e. the radius of the hydraulic capture zone may be less than 250m).

In most cases, use of an appropriate kinematic porosity may avoid the need to undertake this change.

For sources that include an adit that extends outside the Outer Protection Zone, the zone should be extended by a minimum of 250 m around the adit (Section 7.2).

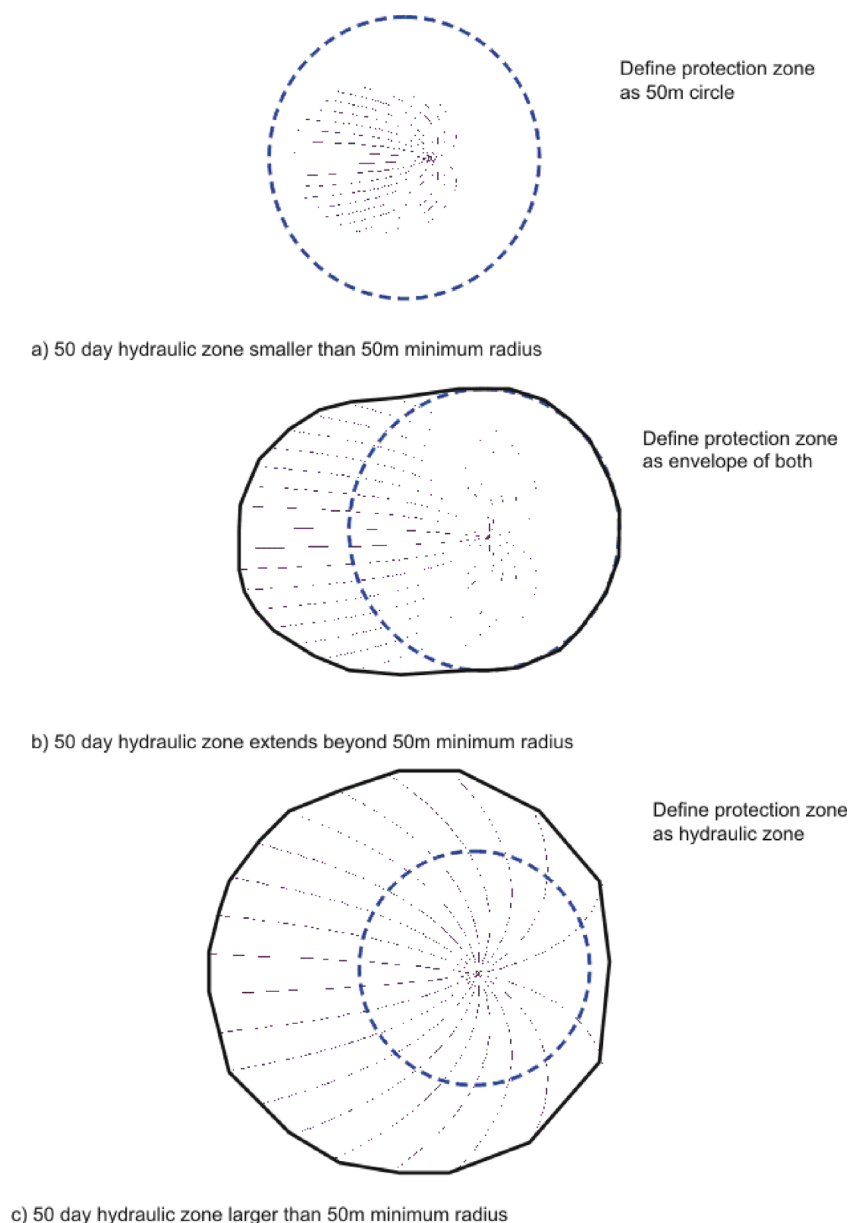


Figure 7.3 Modifications of hydraulic zones to comply with minimum distance criteria

7.5.3 SPZ3 – Catchment protection zone

For heavily abstracted aquifers, the whole recharge area (see Section 2.4) can be defined as the Catchment Protection Zone for a collection of sources. In such cases, the Environment Agency will normally draw boundaries along CAMS groundwater management unit boundaries.

7.6 Delivery of final SPZs

Final SPZs should be produced in electronic format. Electronic format provides the flexibility for end users to produce printed diagrams containing additional layer elements to their own specification.

