# Manual for the production of Groundwater Source Protection Zones

March 2019

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# Executive summary

Source protection zones (SPZs) form a key part of the Environment Agency’s 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 2,200 public potable supplies, major non-public potable and sensitive commercial supplies in England, 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.

The original methodology to be followed to define SPZs was published by the Environment Agency in 1996. This was updated in 2009. Since that time there has been a wider use of the Environment Agency's numerical groundwater models as well as new tools to produce SPZs. SPZs have also become more relevant for activities such as subsurface exploration for onshore oil and gas / unconventional energy sources, and planning pressures such as major national infrastructure projects (e.g. HS2). They are also used in the development of groundwater safeguard zones, and potentially water protection zones and other catchment management schemes, to deal with diffuse pollution and meet WFD requirements.

This report updates the previous manual with the focus on the new tools and with reference to new uses of SPZs. The structure of the report has also changed, with the process described in the main report, and technical details and case studies in appendices.

The definition of source protection zones hasn’t changed since the last update, with the exception of the reinstatement of SPZ4, and the extension of SPZs where there are confining layers or protective cover.

# Contents

# 1. Introduction

The Environment Agency originally published Source Protection Zone (SPZ) methodology guidance in August 1996 (Environment Agency 1996). An updated document "Groundwater Source Protection Zones - Review of Methods" was published in August 2009 as an Environment Agency Science Report (Environment Agency 2009).

This new review and manual is required due to the wider use of the Environment Agency's numerical groundwater models and tools such as FlowSource (Black & Foley, 2013). SPZs have also become more relevant for activities such as subsurface exploration for onshore oil and gas / unconventional energy sources, and planning pressures such as major national infrastructure projects (e.g. HS2). They are also used in the development of groundwater safeguard zones, and potentially water protection zones and other catchment management schemes, to deal with diffuse pollution and meet WFD requirements. In addition the Groundwater protection: policy and practice (GP3) document has recently been replaced by a new document, The Environment Agency's Approach to Groundwater Protection (Environment Agency 2018).

For this version of the manual the background and process of delineating and updating SPZs is described in the main report, with technical appendices describing the modelling and other methods used to delineate SPZs, followed by a number of case studies describing those methods.

## 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 approach to groundwater protection as set out in The Environment Agency's Approach to Groundwater Protection (Environment Agency 2018).
- 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 updated version of the 2009 Science Report – Groundwater source protection zones: review of methods (Environment Agency 2009).

## 1.2. Definition of groundwater source protection zones

The Environment Agency's Approach to Groundwater Protection 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. SPZs are not statutory and are mainly for guidance but they do relate to distances and zones defined in legislation where certain activities are restricted.

The final SPZ is often strongly based on numerical 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 over 2,200 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 2.1).
- SPZ2 – Outer Protection Zone is defined by a 400-day travel time from any point below the water table to the source.[1] This zone has a minimum radius of 250m or 500m dependent on abstraction size (Section 2.2).
- SPZ3 – Source Catchment Protection Zone is defined as the area around a source within which all groundwater recharge is estimated to discharge at the source. In confined aquifers, the source catchment may be displaced some distance from the source (Section 2.3).

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 the previous update it was suggested that these zones were incorporated into other zones, however this has caused some issues and it is now recommended that these zones can be used (Section 2.4).

In 2014 confined / subsurface SPZs were defined where confining layers provide protection from surface activities, but there is a risk from subsurface activities that penetrate or disturb the confining layers. In some parts of the country the existing SPZs already included the confined areas (Section 2.4) to account for both surface and subsurface activities, however elsewhere they were excluded. The requirement was to extend into the confined area, but still using the same travel times of 50 days and 400 days.

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 or achievable rate of groundwater pumping that can take place from the source in question (Section 2.5).

## 1.3. SPZ determination procedure

At present there are just over 2,200 public potable supplies, major non-public potable and sensitive commercial supplies in England for which SPZs have been defined, 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. Environment Agency has obtained some information on such sources from local authorities and the Drinking Water Inspectorate (DWI). Such potable sources are 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. However the details and exact locations of the sources, rather than the property they provide water to, are often not known. Therefore although it is considered important to

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[1] The original methodology gave an option to define SPZ2 as the minimum recharge area required to support 25 per cent of the protected yield. This option was removed in the 2009 update.

protect such sources, it will not be practicable or efficient to formally publish zones around such sources. The protection of small sources is discussed in Appendix B, Section B2.

The previous manual provided an update of the procedure for defining SPZs. The main changes from the original manual were:

- changes in the procedure for definition of the SPZ2 (i.e. dropping the 25 per cent rule)[1] and use of a default minimum radius of 250 or 500 m around the source dependent on the abstraction volume
- 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 were introduced to provide a more pragmatic approach to SPZ delineation, reflecting an improved understanding of groundwater protection and its implementation, and are still included in this updated methodology.

Following the 2009 update some of the SPZs were updated based on the new methodology. This was also used for new sources, and in areas where significant updates were required, due to changes in licences or an updated conceptual understanding.

The determination of a SPZ refers to the overall process that covers:

- identifying the need for an SPZ or updating zones;
- data collation and conceptualisation;
- development of hydraulic capture zones;
- definition of final SPZs;
- QA and reporting of the final zones including producing documentation/report, and maps;
- publication and communication of the final SPZs.

These steps are shown in Figure 1.1, and are described in sections 3, 4 and 5 of this report.

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 unable to be changed. Not only do groundwater conditions change, especially in extensively exploited aquifers, but 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 final 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.  However it should be noted that now a lot of SPZ work is updates, or new zones in well understood aquifers, and aquifers where a well constrained model already exists.

It is also vital that a system of quality assurance, including an audit trail, 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 to conserve its use for water resources. The Environment Agency’s Approach to Groundwater Protection (Environment Agency 2018) contains position statements which provide information about the Environment Agency's approach to managing and protecting groundwater.  They detail how the Environment Agency delivers government policy for groundwater and adopts a risk-based approach where legislation allows.

In Wales, Natural Resources Wales also uses Source Protection Zones as part of its groundwater protection tools.

Table 1 indicates the position statements (including restrictions or extra controls) applicable to certain activities within an SPZ1 including default zones used for private water supplies.

**Table 1. Summary of the position statements that apply to developments and activities in SPZ1**

| Topic | Position statement |
|---|---|
| **Infrastructure** | C2 - Non-nationally significant infrastructure schemes<br>C4 - Transport developments<br>C5 - Pipelines and high voltage fluid filled cables<br>C6 - Underground coal gasification, coal bed methane and shale gas extraction<br>C7 - Oil and conventional gas exploration and extraction |
| **Storage of pollutants** | D2 - Underground storage (and associated pipework)<br>D3 - Sub water table storage |
| **Landfill** | E1 - Landfill location |
| **Discharge of liquid effluents into the ground** | G2 - Sewage effluent discharges inside SPZ1<br>G4 - Trade effluent and other discharges inside SPZ1<br>G6 - Cesspools and cesspits<br>G8 - Sewerage pipework<br>G12 - Discharge of clean roof water to ground<br>G13 - Sustainable drainage systems |
| **Diffuse sources** | H6 - Landspreading<br>H7 - Livestock housing<br>H8 - Storage of organic manures on farms |
| **Cemetery developments** | L1 - Siting cemeteries close to a water supply used for human consumption<br>L2 - Mass casualty emergencies<br>L3 - Cemeteries: protecting groundwater in highly sensitive locations |
| **Burial of animal carcasses** | M1 - Burials close to water supply used for human consumption or farm dairies<br>M2 - On-farm carcass burials<br>M3 - Risk-based approach<br>M4 - Animal carcasses: protecting groundwater in highly sensitive locations |
| **Managing groundwater resources** | N8 - Physical disturbance of aquifers in SPZ1 |
| **Ground source heating and cooling** | R4 - Environmental Risks |

The SPZs 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;
- provide the basis for catchment management work such as safeguard zones

The SPZs produced should be used as a guide for the different zones. However the process of SPZ definition allows adjustments to account for uncertainty once the hydraulic capture zones have been developed. In so doing the Environment Agency is demonstrating greater confidence in applying its approach to groundwater protection in the SPZ. Activities or developments will be considered as being either one side of the zone boundary or the other, despite the uncertainty, as this allows us to do our regulatory duties. If they straddle the line, the activity will also be considered inside.

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 may also use SPZs as the basis for safeguard zones (European Commission 2007) or water protection zones. These are 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 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.