With current Environment Agency GIS systems, a .shp shapefile is most appropriate.

SPZ shapefiles should comply with the Environment Agency's standard format including a completed attribute table.

The shape and associated ArcGIS files should be forwarded to the national SPZ dataset custodian.

It is not necessary to produce paper map output.

Delivery of SPZs within ArcGIS project files (.mxd) should be avoided.

8 Quality assurance, reporting and publication

Source protection zones (SPZs) form an important element of the Environment Agency's groundwater protection policy and approach (Environment Agency 2007a) in controlling unwanted development or land use changes.

From a developer's point of view, the reasoning behind the delineation of each SPZ should be readily available and open to public challenge.

From the source operator's point of view, the method of deriving each SPZ should be freely available in order to give confidence in the degree of protection to groundwater supplies.

For these reasons, the methods of quality assurance used in deriving the SPZs and in particular a report documenting the process are important.

A final publication step is required in order for SPZs to be used for groundwater protection.

8.1 Quality assurance

The different hydrogeological environments, levels of understanding, data and methods adopted in deriving each SPZ makes a uniform approach to quality assurance difficult. The aim of the quality assurance recommendations made below is to:

- help achieve consistent quality;
- ensure calculations are repeatable;
- justify the decisions made to, and within, the Environment Agency and to third parties.

The recommendations for quality assurance procedures are as follows:

- The production of SPZs should be carried out using accepted project control procedures and a declared quality plan that conform to QA standards such as ISO 9001. This applies to SPZs produced both internally and by external contractors.
- There should be a clear audit trail that details the technical and practical decisions used to derive each SPZ. The audit trail should cover all steps of the process including:
 - information sources used;
 - conceptual model;
 - description and justification of assumptions;
 - calculations;
 - model files and calibration (where appropriate);
 - adjustments of hydraulic capture zones and their justification.

This is in effect a report on the derivation of each SPZ. The format of this report is discussed in Section 8.2.

- The provenance of the data used in deriving each SPZ should be made clear. For example, the rationale behind the protected yield used to derive each SPZ should be clear and, wherever possible, agreed with the source operator.
- Where practical, the data used in deriving each SPZ should be cross-checked. Where information is thought to be uncertain, decisions on its verification, use or exclusion should be documented.
- All the data and reports specific to deriving each set of SPZs should be open to public inspection. In particular, groundwater source operators should be made aware of the existence of SPZs as well as the reports detailing their delineation. Equally, consultants representing developers should have access to the same reports – especially when investigations associated with particular developments may result in data that may support, or lead to, revision of zones. Equally any proposed changes to SPZs made by other parties needs to be supported by the same level of information.
- Development from simple calculations and analytical solutions through to more complex modelling is encouraged. Simple ‘back of the envelope’ calculations can help to highlight errors and inconsistencies when developing more complex models. Such cross-checking would be recorded when working under a quality assurance system such as ISO 9001.
- The method use for SPZ calculations should be well-documented. If new techniques are adopted, these require testing against analytical or well understood situations. For instance, the recommendation of WHAEM follows an evaluation of the model in a range of situations.

8.2 Source evaluation reports

The reporting of SPZ zone delineation is made in Source Evaluation Reports (SERs). The aim is to maintain a record of the SPZ definition process and the data used. SERs should include:

- **Source data.** This should include licence details, grid references of boreholes, Ordnance Survey location map, construction details, pumping test information, etc.
- **Conceptual model.** This can be source-specific, but may refer to existing reports or an overall conceptual model for an aquifer or resource unit.
- **Model representation.** Again this may be source-specific or for an aquifer or resource unit.
- **Hydraulic capture zone creation** through to adjustments and final definition of SPZs.

The 1990s proformas filled out by Environment Agency hydrogeologists contain detail concerning the source(s), aquifers and known hydrogeological understanding.

Documentation and justification of any alterations made during the SPZ delineation process is required – particularly the final definition steps described in Section 7.

In terms of reporting the SPZ process, the combination of database and GIS means that much of the SER content can be prepared automatically. However, manual incorporation of information such as conceptual model sketches and diagrams not developed in electronic form is still necessary.