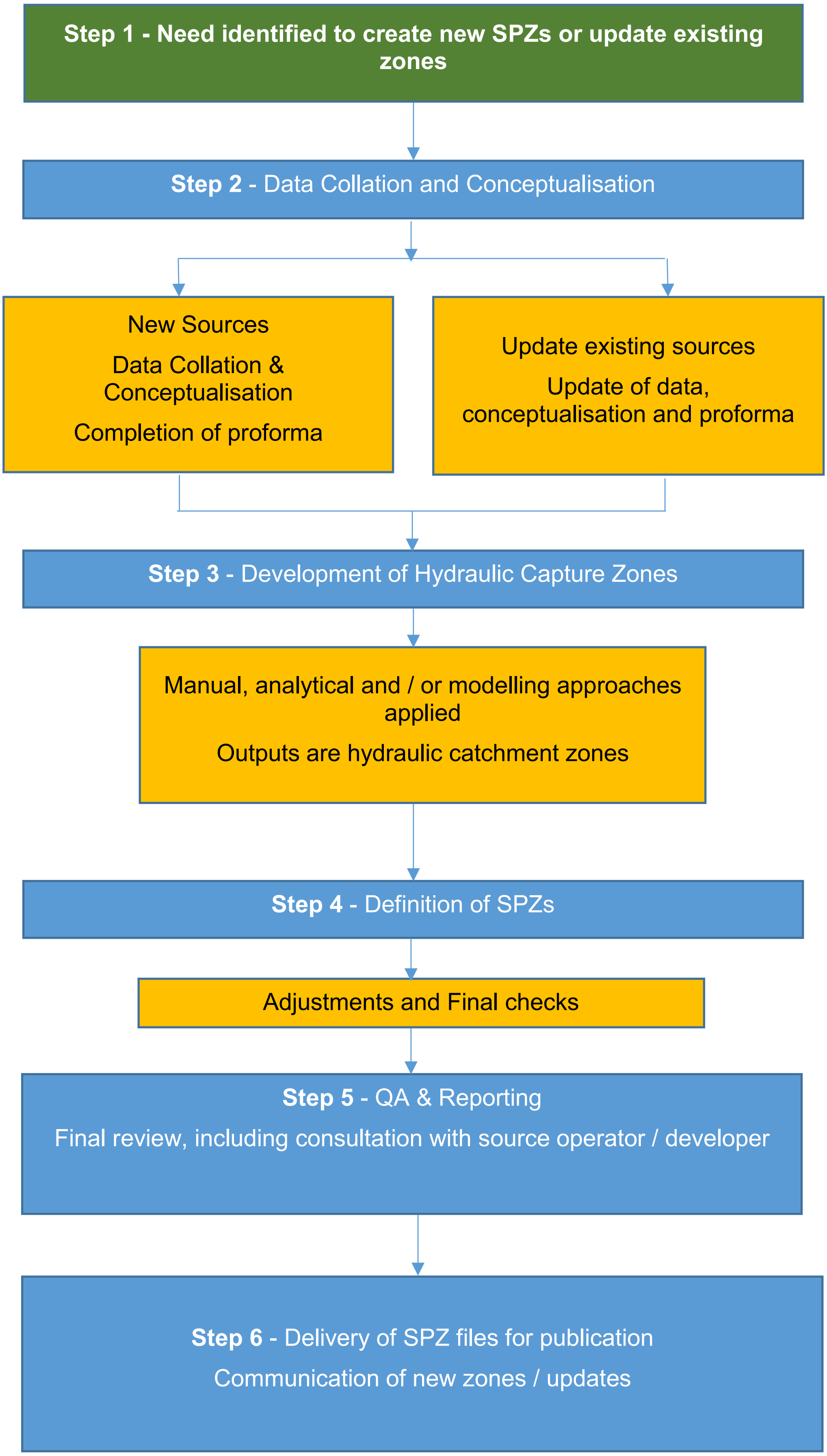


**Figure 1.1 Overview of SPZ definition process**

# 2. Source Protection Zones

This chapter describes the basis for defining inner, outer and catchment zones, and how and why they are defined. The first two zones are based on the travel time of potential pollutants through the saturated zone. SPZ3 represents the recharge area. All the zones should cover the maximum possible extent based on that abstraction.

## 2.1. SPZ 1 - Inner Protection Zone

The 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 usually located immediately adjacent to the well, although in karst terrain can be remote. The Environment Agency's Approach to Groundwater Protection (2018) sets the tightest controls on human activity in this zone.

The zone is used to control a wide range of activities that could pose a significant risk to groundwater as outlined in Table 1. 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 volume (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 Appendix B, Section B5).

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 kinematic porosity (e.g. fissure rather than intergranular porosity as discussed in Appendix B); and/or
- manually adjusted to include the identified source and pathway (Section 3.5).

The SPZ1 boundaries are adjusted where the aquifer is confined beneath substantially low permeability material (protective cover) or where deep unsaturated zones or patchy superficial deposit cover are present. Some of these zones are labelled SPZ1c after further work was done in 2014 to take account of these areas.  This work was done due to the risk from subsurface activities, and specifically at the time, deep drilling.  In some parts of the country the zones already included areas of protective cover to account for both surface and subsurface activities. Further details on protective cover / confining layers is provided in Section 3.5.4.

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.

## 2.2. SPZ 2 - Outer Protection Zone

SPZ2, the Outer Protection Zone, is defined as a 400-day travel time. The zone will default to a minimum radius of 250 or 500 m, depending on the size of the abstraction, if the 400-day travel time zone is smaller. 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)[2].

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 3.5);
- 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 Appendix B, Section B5);
- minimum radius of 250 m, though this should not extend outside the source capture zone for sources with a protected yield of <2,000 $m^3$/d;
- minimum radius of 500 m for sources with a protected yield of >2,000 $m^3$/d but not extending beyond the source capture zone.

In many cases, the 400-day hydraulic zone is likely to exceed the minimum radius, although in the Permo-Triassic Sandstone this often isn't the case; its purpose is to afford a minimum level of protection to the source and to provide a default zone where hydrogeological data are limited.

As for SPZ1 where there is protective cover i.e. aquifer is confined beneath substantially low permeability material, the SPZ2 has been extended in places due to the risk from subsurface activities including deep drilling.  These extensions are labelled SPZ2c, although in some parts of the country the zones already included areas of protective cover to account for both surface and subsurface activities. Further details on protective cover / confining layers is provided in Section 3.5.4.

## 2.3. SPZ 3 - Source Catchment Protection Zone

SPZ3 – Source Catchment Protection Zone, also referred to as the total catchment, Total Capture Zone or Catchment Protection Zone, is defined as the area needed to support the protected yield from long-term groundwater recharge. In areas where the aquifer is confined

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[2] The original methodology included the option for the zone to be 25% of the catchment area. However this was removed in the 2009 update.

beneath low permeability strata, this source catchment may be located some distance from the actual abstraction.

For heavily exploited aquifers (i.e. where 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.

The main position statements that apply to the SPZ in the Environment Agency's Approach to Groundwater Protection (2018) relate to landfill location and sub-water table storage. These are similar to those applied to the principal aquifer as a whole. As a result, it has been suggested that there is limited benefit in defining individual SPZ3s. However there are a number of reasons and situations where they are useful, for example there are also SPZs on secondary aquifers, and SPZ3 is often used as the basis for safeguard zones for diffuse pollution, and Drinking Water Safety Plans for water companies. It can also be important to know which source catchment an area is within, for example for pollution incidents. Therefore it is considered sensible to produce SPZ3s for individual and groups of sources.

However to provide a more pragmatic approach to zone delineation in heavily exploited aquifers the entire outcrop area of such an aquifer can be defined as the Catchment Protection Zone, when the ratio of licensed 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 groundwater management unit or groundwater body scale. In this case the published SPZ3 would be the whole aquifer, but with individual SPZ3s used for some purposes.

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

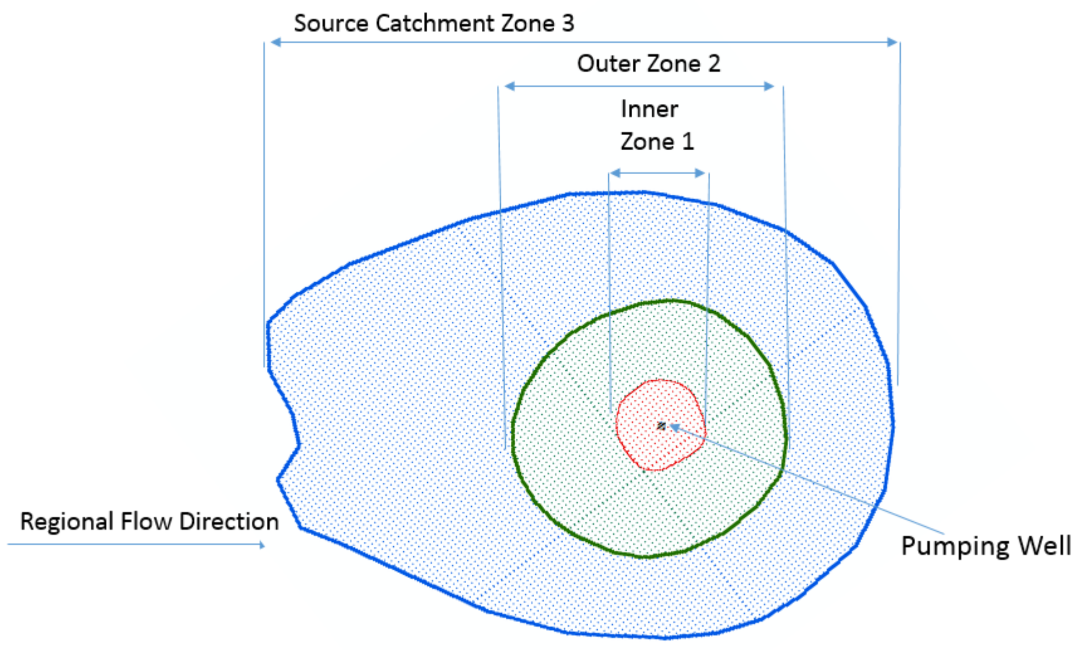


**Figure 2.3 Schematic representation of Inner, Outer and Source Catchment Protection Zones**

## 2.4. Special Zones (SPZ4), Subsurface Zones and Catchment Management

The original SPZ methodology 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 2009 methodology stated that we will no longer define or use SPZ4 and that where protection is needed we will define a Safeguard Zone or assign the appropriate SPZ1, SPZ2 or SPZ3 to the area in question. However there have been issues with this approach in some areas of the country, including a reduced level of protection to that required, and confusion externally. Therefore it is recommended that the zones can be used again. This would allow areas to provide the correct level of site specific advice.

Since 2014 the published source protection zones have included extensions to some zones to take account of subsurface activities including deep drilling. These are identified on the maps with zones 1c, 2c and 3c. They take account of areas where there is protective cover i.e. where the aquifer is covered by an effective thickness of at least 10m of protective cover and may be affected by deep drilling or other subsurface activities. More details are provided in Section 3.5.4.

SPZs can be used to help with catchment management issues, for example delineation of safeguard zones, and water protection zones. Safeguard zones (SgZs) are used for areas around abstractions where water quality is poor. A SgZ means that there will be strict enforcement of existing measures for particular pollutants and activities, and possibly new voluntary measures. SgZs are not statutory designated areas but areas where additional measures are needed to improve water quality. The Environment Agency establishes SgZs under the Water Framework Directive. There are over 200 groundwater SgZs in England.

When SgZs were first designated it was suggested that they were based on the SPZ2 for the source. However this varies across the country and is dependent upon the pollutant for which they are designated. Therefore SgZs can use any of the SPZ zones, and in many cases bespoke zones based on other information have been drawn. In some cases modelling work for catchment management and SgZ delineation can help us update and refine our SPZs.

## 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, in consultation with the licence holder, and when considering the conceptual model. In the case of water company sources, proposed protected yields should be checked and approved first so that operational use for the boreholes is protected.

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 staff responsible 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 staff should be consulted.

There is further discussion on protected yields in the appendices, including protected yields for spring sources in Appendix B, Section B3, and adjustments in groundwater models in Appendix C, section C4.2

# 3. SPZ production procedure

## 3.1. Introduction

This chapter considers steps 1 to 4 of the process that needs to be followed to produce SPZs, as well as updating existing zones as shown in Figure 1.1, and includes:

- confirming whether a source needs a zone
- data collation and conceptualisation
- the best approach to take to produce the hydraulic capture zones
- the delineation of the source protection zones

The following sections consider these issues, with technical guidance on the modelling and other approaches included in Appendix C.

The first part of the process – Step 1- is identifying the need for the new SPZ or update, including deciding whether the source or sources need a bespoke source protection zone. Section 3.2 has more detail.

Prior to making a decision on the best approach to use to produce SPZs some idea of the conceptual model is needed, and a certain amount of data collection would be required – Step 2. This may already have been done as part of other studies but more details are provided in Section 3.3.

Following this a decision needs to be made on the best approach to take in producing the source protection zones i.e. whether we use a simple shape or manual methods, whether to produce and use a numerical groundwater model etc. The available approaches are provided in more detail in section 3.4, however factors to consider include:

- Is it a new source or are we updating the source / sources?
- What is the hydrogeological conceptual model?
- What data is available to help with delineation?
- Is it simple or complex?
- Is there already a numerical model of the aquifer where the source is?

Whatever approach is used it involves the development of hydraulic capture zones, rather than the SPZ itself - this is Step 3. Another step, Step 4, is required to convert these zones to the final source protection zones including doing any adjustments and final checks. This is discussed in section 3.5.

## 3.2. Step 1- Identifying the need for a new or updated SPZ

The steps outlined in this methodology can be used for both new SPZs and updating existing SPZs. Updating of SPZs could be done for a number of reasons including:

- changes in licences, either for the abstraction which has the SPZ, or other abstractions within the aquifer
- changes in conceptual understanding of the aquifer, or a new or update to a numerical model
- changes to the methodology and tools used, for example some areas are updating zones using outputs from FlowSource (Black & Foley, 2013)

The level of detail required depends on the nature of the update, for example it may be that a standalone SPZ3 needs updating when another abstraction in the area has ceased, potentially changing the catchment area of the source. Alternatively an updated groundwater model may have led to changes in the conceptual understanding of the aquifer, and the need to review any SPZs. The work should also be proportionate to the importance of the SPZ i.e. it's more important to have an accurate SPZ1 than SPZ3, in most cases.

### 3.2.1. Confirming which sources require an SPZ

The 2009 methodology didn't provide detailed guidance on which sources require an SPZ. As stated in the introduction to this guidance SPZs are primarily a policy tool used to control activities close to water supplies intended for human consumption and SPZs have been defined for over 2,200 groundwater sources. These are wells, boreholes and springs used for major potable uses, in particular public drinking water supply. As stated in Section 1.3 there are also upwards of 70,000 private supplies. However, these small sources will not have bespoke zones that are shown on published maps and datasets.

Section B of The Environment Agency's approach to groundwater protection states that all abstractions, including private water supplies, that are used for drinking water supply or food production purposes are by default in an SPZ1 or SPZ2. Position statement B2, shown below, then provides more detail on what sources the Environment Agency has prioritised for the production of bespoke zones.

**B2 - Designation of SPZs around groundwater abstractions**

SPZs and the associated position statements apply to the area around any groundwater abstraction intended for human consumption, as defined in the Drinking Water Directive 98/83/EC. However, for production of bespoke SPZs the Environment Agency has prioritised:

- public drinking water supplies
- other commercial potable supplies (including mineral and bottled-water)
- groundwater abstractions used in commercial food and drink production*
- other sources where additional protection is required i.e. sensitive commercial supplies.

* *This does not relate to groundwater that is used solely for the irrigation of crops.*

Neither the previous guidance, nor our approach to groundwater protection document, provide a cut-off abstraction volume for the production of bespoke SPZs, although the previous guidance does refer to small sources as those with typically abstraction rates of <100 $m^3$/day. Review of the previous work in the different EA area shows that whilst there is consistency in the approach on the type of abstractions, there is some inconsistency in the cut-off abstraction volume for bespoke zones.

Based on previous guidance and practice from within the EA it is recommended that abstractions as defined in position statement B2 and with abstraction rates above 250 $m^3$/d are prioritised as having bespoke zones.

## 3.3. Step 2 - Data Collection and Conceptualisation

### 3.3.1. Data collation and assessment

When SPZs were first developed significant original data collection was required to enable their delineation. This was because for a lot of sources there was no numerical model and it was likely that no previous collection of data about the source and the local aquifer conditions had taken place. It was also the case that a lot of the original SPZ delineation was done prior to the use of GIS and other electronic datasets. Since that time regional models covering the majority of the principal aquifers have been developed. It should be noted that most future SPZ work will be for new sources, or updates to existing sources, where information is now readily available.

For 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 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
- groundwater/surface water interaction

For new sources a lot of the relevant information should have been collected and assessed at the appropriate level during the source investigation and licence determination period, whereas for updates the information should be available from the original delineation.

The following is a list of some types and features of data and information required for new SPZs and updates:

- **Licence and source information** - for new sources this will be collected as part of the requirement of the licence determination. For updates it should already be available and any licence changes part of that licence changes determination.
- **GIS and hydrometric data** - GIS is used for geological and topographic maps and data such as digital terrain / elevation data, as well as layers showing rivers and other water features. 3D geological models are also available for use in some areas. Hydrometric data is stored in the EA's hydrometric archive. Detailed information is likely to be required for a new source, but for an update this would depend on a number of factors such as the reason for the update and the age of the original SPZ.
- **Previous studies, reports and data -** these may need to be referred to for updates to an existing source, or for new sources in areas with less data or no model, but again for new sources these should have been considered and reviewed as part of the initial source investigation and licence determination.
- **Spatial extent of data collation -** what is required would depend on whether it's a new SPZ or an update, and also on the size of the abstraction and the aquifer. Again a lot of the decisions should have already been made for a new source, and the data already available in the previous determination for an update.

### 3.3.2. The conceptual model

As with data collection and assessment, the conceptual model required for the delineation of SPZs may already have been produced either as part of a regional numerical modelling project, or for a previous version of the SPZ delineation if an update is being done. Therefore the amount of detail required will depend upon the circumstances of the SPZ delineation. A new source in an area without much previous development will require a conceptual model to be developed.

The following is the type of information that could be included in a conceptual model:

- a text description;
- sketch diagrams of the groundwater–surface water flow and transport system and processes;
- a map or maps showing:
- – bedrock geology and, where appropriate, superficial deposit cover;
- – aquifer extents and boundaries
- – water table/piezometric surface for main aquifer units;
- – surface and groundwater abstractions and discharges;
- – direction of groundwater flow;
- – details of the source boreholes including locations and aquifer tapped;
- – 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.
- 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;
- maps and description of karstic features where relevant.

## 3.4. Step 3 – Development of Hydraulic Capture zones

This section of the report provides an introduction to the approaches that can be taken in developing the hydraulic capture zones. Technical details on the development of the zones are provided in the Appendices. Appendix A provides details on the factors that control the geometry of hydraulic capture zones. Appendix B discusses development in special cases including spring sources, and karst. Appendix C describes both manual methods and methods using models in more detail. Finally Appendix D includes 5 case studies

### 3.4.1. Decide on approach

A wide range of techniques are available for calculating hydraulic capture zone areas around sources, which are used to define the final SPZs. Table 3.1 presents a hierarchy of approaches to defining 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
- whether we are considering single isolated sources or multiple abstractions
- whether a numerical model has already been developed for the aquifer

Table 3.2 lists the applicable methods and their respective advantages and disadvantages.

The choice of method can be a complex decision and the temptation to use a more sophisticated (generally more rigorous but more resource intensive) method must be resisted if the existing data are inadequate or the use of the results does not demand it. If a model is developed it 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 CoGAP (https://www.gov.uk/government/publications/protecting-our-water-soil-and-air) where a minimum 50 m radius protection zone (equivalent to SPZ1) 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, 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 generally 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 managed aquifer recharge (MAR) 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

The biggest changes to approach since the last update of the methodology are the use of the numerical models that have been developed for many principal aquifers and the use of FlowSource as a post-processing tool from the models to help produce the hydraulic capture zones. Details about model set-up and guidance on the most appropriate use of FlowSource are in Appendix C, Section C4.

**Table 3.1 Hierarchy of hydraulic capture zone delineation approaches**

| Method of Delineation | Comment on applicability |
|---|---|
| **Best Professional Judgement (BPJ)** | 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.<br><br>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.<br><br>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 Appendix B. Examples of using BPJ can be seen in case studies 3, 4 and 5 in Appendix D. |
| **Manual methods/ analytical solutions, e.g. simple recharge circles and Bear and Jacob** | 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. Case studies 3 and 4 in Appendix D use manual methods in some way. |
| **Analytical element models e.g. WHAEM, Split, WinFlow** | Although a widely applicable method in some countries, analytical models such as WHAEM haven't been used widely within the EA. This is because recent experience has shown that it is just as easy to set up a distributed numerical model such as MODFLOW and use tools such as MODPATH and FlowSource e.g. West Cumbria Sandstone sources - see case study 2 in Appendix D |
| **Distributed numerical models e.g. MODFLOW/ MODPATH and FlowSource** | MODFLOW models can be developed specifically for hydraulic capture zone delineation. MODPATH and FlowSource can then be used to delineate the capture zones. Previously it was thought that using analytical element methods would be easier and quicker in some cases, however recent experience has shown that producing a standalone MODFLOW model is just as easy (see case study 2 in Appendix D). |
| **Using Time Variant regional models with MODPATH and FlowSource** | Since the methodology was last updated most principal aquifer areas have had time variant models developed, and hydraulic capture zones have been produced using these models with MODPATH and FlowSource. Case study 1 in Appendix D provides an example of using a time variant model to define SPZs. |

**Table 3.2 Advantages and Disadvantages of methods**

| Capture zone method | Advantages | Disadvantages |
|---|---|---|
| **Best Professional Judgment - Hydrogeological mapping** | Low cost<br><br>Good for karst and fractured aquifers with strong geological control | Poor in areas with indistinct boundaries<br><br>Not quantitative |
| **Fixed radii circular zones** | Low cost<br><br>Easy and quick to implement<br><br>Highlights lack of data | No technical basis<br><br>Does not have regard to local hydrogeological conditions |
| **Calculated zones based on recharge and abstraction** | Low cost<br><br>Easy and quick to implement with minimal data requirements<br><br>Some technical basis | Simplistic, does not represent detailed local hydrogeological conditions |
| **Standard shaped zones based on idealized representation of local conditions** | Can represent a very simple system<br><br>Easy and quick to implement<br><br>Semi-quantitative | Local conditions may differ significantly from those used in the initial delineation<br><br>Data may not be available |
| **Analytical modelling** | Capture zones based on idealized representation of local aquifer conditions<br><br>Can represent a simple system<br><br>Quantitative<br><br>Simple and uniform boundaries and recharge allowed for<br><br>Can test different scenarios | Darcian flow assumed<br><br>Modest data requirements<br><br>Assumes infinite aquifer<br><br>Does not allow complex boundary and recharge effects to be considered |
| **Distributed numerical models with MODPATH and FlowSource** | Capture zones based on idealized representation of local aquifer conditions<br><br>Quantitative<br><br>Allows for complex boundaries and recharge effects<br><br>Can test different scenarios | Darcian flow assumed<br><br>Data requirements can be large<br><br>Assumes infinite aquifer |

## 3.5. Step 4 - Definition of SPZs

This section describes the process for the final definition of SPZs following the process to define hydraulic capture zones. The transition from calculations to definition of final SPZs is an important step.

If the hydraulic capture zones have been delineated using tools such as FlowSource and MODPATH then there is potentially a large amount of output to consider. The zones produced should be examined carefully, the conceptual model and spatial datasets such as the 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.