The record should detail the methods used to construct the sets of SPZs around each source. Under relatively uniform hydrogeological conditions where multiple sources have been defined simultaneously, it is recommended that a shared report section be developed describing common elements.

Overall, the reporting should contain sufficient detail such that an independent professional hydrogeologist can understand the data and methods used, and the decisions made to construct each SPZ.

8.3 Review

Before finalisation and publication, all SPZs will be reviewed internally by senior Environment Agency hydrogeologists. The Environment Agency will also seek review by the source operator.

In some cases, newly defined SPZs may be put out for wider consultation if the Environment Agency considers it necessary to obtain views from other interested parties.

Nevertheless, the Environment Agency will always be the final arbitrator on the shape of the published SPZs.

List of abbreviations

2D	two-dimensional
3D	three-dimensional
AEM	Analytical Element Method
AFRC	arbitrary fixed radius circles
BGS	British Geological Survey
BPJ	Best Professional Judgement
CAMS	Catchment Management Abstraction Strategy
GIS	geographical information systems
GP3	<i>Groundwater Protection: Policy and Practice: Part 3 –tools</i> [Environment Agency 2007a]
MI/d	million litres/day
PPPG	<i>Policy and practice for the protection of groundwater</i> [NRA 1992]
SER	Source Evaluation Report
SPZ	source protection zone
US EPA	US Environmental Protection Agency
USGS	US Geological Survey
WHAEM	Well Head Analytical Element Model

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Appendix A: Outer zones and Permo-Triassic Sandstone

This appendix provides an overview of the options for delineating Outer Source Protection Zones (targeted at Permo-Triassic Sandstone aquifers) assuming that the 25 per cent rule is dropped.

Dropping this rule could potentially result in under-protection of some sources (Section 4.3) and, therefore, the following rules have been considered:

1. Use lower kinematic porosity for sandstone in the range 1 per cent (fissure) to 15 per cent (intergranular). The Permo-Triassic Sandstone aquifer is characterised by a high total porosity (typically 20–30 per cent), but tracer tests (Ward et al. 1998) indicate that kinematic porosities of 10–15 per cent are more appropriate (Section 4.2).
2. Use minimum radius (as per Inner Zone). Radii in the range 250–1,000 m have been considered.

Simple calculations (Section 6.5) have been used to examine:

- different default radii and values for kinematic porosity;
- degree of protection provided in terms of the percentage area of the source catchment recharge zone.

A review of licensed abstractions from the Permo-Triassic Sandstone aquifer in the Midlands area indicates yields ranging from 500–30,000 m³/day, with an average of about 5,500 m³/day. The depth of these boreholes ranges from 50–300 m, with a typical depth of 150 m. This might suggest that a typical aquifer thickness of about 100 m is not unreasonable.

Analysis

The following analysis has been undertaken to examine these options:

1. Compare default radii of 250–1,000 m with calculated radius for 400 day zone for range of values for pumping rate, recharge, kinematic porosity and aquifer thickness (Figure A.1). These calculations assume a flat water table.
2. Calculate percentage area (compared with source catchment recharge area) for 400 day zones for a range of values for pumping rate, recharge, kinematic porosity and aquifer thickness (Figure A.2).
3. Calculate travel time for different default radii (Figure A.3).
4. Calculate percentage area of outer hydraulic zone (compared with source catchment recharge area) for different default radii (Figure A.4).

The values used are:

- pumping rates of 1,000–10,000 m³/day;
- aquifer thickness 50–150 m;

- kinematic porosity 0.01–0.15, though the focus has been on values of 0.03–0.05;
- recharge of 0.25 m/year.

Some of the examples of the size of the outer hydraulic zone resulting from a combination of kinematic porosity and minimum radius are illustrated in Table A.1.