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.

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.

Once hydraulic capture zones have been produced using the relevant modelling technique they need to be converted to the source protection zones within GIS. The following process is the basis for doing this:

- Import zone files containing the 50 day, 400 day and catchment zone information
- Draw an envelope around the particle tracks, and other outputs to create an area for the basis of the zones
- Using these shapes decisions can be made on whether adjustments are required to the zone shape as described below.

### 3.5.1. 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.

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. The distance to the river can be important in this context.
- 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 any sensitivity analysis (Appendix C, Section C5) 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 Appendix B4) 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.

All adjustments to hydraulic capture zones require documenting.

### 3.5.2. Tails and Holes

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

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.

### 3.5.3. Adits

The models for SPZs for sources made up of adits or other elongate features 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 or 500m (for abstractions of < 2,000 $m^3$/d and >2,000 $m^3$/d respectively) Outer Protection Zone need to be defined.

### 3.5.4. Protective cover / Confining layers

As noted in Section 2.4, since 2014 the published source protection zones have included extensions to some zones to take account of subsurface activities including deep drilling, following a request to make sure SPZs could be used to manage the risk from oil and gas exploration. In some parts of the country the existing SPZs already included the confined areas, however elsewhere they were excluded. The requirement was to extend into the confined area, but still using the same travel times of 50 days and 400 days for SPZ1 and SPZ2. These are identified on the maps with zones 1c, 2c and 3c.

Prior to this there has been some uncertainty and inconsistency in whether zones included confined areas and how to define them. For example in the 2009 methodology for SPZ2 a confining layer of 5m was mentioned, but not included for SPZ1, and hatching was recommended for confining layers for SPZ3 but wasn't used.

Therefore there has been a review of the approach for confining layers and subsurface zones. This review recommends that we should move away from using the term confining layer, and instead call it protective cover of low permeability. This is because describing these aquifers as confined suggests that the groundwater level may be above the top of the aquifer whereas it could be well within the aquifer and therefore not confined in a hydrogeological sense. Therefore we should describe confined aquifers as concealed aquifers with protective cover.

The other recommendation is that the minimum thickness of the protective cover should be 10m and not the 5m referred to in the 2009 methodology. Therefore if a zone extends beyond the extent of the 10m thick protective cover this should be displayed as a protective cover zone i.e. zone 1c, 2c, or 3c.

Based on these recommendations the zones defined in the work in 2014, and others that fit the definition, would be called Zone 1 – Inner Protection Zone (Protective Cover), Zone 2 - Outer Protection Zone (Protective Cover) and Zone 3 - Total Catchment (Protective Cover).

The description of the zones would be, for example for Zone 1: Inner Zone with protective cover – Zone 1c where the aquifer is covered by an effective[3] thickness of at least 10m of protective cover and may be affected by deep drilling or other subsurface activities.

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[3] Effective – covers situation where protective cover is not impacted by features that connect the surface to the aquifer that is covered, for example abandoned boreholes, pingos etc

### 3.5.5. 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.

### 3.5.6. 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 3.1 illustrates the modification of hydraulic zones to comply with minimum distance criteria.

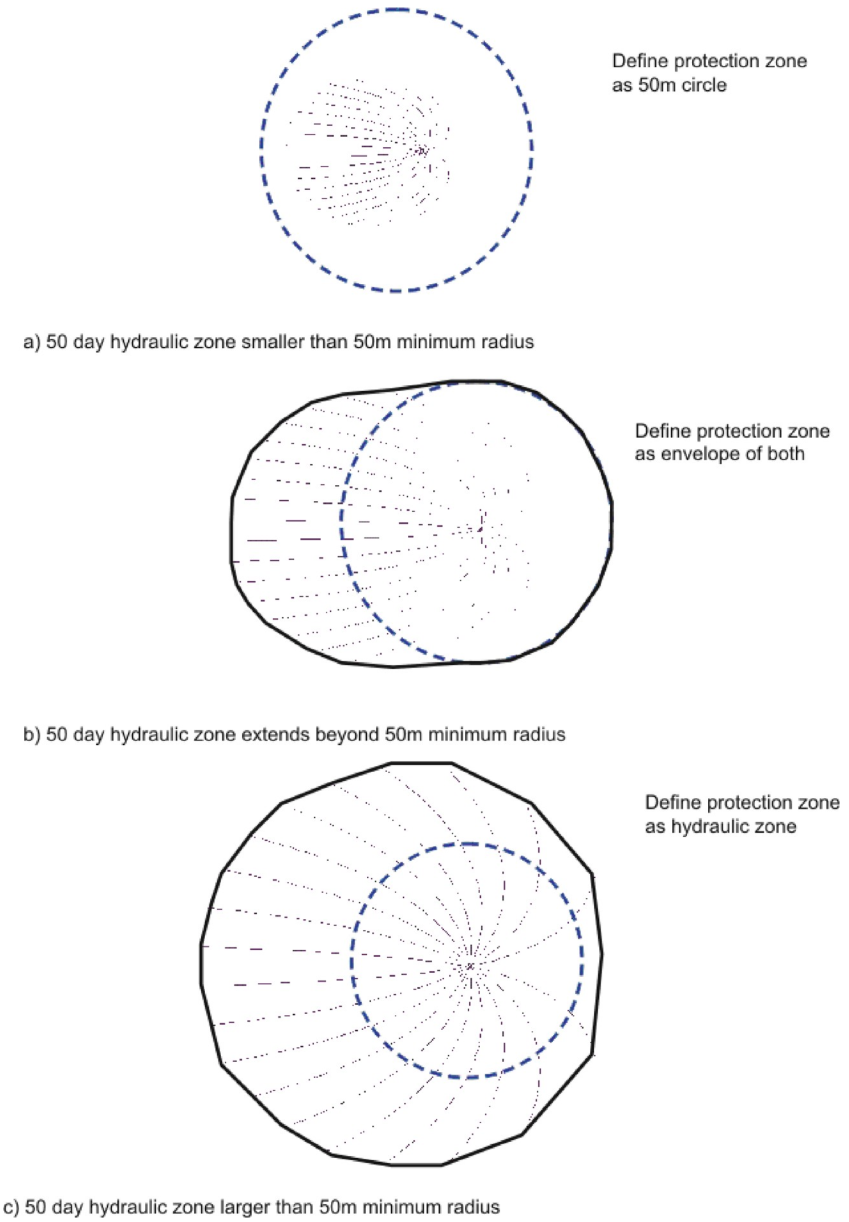


**Figure 3.1 Modifications of hydraulic zones to comply with minimum distance criteria**

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 3.1). 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 and are located accurately on the final output.

### 3.5.7. SPZ2 – Outer Protection Zone

The minimum radius around the source should be 250 m (protected yield <2,000 $m^3$/day) or 500 m (protected yield >2,000 $m^3$/day), but should not extend beyond the boundary of the SPZ3. 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 (500m if the abstraction is greater than 2 Ml/d) around the adit (Section 3.5.3).

### 3.5.8. SPZ3 – Catchment protection zone

For heavily abstracted aquifers, the whole recharge area (see Section 2.3) can be defined as the Catchment Protection Zone for a collection of sources. In such cases, the Environment Agency will normally draw boundaries along appropriate aquifer boundaries such as groundwater management units or groundwater bodies.

# 4. Quality assurance and reporting

Source protection zones (SPZs) form an important element of the Environment Agency's Approach to Groundwater Protection (Environment Agency 2018) in controlling development or land use changes that have the potential to cause adverse impact to groundwater.

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, producing a report documenting the process, a review of the process and the methods of quality assurance used in deriving the SPZs are important.

This section of the methodology refers to Step 5 in the process shown in Figure 1.1.

## 4.1. Quality Assurance and Review

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

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

Therefore 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, and known as the Source Evaluation Report (SER). The format of this report is discussed in Section 4.2.

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.

The method used 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 FlowSource follows an independent review of the software.

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, such as the water company, or private abstractor.

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. For example with regards to protected cover zones there may be a need to consult with the Department for Business, Energy & Industrial Strategy (BEIS).

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

## 4.2. 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.

The format of SERs will have varied over time and also across the country. For example they originally consisted of paper ring binders that include maps and diagrams produced by hand. These would be open files that could be added to if there were changes to the sources and the SPZs. In recent years local EA offices should have scanned the SERs to make an electronic copy.

More recently the reporting of zone delineation is likely to have been in one report including all the relevant maps and figures produced electronically. Some of this will be aided by the use of databases and GIS systems containing the relevant information.

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 original 1990s proformas filled out by Environment Agency hydrogeologists contain detail concerning the source(s), aquifers and known hydrogeological understanding of the SPZs created at that time. Later SPZs may not have the same style proformas, although the relevant information will still have been collated.

Documentation and justification of any alterations made during the SPZ delineation process is required – particularly the final definition steps described in Step 4, Section 3.5.

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.

# 5. Final SPZs - Delivery and Communication

The final step in the process, shown as Step 6 in Figure 1.1, is to update the SPZ datasets and communicate these new and updated SPZs to customers.

## 5.1. Updating Datasets

### 5.1.1. Introduction

The Source Protection Zones and Source Protection Locations datasets are updated every 3 months, in line with our Quarterly Data Release for publishing on data.gov.uk, where they are available to download. The updates also feed the Natural England MAGIC (https://magic.defra.gov.uk/) mapping portal where the maps are available to view, and also internal EA systems.

The update process is primarily automated, but there is some preparation of data required.

### 5.1.2. Dataset description

The Source Protection Zone maps are 1:50,000 scale polygon shapefiles, in British National Grid projection. This data has no topology. A ground accuracy of 10 metres is used, with a maximum distance of 250 metres between points.

The existing National GIS datasets consist of three components:

- One data set (point) holding the locations of the abstraction sources
- One data set (polygon) holding individual zones (EA internal only)
- One data set (polygon) holding zones that have been merged

The shapefiles are named as follows:

- source_protection_locations_50k
- source_protection_zones_indiv_50k (EA internal only)
- source_protection_zones_50k

The EA Data Management team receives updates to SPZs from area staff via the Environment & Business (E&B - national) Groundwater team. The changes are then incorporated into the national dataset.

### 5.1.3. Update process

Updates are submitted quarterly, presently in January, April, July and October, although EA area leads may submit their shapefiles and spreadsheets detailing which SPZs and Source Protection Locations (SPLs) need to be inserted, updated or deleted at any time leading up to each deadline.

At the end of the updating process each quarter, the national data team provide a link to the uploaded files to the E&B Groundwater team. This is forwarded to areas for them to check the changes they submitted have been applied correctly as part of the QA process.

### 5.1.4. Publishing process

Once any errors have been fixed, and areas have confirmed all inserts, updates and deletions are correct (or the QA feedback window has elapsed), the revised data is distributed to the various publishing locations so that they are available to view or download.

One important point to note is that only the merged zones are published externally on MAGIC and data.gov.uk. At present the SPZs for the individual sources aren't approved for access externally.

## 5.2. Communication

It is likely that abstractors would have been involved in some ways during the production of new SPZs, or SPZ updates that have changed the zones for their sources. This communication may have been just to inform the abstractor of the new zone or update, and the process used to produce it. For public water supply zones, the water company may have been more involved throughout the process. In both cases it is recommended that the source operator has the opportunity to see the final zones before they are published.

It is recommended that the source operator is told once the final zones are published. As the publishing is now via MAGIC and data.gov.uk, it is likely that this information can just be emailed with a link to the viewer and data, although it could be useful to produce a pdf describing the zones, any changes and including a map.

As many of the position statements related to SPZs (as shown in Table 1) are linked to development planning issues it is also recommended that the relevant local planning authority (LPA) is informed of any changes to SPZs, including new zones, updates and removals. Any communication with the LPA could go through the relevant EA area team that deals with development planning. As with source operators it is useful to produce an update document / report providing details of the update, where to view and download them and a map.

Other internal EA communication is likely to be required, especially with local teams who deal with water quality and environmental incident issues. The changes should be picked up by use of internal mapping systems such as Easimap2, however it is still recommended that proactive communications are produced.

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# List of abbreviations

| | |
|---|---|
| 2D | two-dimensional |
| 3D | three-dimensional |
| 4R | Routing of Rainfall to Runoff and Recharge Model |
| AEM | Analytical Element Method |
| AFRC | Arbitrary Fixed Radius Circles |
| BEIS | Department of Business, Energy and Industrial Strategy |
| BGS | British Geological Survey |
| BPJ | Best Professional Judgement |
| CAMS | Catchment Management Abstraction Strategy |
| CoGAP | Code of Good Agricultural Practice |
| DWI | Drinking Water Inspectorate |
| GIS | Geographical Information Systems |
| GPZ | Groundwater Protection Zone |
| GWMU | Groundwater Management Unit |
| HS2 | High Speed 2 Railway |
| LPA | Local Planning Authority |
| LTA | Long Term Average |
| MAR | Managed Aquifer Recovery |
| Ml/d | million litres/day |
| NALD | National Abstraction Licence Database |
| NGMS | National Groundwater Modelling System |
| NRW | Natural Resources Wales |
| PY | Protected Yield |
| SER | Source Evaluation Report |
| SgZ | Safeguard Zone |
| SPZ | Source Protection Zone |
| TCZ | Total Capture Zone |
| US EPA | US Environmental Protection Agency |
| USGS | US Geological Survey |
| WFD | Water Framework Directive |
| WHAEM | Well Head Analytical Element Model |
| WRGIS | Water Resources GIS |

# Appendix A - Factors controlling the geometry of hydraulic capture zones

This Appendix 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.

## A1. Hydrogeological factors

### Principal components

The hydraulic capture zone to an abstraction borehole is the area within which all aquifer recharge, whether derived from precipitation or from leakage from surface watercourses, may flow to that borehole. This is not generally the same as the area of influence, which is the outer limit of the cone of depression to an active abstraction borehole. Where the piezometric surface is horizontal, the hydraulic capture zone and the area of influence are the same but where there is a regional hydraulic gradient, the two will be different as shown in Figure A.1. The geometry of hydraulic capture zones is dependent on several factors, many of which are interdependent.  Their influence on protection zone delineation is summarised in Tables A.1 and A.2.

The ability to accurately simulate hydraulic capture zones is limited by the availability of data, particularly where aquifer properties are heterogeneous at the small scale.  Most numerical models used to generate hydraulic capture zones use a simplified distribution of aquifer properties across the model domain.  Aquifer property heterogeneity is less of an issue for more extensive outer capture zones where model aquifer properties are often representative at the regional scale.

Inaccuracies in capture zone delineation are typically greater for zones of a length-scale less than two kilometres and/or for aquifers with heterogeneities affecting flow and transport at a km scale or greater, in particular aquifers with dominantly fracture flow and/or karst such as Chalk and Carboniferous Limestone.

Manual modifications to modelled hydraulic capture zone boundaries should be made where source-specific information shows that the hydraulic capture zone is incorrect (Section 3.5).

The geometry of hydraulic capture zones will also vary with time as groundwater head changes in response to variations in aquifer inflows such as recharge and discharges to ground, and outflows such as abstraction.  In aquifers with significant variation in water levels, the shape of the capture zone could also change in response to variations in transmissivity at different elevations in the aquifer.  Such significant variations in water table could be seasonally controlled, drought related, or linked to variable abstraction rates.  If there is not enough data to determine the variability in capture zone shape due to groundwater head fluctuation then it may not be possible to represent these potential variations. However, where possible such variability in capture zone geometry should be included in the delineation process.

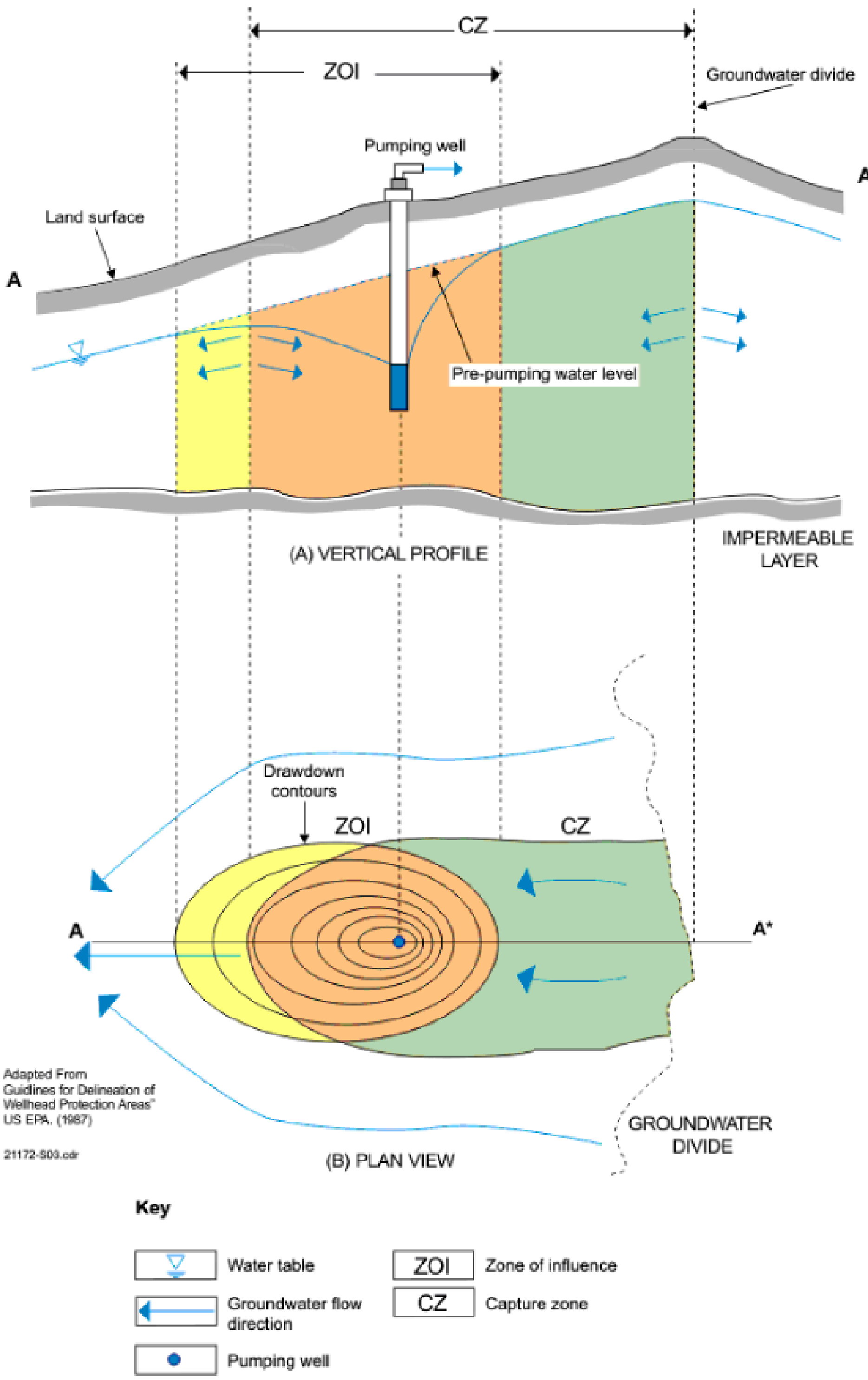



Figure A.1 Source capture zone and the zone of influence around a pumped well.

**Table A.1 Factors controlling the shape and size of hydraulic capture zones**

| Type of Zone | Size | Shape |
|---|---|---|
| **50 and 400 days (SPZ1 and SPZ2)** | • Abstraction rate<br>• Kinematic porosity and its spatial variation both vertically and horizontally<br>• Aquifer thickness<br>• Hydraulic conductivity and its spatial variation both vertically and horizontally<br>• Recharge rate (direct and indirect)<br>• Hydraulic gradient and direction of groundwater flow[1] | As for factors in size column plus:<br>• boundary conditions edge of aquifer, stream, lake, etc. |
| **Catchment Protection Zones (SPZ3)** | • Abstraction rate<br>• Recharge rate (direct and indirect) | As for factors in size column plus:<br>• Hydraulic conductivity<br>• Aquifer thickness<br>• Boundaries<br>• Hydraulic gradient and direction[1] |

Notes: [1] Hydraulic gradient is dependent on aquifer inflows and outflows, aquifer thickness and hydraulic conductivity.

**Table A.2 Influences on the geometry of hydraulic capture zones**

| Parameters | Influences |
|---|---|
| **Aquifer thickness** | Affects transmissivity and the volume of water in an aquifer, and hence the extent of 50 and 400 day zones and the shape of hydraulic capture zones. For example, a halving of aquifer thickness results in an approximate doubling of size and an increase in width of the zone. |
| **Kinematic Porosity** | Affects the size of the 50 and 400 day zones. For example, halving porosity results in a 2 to 4 fold increase in zone size. |
| **Hydraulic conductivity** | Mainly affects the width and the downgradient extent of the zone. An increase in the horizontal hydraulic conductivity will decrease the width of the capture zone. Variations in vertical horizontal conductivity can affect the size of the zone at different water levels. |
| **Hydraulic gradient** | Affects the width and downgradient extent of the hydraulic catchment zone – the steeper the gradient the narrower the zone. |
| **Abstraction rate** | Directly affects the size of zones. Interference between nearby abstraction boreholes affects the shape of zones, producing ‘tails’ and ‘holes’ (Figure A.2). |
| **Recharge (annual)** | Directly affects the size 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 superficial deposit or karstic areas can extend the catchment zone to capture these areas of potential recharge. |
| **Boundaries – no flow** | No-flow boundaries, faults and groundwater divides constrain the shape of zones. |
| **Boundaries – recharge head dependent** | Head-dependent boundaries affect the shape and possibly reduce the size of capture zones (particularly the catchment zone). |

### SPZ1 – Inner Protection Zone

Inner Protection Zones generally have a simple geometry as they are normally based on models or parts of models where aquifer properties are close to uniform. They tend to be circular or elliptical reflecting the cone of depression around the abstraction borehole.