Table A.1 Size of outer hydraulic zone

Pumping rate (m ³ /day)	Aquifer thickness (m)	Recharge (m/year)	Kinematic porosity	Calculated radius (m)	Percentage area source catchment zone	Comment
5,000	100	0.25	0.01	798	27	Use of 1% for sandstone difficult to justify over this length scale
5,000	100	0.25	0.1	252	3	Small area and limited protection to source Need for large default radius or lower porosity
5,000	100	0.25	0.05	357	5.5	Relatively small area; use of default radius of 400 m would increase area to 6.9%
5,000	100	0.25	0.03	461	9.1	Use calculated 400 day zone
1,000	100	0.25	0.01	252	27	Use of 1% for sandstone difficult to justify over this length scale
1,000	100	0.25	0.1	113	3	Small area and limited protection to source Need for large default radius or lower porosity
1,000	100	0.25	0.05	160	5.5	Use of default radius of 250 m would increase area to 13.6%
1,000	100	0.25	0.03	206	9.1	Use of default radius of 250 m would increase area to 13.6%
10,000	100	0.25	0.05	505	5.5	Use of default radii <500 m makes no difference
10,000	100	0.25	0.03	602	9.1	Use of default radii <500 m makes no difference

A simple calculation has also been made for an equivalent kinematic porosity assuming the pathway consists of a combination of fissure flow (1 per cent) and intergranular porosity (10 per cent) as illustrated in Figure A.5. The available information on fissure interconnection in the Permo-Triassic Sandstone (Tellam and Barker 2006) indicates that path lengths are of the order of tens of metres, although one tracer test (Ward et

al. 1998) proved fissure flow over a length of 280 m. This indicates that the fissure length necessary to give an equivalent porosity of 5 per cent for a path length of 250 and 500 m is about 140 m and 280 m respectively. This is a relatively long fissure length and suggests that the lower end of the default range of kinematic porosity for the 400-day travel zone is 5 per cent.