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

Their simple shape is often due to the limited information on the variability of aquifer properties around the source and the limitations of model cell size. Numerical models which allow refinement of model grids around abstractions, or more detailed sub-grid scale modelling (e.g. MODFLOW USG or MODFLOW 6) where available could allow more detailed modelling of SPZ1, with the possible inclusion of fracture networks and adits.

### SPZ2 – Outer Protection Zones

Outer Protection Zones are generally intermediate in shape complexity, between Inner and Catchment Protection Zones. Complex shapes arise through interference with other abstractions; heterogeneous aquifer characteristics; or due to the characteristics of the source (e.g. the presence of adits).

### SPZ3 – Catchment Protection Zones

The shape of Catchment Protection Zones can vary from the simple to the complex as illustrated by Figure A.2. Increased complexity can generally be attributed to:

- interference between groundwater abstractions;
- groundwater/surface water interactions;
- lateral variations in hydraulic properties; and
- natural patterns of diverging and converging groundwater flow.

If there is limited information on the variability of aquifer properties, then modelling hydraulic capture zones using uniform aquifer properties is unlikely to show the full effects of aquifer heterogeneity.

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

The amendment of modelled complex and long shapes to provide usable SPZs is discussed in Section 3.5.2.

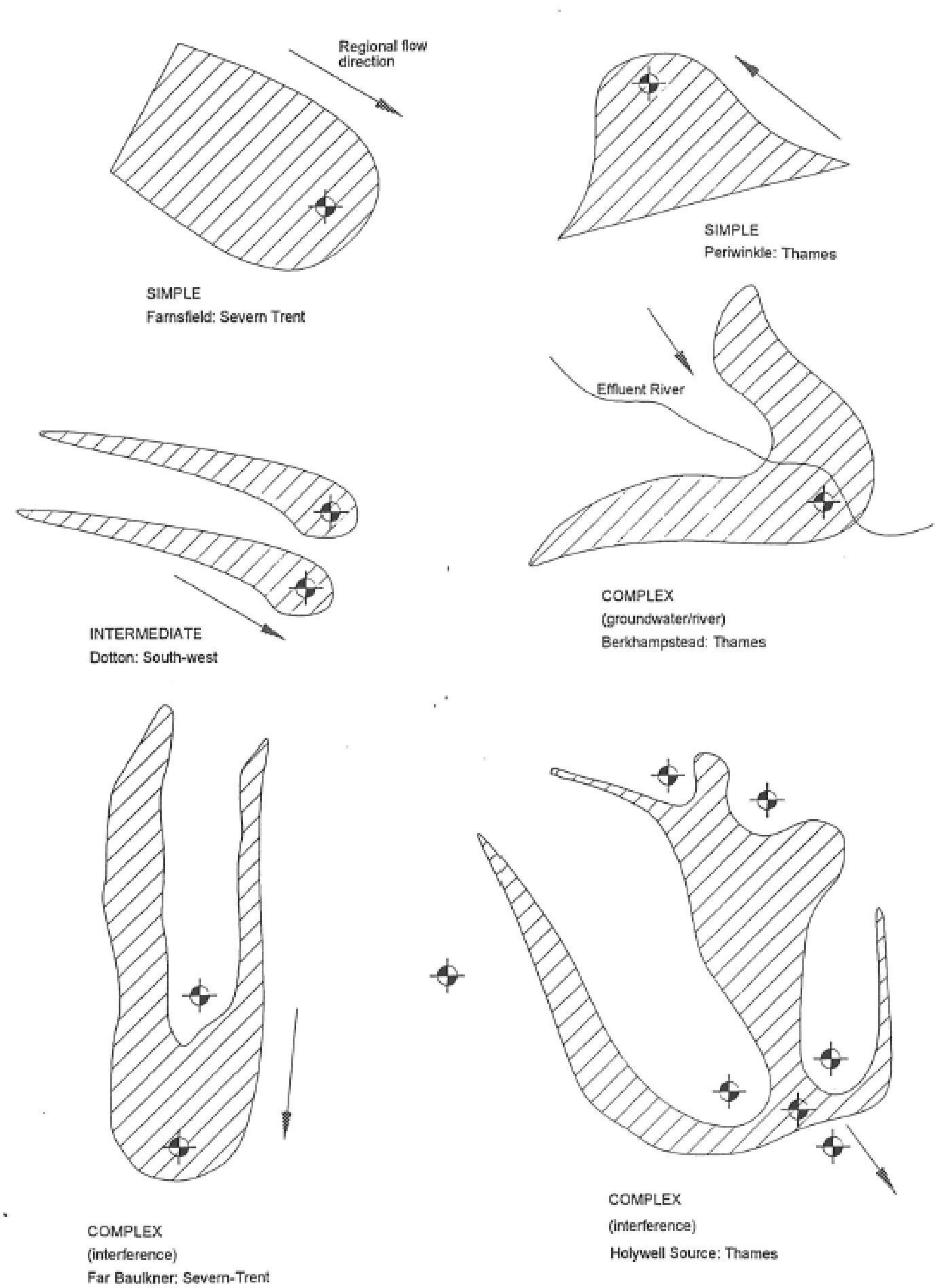



**Figure A.2 Example source catchment zone shapes**

## A2. Field data factors

The accurate determination of hydraulic capture zones depends on the accuracy and detail of the available field information describing the aquifer system in question. Uncertainty associated with this data is due to:

- field data are sparse but parameter values are required for the whole aquifer;
- data is based on estimates of average or regional conditions which may not represent local conditions;

- aquifer parameters may be derived from aquifer testing at locations that do not represent 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 will vary 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 measurements of field values and parameter estimates over the model domain.

Examples of the problems that can be associated with data used to construct groundwater flow models are given in Table A.3. For most regional groundwater models, the accompanying reports on model construction and calibration should identify where any of these factors may be significant.

Table A.3 Possible problems when transferring field data to a model

| Parameter | Field | Implication for model |
|---|---|---|
| **Hydraulic conductivity** | Pumping test data is typically biased towards larger groundwater abstractions in areas of higher hydraulic conductivity because this is where water is most readily available.<br>Pumping tests may have been carried out at different rates or durations, and at different times of the year, and the values derived may be representative of variable volumes of the aquifer.<br>A range of values may be derived from different methods of analysis of a single pumping test. Transmissivity values only may have been quoted with no information on aquifer thickness. | Model values may be overestimates and will have uncertainty. |
| **Kinematic porosity** | Limited data availability. Kinematic porosity is derived from tracer or laboratory testing but these are rarely undertaken. | Model values generally based on estimates or expert opinion. |
| **Groundwater levels** | Contours are often an interpretation of sparse water level data and may not fully account for lateral and horizontal variations in aquifer properties.<br>Water levels measured at a borehole may be more representative of local conditions (e.g. the borehole may only partially penetrate the aquifer).<br>Groundwater levels vary with time whereas a single average value is often used in simple models. | Simple models take no account of seasonal or long-term variation.<br>Model calibration accuracy may vary across the model domain. |
| **Aquifer base elevation** | 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 effective thickness are available and the model base of the aquifer is defined by subtracting this value from the groundwater surface. This approach involves interpolation of field data. |
| **Recharge** | Values may be estimates, particularly where superficial deposit cover limits recharge. A single value, or a limited range of values may be used across a model area. | SPZ3 may be in error, particularly for catchments with a superficial deposit cover or in karstic areas. |
| **Groundwater/river interaction** | Stream gauging data to provide a measure of the gain or loss in river flow due to groundwater interaction may be limited, and only represent certain flow conditions i.e low or high flow. Little or no data on valley bottom/alluvial deposits separating river from aquifer. | Modelled groundwater/river interaction cannot easily be checked with reality and hence hydraulic capture zones may be in error. |

## A3. Assumptions and limitations of calculations and models

The geometry of capture zones is also influenced by the methods used for their delineation. For example, manual methods (Appendix C2) generally produce simple SPZs. Numerical models (Appendix C4) may allow 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 of delineation, assumptions have to be made to simplify the complex real hydrogeological system. Assumptions that could lead to issues with delineation of capture zones include:

- **Fixed conditions (steady state model).** In reality groundwater flow rates and direction normally vary with time but steady state models will not fully represent this variation. It could be that the variation in flow regime is not significant enough to lead to large fluctuations in capture zone extent for example in sandstone aquifer with a slow response time to such changes. However, the orientation and geometry of predicted capture zones should still be checked with field data to ensure that the fixed conditions chosen are reasonably representative.
- **Horizontal groundwater flow (simple model).** This approach 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 borehole capture zone may be different to that delineated with a two dimensional model. In more complex multi-layered models, vertical hydraulic conductivity and its spatial variation will be incorporated into the model, although it may be based on limited information.
- **Flow is intergranular or diffuse fracture flow.** Where the abstraction is from a karstic aquifer, groundwater flow will be non-Darcian, i.e. conduit flow occurring in discrete open fractures, fracture zones and cave systems. In these conduits, flow velocities are high (up to several km/day) and travel times from the edge of the catchment to the source can be short (days or even hours) such that the Inner Protection Zone (50-day travel time) may be the same as the Catchment Protection Zone. Therefore, catchment zones in such environments cannot be adequately delineated using methods that assume Darcian flow. More detail on source protection in karst systems is given in Appendix B4.
- **The model is an accurate representation.** Accuracy of the model should be checked against observed conditions such as groundwater levels or stream flows, or evidence from pollution events.

In addition, hydraulic capture zones will be influenced by:

- **Assumptions** made in model construction, 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 also require a different approach to delineation. Adits can be several hundred metres in length and exert controls on flows to the borehole over a wide area, presenting particular problems for modelling. To some extent these issues can be eliminated through grid refinement around the adit. In some cases model diagnostic tools have been used to improve model stability where adits are present in the numerical groundwater model. A series of guidelines has been developed for delineating the associated capture zones (Appendix B7).

## A4. 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 (grid) spacing (Figure A.3). Too low a resolution around pumped wells can result in a poor approximation of the cone of depression. This leads to particle tracks not diverging enough resulting in overly narrow capture zones.
- Weak sinks. These occur where an abstraction does not account for all the flow into a model cell. Where there is a weak sink, particle tracking algorithms can struggle to determine the pathway for individual particles, i.e. whether they go to the abstraction or out of the cell.

- Partial penetration (Figure A.4). Single layer models cannot adequately represent boundary conditions (e.g. a river or a well) that only partially penetrate the thickness of the aquifer, represented by that single layer.

These issues apply to finite difference models, such as MODFLOW that have been used to construct many regional models. 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. Advances in MODFLOW based modelling (e.g. MODFLOW 6 or USG) mean that numerical approaches may be available in the near future which remove some of these issues.

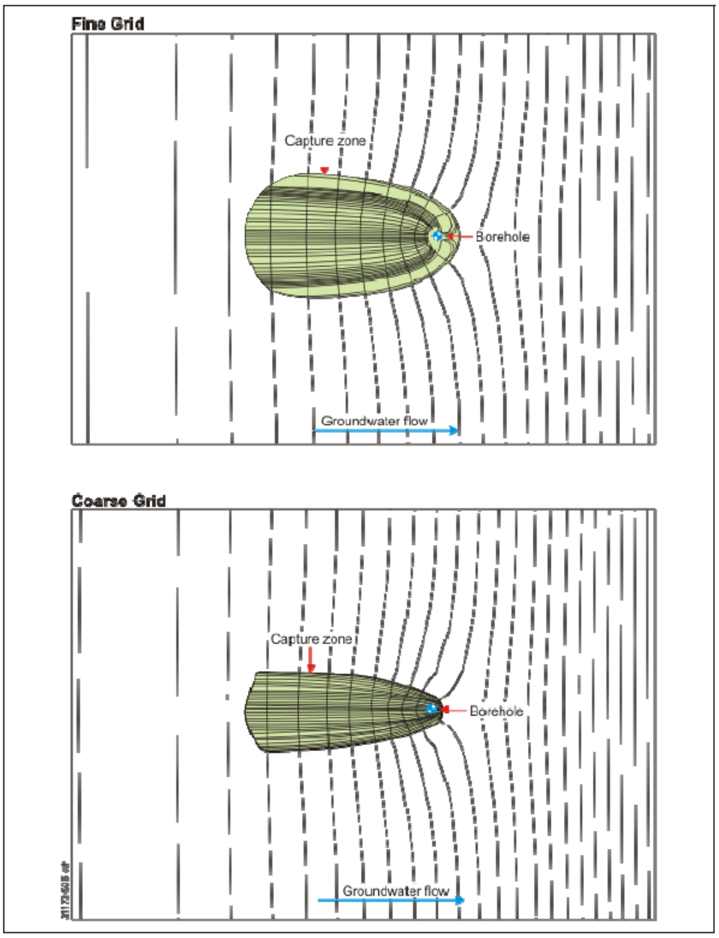



Figure A.3 Influence of model grid spacing on zone definition

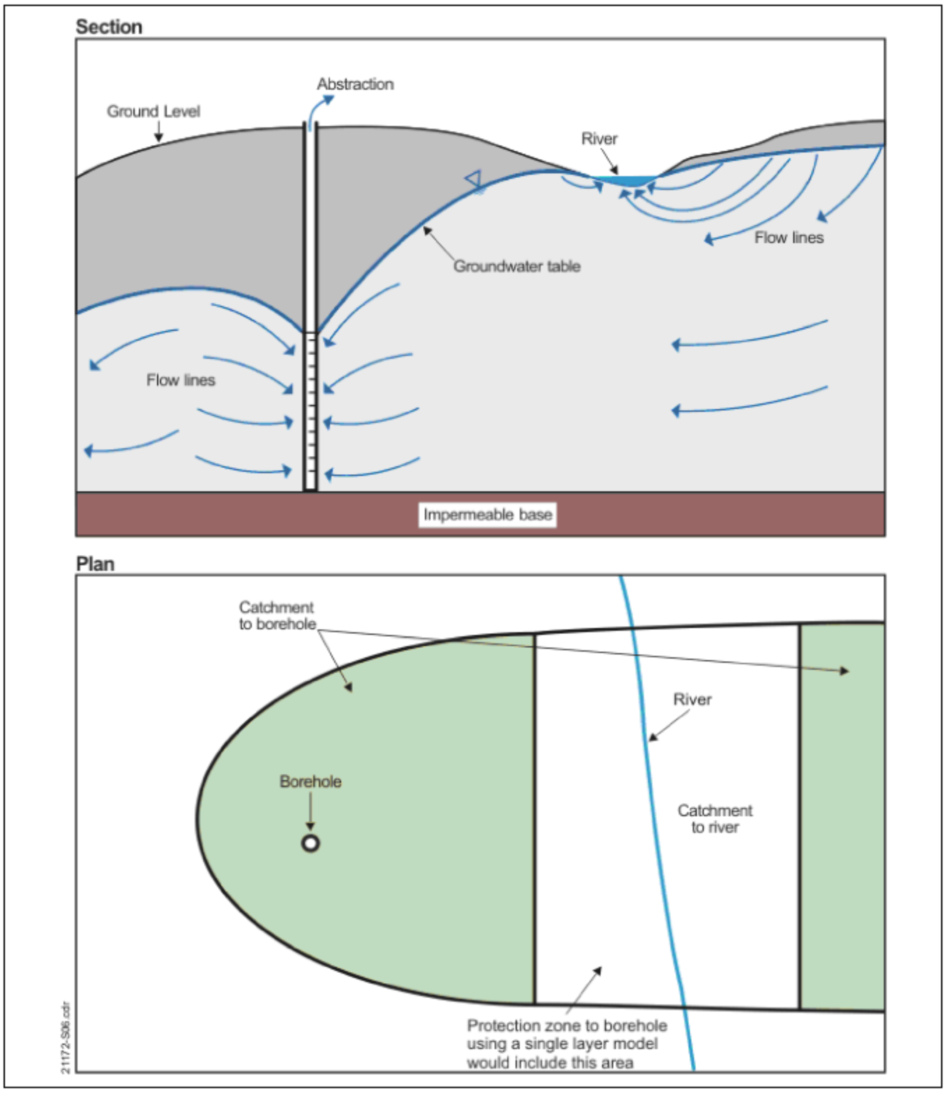



**Figure A.4 Influence of stream partial penetration on capture zones**

## Model calibration

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. The accuracy of modelled capture zones depends on the satisfactory calibration of the model. Figure A.5 illustrates the effect of poor calibration to groundwater levels on protection zone definition in a thin unconfined aquifer.

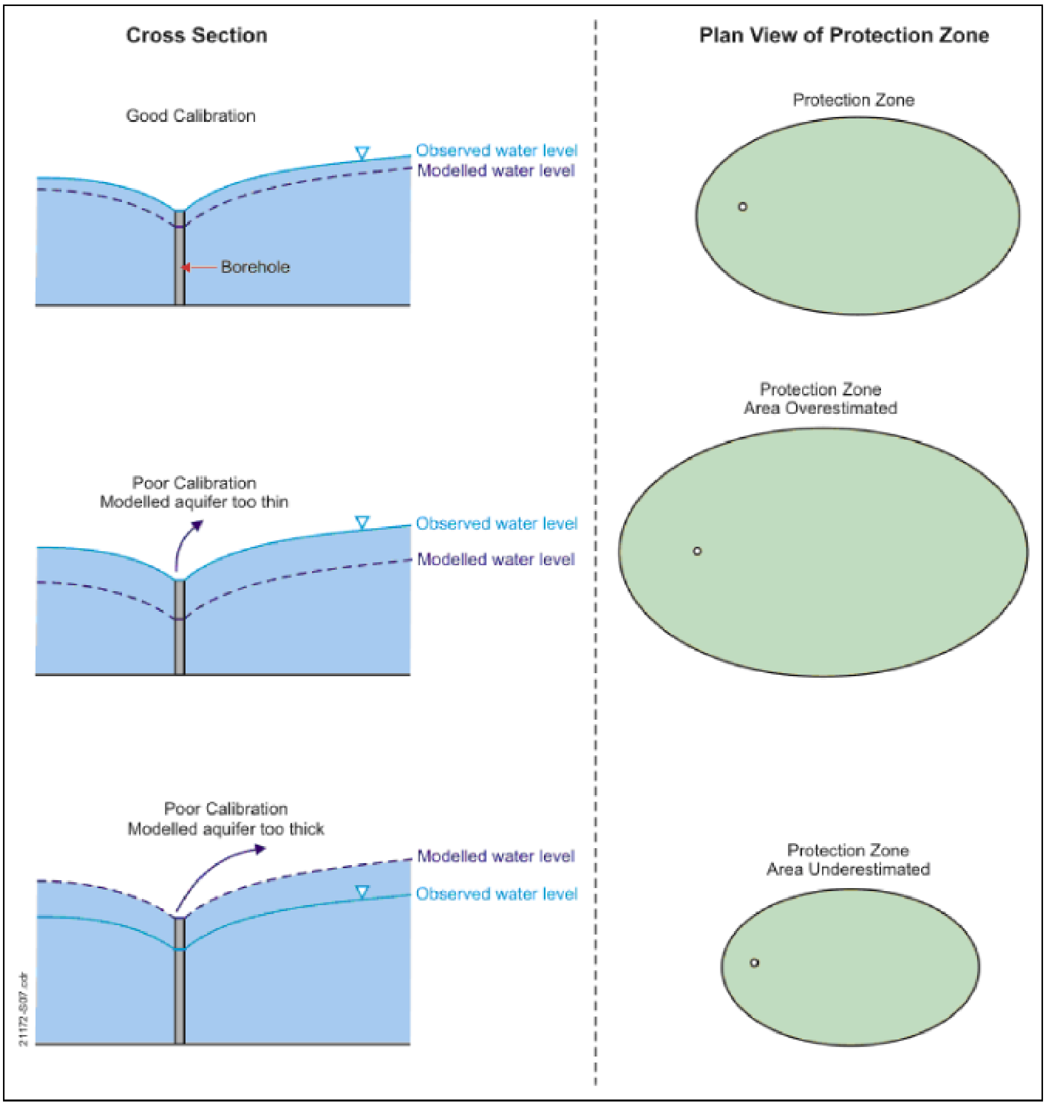



**Figure A.5 Influence of calibration of groundwater levels on protection zone definition in a thin unconfined aquifer**

# Appendix B Source protection in special cases

This appendix draws together issues related to SPZ definition in particular hydrogeological environments and aquifers. It deals with:

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

## B1. Sources with limited data

These are typically small sources in Secondary aquifers that do not generally sit within a regional model. Case studies (3 and 4) in Appendix D are on SPZ delineation for sources with limited data. SPZs for these sources should be defined using manual methods (Appendix C2).

The minimum information that must be obtained is the licensed abstraction rate, and, if an existing abstraction, the actual abstraction rate. For spring sources, the maximum discharge of the spring, in addition to the abstraction rates, should be measured or estimated. In addition, delineation should include:

- The measured or estimated spring or borehole water level elevation to support defining the catchment that could contribute to the source based on elevation.
- Collection of information on geological and hydrogeological boundaries that could be used to define SPZ boundaries;
- A site visit to obtain catchment details, including the location of geological and other features adjacent to the source.