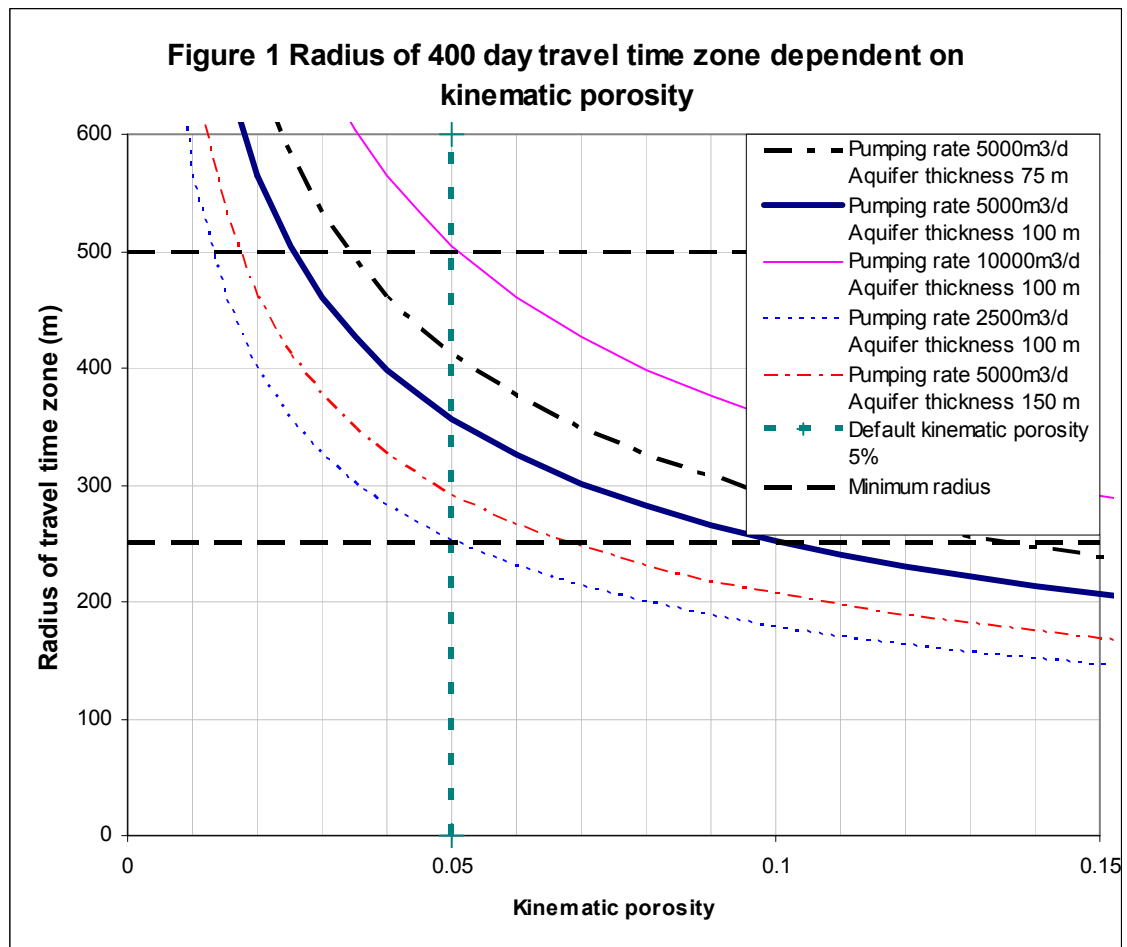
Observations

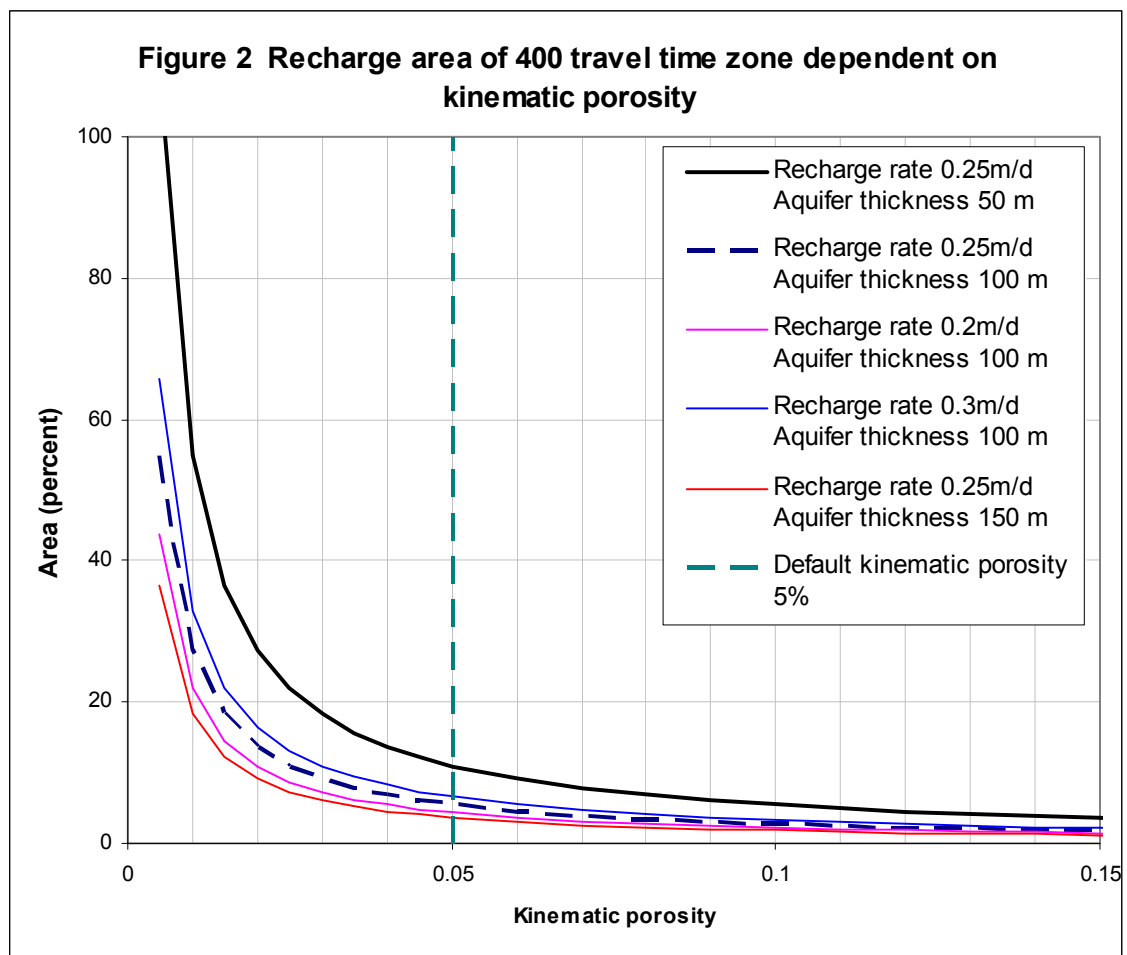
The main observations from this analysis are:

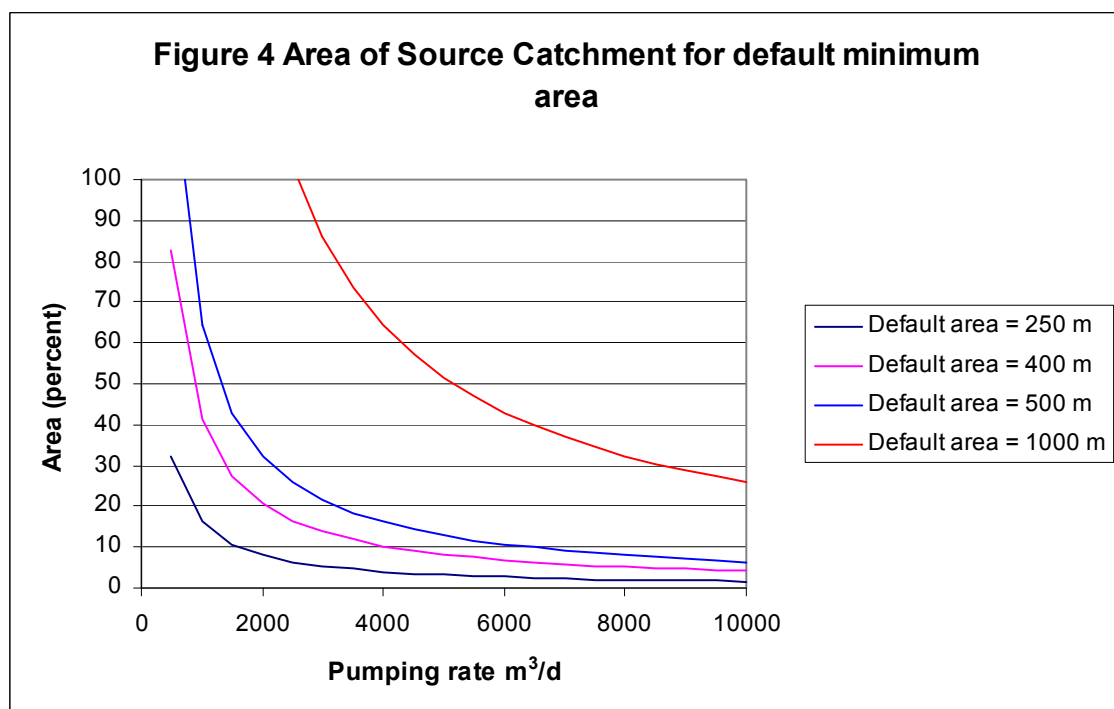
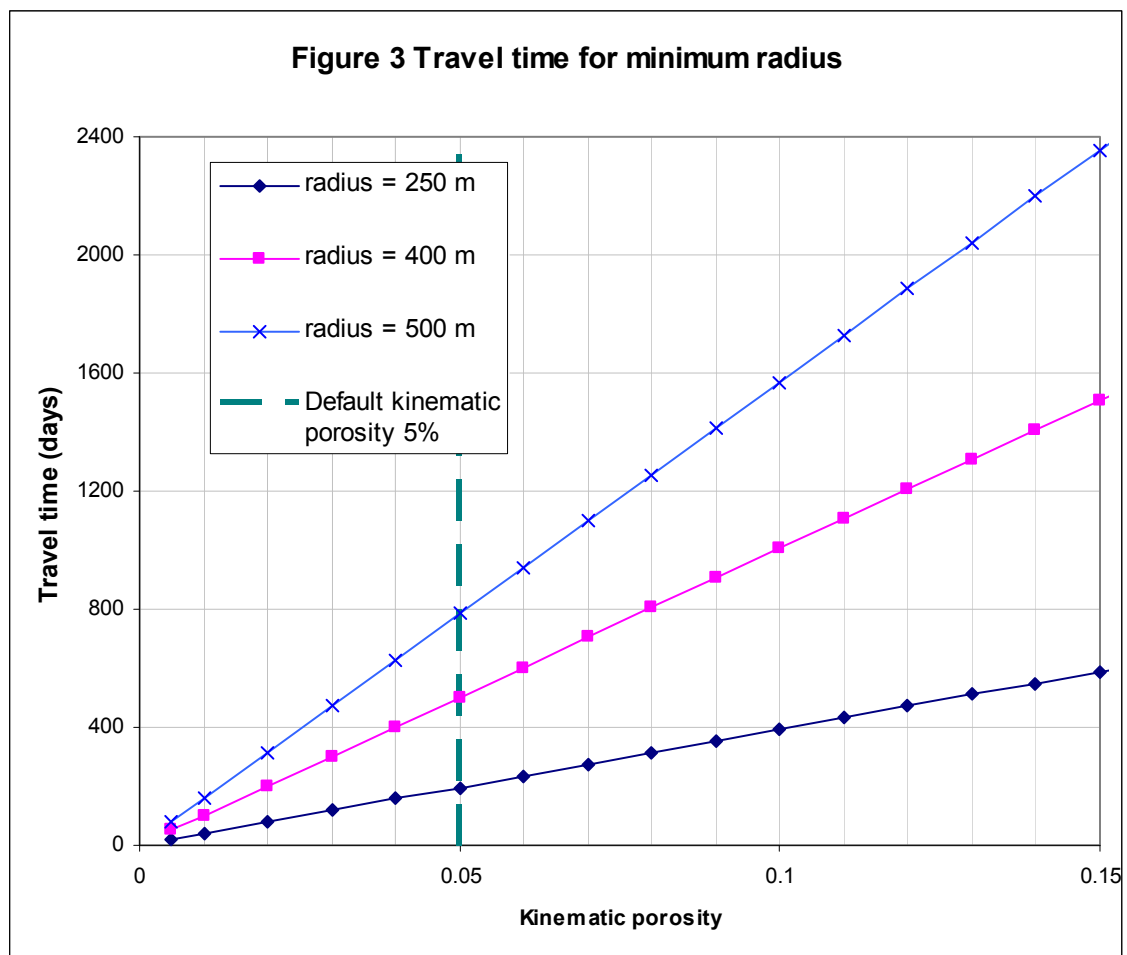
1. A 250 m circle appears reasonable for small sources ($<2,000 \text{ m}^3/\text{day}$) when compared with the source catchment area. For larger sources, however, this gives a relatively small percentage area. A 500 m circle provides a more reasonable zone size for higher pumping rates.
2. Using kinematic porosities of >0.05 results in relatively small 400-day zones (less than 5 per cent for source catchment area for aquifer thickness of 100 m and recharge rate of 0.25 m/year) results in a need to place greater reliance on default radius or to use a lower value for kinematic porosity.
3. Fissure kinematic porosity of 1–2 per cent is difficult to justify over length scales of several hundred metres. Five per cent is more reasonable, but needs to be used in combination with a default radius to provide adequate protection for some sources (e.g. sources characterised by a thick saturated aquifer thickness).

Recommendations

- Use a default kinematic porosity of 0.05 for the 400-day hydraulic zone.
- Use the following different radii, according to the pumping rate, to prevent small outer zones for large sources.
 - Use a 250 m circle with a pumping rate $<2,000 \text{ m}^3/\text{day}$.
 - Use a 500 m circle with a pumping rate $>2,000 \text{ m}^3/\text{day}$.
- Compare the 400-day zone with the default radius and adjust manually as illustrated in Figure A.6.







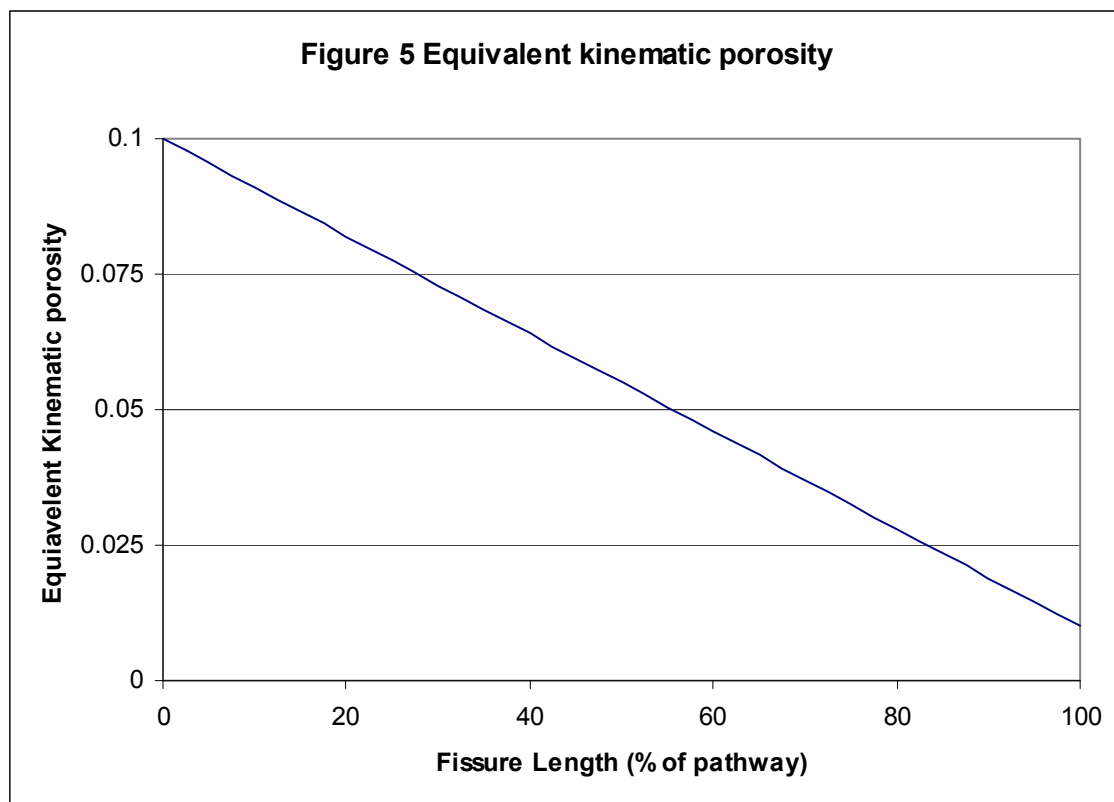
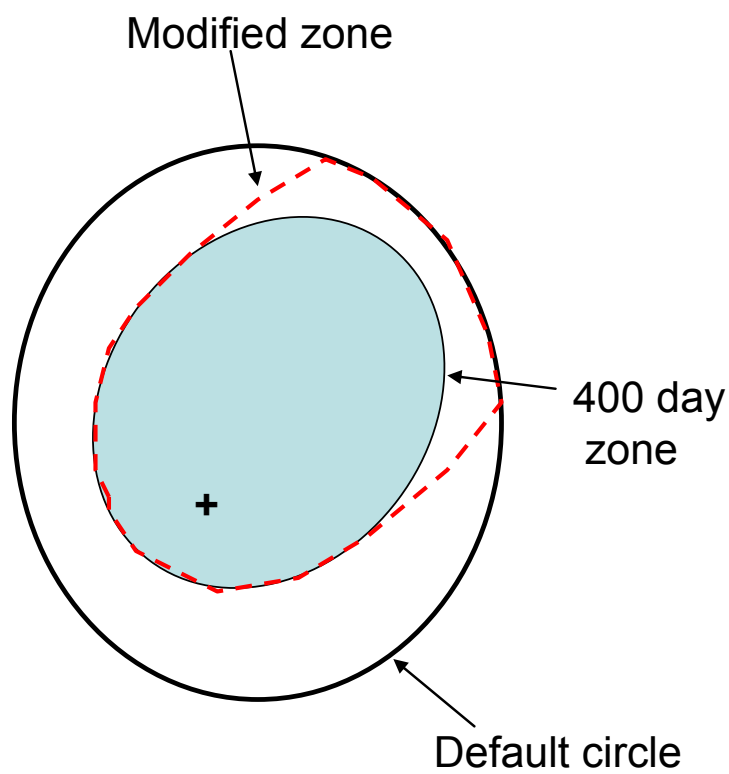


Figure A.6 Modification of 400-day hydraulic capture zone



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