## B2. Small sources

As described in Section 3.2, SPZs and the associated position statements apply to all groundwater abstractions for the purposes of human consumption. Small sources with abstraction rates of > 250 $m^3$/day should be prioritised for bespoke SPZ delineation. For small sources with low abstraction rates the following problems for hydraulic capture zone delineation may arise:

- Limited or poor quality data.
- The catchment protection zone is likely to be narrow meaning that if there is limited information on the direction and gradient of groundwater flow, there will be significant uncertainty on the location of the zone.
- Unless a regional groundwater model already exists and includes the small source, the use of numerical methods (e.g. MODFLOW) may be impractical as there is unlikely to be sufficient data and setting up a model grid of sufficient accuracy to represent the flow field will require additional effort / complexity. Analytical methods are generally more suitable for hydraulic capture zone definition.

An example of limited data for the definition of hydraulic capture zones for small zones is uncertainty in the hydraulic gradient. If the hydraulic gradient is unknown, for example, the default is to assume a flat water table, which gives zones as circles. This will underestimate the extent of the SPZ in the up-gradient direction. This problem can be overcome to some extent by using estimates of hydraulic gradient based on surface topography, although sensitivity analysis is required to assess the effects of uncertainty on this parameter.

Section 3.4 summarises techniques used in England to delineate hydraulic capture zones. Recommendations on their use for small sources are given in Table B1. In summary the methods are:

- Manual approach supported by hydrogeological mapping where data are limited;
- Analytical solutions or analytical element methods (Sections C2.3 and C3) where groundwater flow is Darcian, the direction and hydraulic gradient are known with reasonable certainty, and estimates of hydraulic conductivity and kinematic porosity are available.
- Pre-defined zone 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. In all cases, SPZ boundaries should take account of:
- geological and hydrogeological boundaries (Section 3.5.1);
- any additional local information such as tracer tests and pollution incidents.

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

**Table B.1 Recommended techniques to delineate small source protection zones**

| Description | Comments |
|---|---|
| **Hydrogeological mapping** | Groups wells into hydrogeological domains/aquifer types enabling classification of behaviour.<br><br>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.<br><br>Easy to apply. |
| **Calculated circular zones based on recharge and abstraction (plus kinematic porosity and thickness for Inner and Outer Protection Zones)** | Is clearer when applied to groups of similar abstraction and recharge.<br><br>Where no aquifer parameters are available, this could be used with 50 m default AFRC.<br><br>Problematic if actual daily rates are much greater than annual licensed quantity divided by 365.<br><br>Only suitable for Inner and Outer Protection Zones if no hydraulic gradient available.<br><br>Underlying concept easy for non-specialists to grasp. |
| **Standard simple shapes based on idealised representation of local conditions** | Review the shapes of current SPZs with the conceptual understanding of the aquifer to identify the most appropriate shape that reflects the flow field. |
| **Numerical modelling with MODFLOW, MODPATH, Flowsource etc.** | Where the source is covered by such a numerical model, and it is the best available technology for SPZ delineation. |

## B3. Spring sources

For spring sources, the licensed abstraction rate is typically less than the total spring discharge rate. However, the maximum spring discharge rate should be used for SPZ delineation as the whole catchment requires protection. Based on the information available spring SPZs can be manually drawn using spring elevation, geology and topographic contours as a guide (Appendix C2) or numerically modelled. A spring source can be complex; for example the source may comprise a number of spring locations along a spring line feeding into a collection system that allows treatment and distribution for supply purposes. The actual location of the spring discharge point may change in a dynamic groundwater system. Therefore more information on the characteristics of the spring and its catchment should be collected, including a site visit for poorly understood spring sources.

## B4. Karst sources

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

### B4.1. Karst

The term "karst" describes the effect of solution-enhanced weathering on topography and hydrogeology. Karst features are found in aquifers that undergo solution-enhanced weathering and include:

- conduit flow and underground rivers;
- caves;
- stream sink (sometimes called swallow hole) - surface karst feature through which water enters the aquifer;
- doline - a dry surface depression formed by karst processes
- epikarst – uppermost part of the unsaturated zone of the karst rock where there is enhanced weathering and fracturing;
- very rapid groundwater flow (velocities of km/day);
- springs;
- dry valleys.

The Carboniferous Limestone (and some other older limestones) are classically karstic with extensive cave development, whilst others (e.g. the Chalk and Jurassic and Permian limestones) have little cave development and smaller scale karst features. Karst presents significant challenges in defining SPZs that are adequately protective without covering large areas of land. In karst aquifers a large component of flow may be rapid and non-Darcian. Flow pathways within the karst system itself may be complex, crossing surface water divides, potentially flowing in different directions at different depths and within different stratigraphical units. Sink points of streams vary as some become blocked and others open up. The sink point also varies in response to rainfall, moving further downstream in high flow conditions

The catchment to an abstraction from a karst aquifer, or one with karst features, may be fed by sinking surface water streams which enter the aquifer through swallow holes. The streams may potentially drain large areas of impermeable or low permeability ground adjacent to or above the karst area, meaning that the area of land over which recharge drains to the abstraction can be very large. 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 low permeability part of the catchment poses a risk to karstic sources, groundwater discharge from this low permeability area to the karstic aquifer is considered insignificant.

Travel times from the swallow hole capturing a sinking stream to the groundwater abstraction may be in the order of hours or days. In such situations, to protect the abstraction the SPZ must include the surface water catchment feeding the karst system. However, including areas of land in the SPZ from which such run-off or perched groundwater does not reach the source within a relevant timescale would be overprotective. The groundwater SPZ in a karst aquifer may therefore comprise two components:

- a surface water catchment over impermeable superficial deposit non-karstic strata that concentrates recharge through swallow holes within a relevant timescale;
- a more conventional saturated groundwater flow capture zone.

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

For the majority of sources in karst areas, SPZs are best delineated using field mapping and manual methods. Analytical or numerical techniques which assume Darcian flow are likely to be unsuitable. Although numerical models have been developed to represent karstic systems they are impractical for SPZ delineation due to the large uncertainty around times of travel close to the abstraction.

## B4.2. Methodology for delineation of SPZs in Karst

Delineation of SPZs in karst aquifers typically uses a manual approach, including information gathered from field investigations (e.g. tracer tests) and appropriate calculations to build a conceptual understanding of the catchment to the abstraction. In most karst aquifers in Europe SPZs are delineated using a catchment vulnerability type approach (e.g. Dörfliger et al. 1999; Pochon et al., 2008), however these approaches haven't been used in England at the present time.

A case study on SPZ delineation in the Karst for the Corallian is provided in Appendix D (case study 5).

Basic principles of karst catchment delineation are:

1. Build and agree a conceptual understanding of the water flow in the aquifer to the abstraction before starting SPZ delineation.

2. Land beyond the edge of a karst aquifer formation, from which surface or overland flow provides run-off into the aquifer, and therefore contributes to the abstraction, should be included in the SPZ. Where areas of land clearly do not contribute water to the abstraction they should not be included within the SPZ.

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 (50 or 400 days). SPZs in general should be delineated on horizontal and vertical flow travel times of water from the water table to the abstraction. Calculations of travel times in karst aquifers should consider: overland flow from an aquitard that runs off into a high porosity fracture flow aquifer; and perched shallow interflow in cave systems / solution enhanced fissures.

Where the conceptual understanding suggests that an impermeable covering layer could support exclusion of areas of land from the SPZ, the nature of that 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 we would need additional and extensive evidence that this is the case before this area could be excluded from the SPZ.

The method for karst aquifer SPZ delineation is set out as follows:

1. Data collection including tracer tests (see Section B4.3).

2. Field inspection of each source and its possible catchment area to assess the importance of active or dry springs, watercourses, and topographic and geological features.

3. Develop a conceptual understanding of the source catchment based on spring/borehole behaviour, karst features, dry valleys, interfluves, etc.

4. Define the boundaries of the hydraulic capture zone based on:

– The recharge area required for the abstraction, using water balance calculations. This will be the minimum area as tracer tests may show that recharge is drawn from a larger area, and the catchment area will also vary with water level, which often changes seasonally, and the capture zone should reflect this. The total catchment area (SPZ 3) should incorporate all areas that can contribute at both high and low water levels.

– Information on the geology and hydrogeology of the aquifer (geological and hydrogeological boundaries);

– Information on the karst flow regime from mapping of underground cave systems, tracer tests (see Section B4.3) and evidence of pathways from pollution incidents;

5. Define 50 day zone (SPZ 1) based on:

- tracer tests (where available) or other information such as pollution incidents;
- understanding of the behaviour of the surface water catchment and its interaction with the aquifer, e.g. the location of sinking streams that support the potable source;
- manual calculations (see Appendix C) assuming low fissure porosity.

6. Define the 400 day zone and catchment zone (SPZ 2 and 3). In most cases the boundaries of the 50 and 400 and catchment zones will be drawn as coincident (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 day travel time boundary in this geology type, prior to discharge to the karstic aquifer in which the potable source is located

7. Define the part of the catchment underlain by low permeability strata upstream of the sinking stream. 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.

8. 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.

9. Define proposed SPZ boundaries and review these based on conceptual understanding of local and regional groundwater flow.

10. Finalise SPZ boundaries.

11. Record the basis for SPZ determination (see Section 4).

## B4.3. Data sources, data reliability and records of methodology

The main sources of data for karst aquifer SPZs will be: the abstraction licence file, geological and hydrogeological mapping, tracer tests, historic records (e.g. cave group memoirs and local archives), and local knowledge. The British Geological Survey (BGS) have a karst database which can be an important source of information. Peter Brett Associates (now part of Stantec) also hold a natural cavity database. Local knowledge should be validated using independent sources where possible to avoid conflict, while historical records should be checked at source to ensure reliability. This process may be supported by discussions with quarry operators and local groups (nature trusts, cavers, etc.). A review of the collated data should focus on identifying karst features, spring flows, and variations in groundwater level and flow direction.

Tracer tests to identify water flow pathways can provide the most robust evidence in defining Inner Protection Zones. When using the results from tracer tests, it is essential to assess whether they are appropriate to the abstraction 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;
- water levels when the tests are carried out. Measurements made at different times of year, and with different flow conditions could provide different information. 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.

## B4.4. Karst or Karstic Aquifer types

*Palaeozoic limestones (Carboniferous limestones)*

The limestones and limestone conglomerates of the Mendip Hills, the Pennines, and north and south Wales, are characterised by mature karst landscapes and very extensive cave development. Caves and major conduit 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 B4.2 is likely to be the most appropriate for Palaeozoic limestone sources.

*Jurassic limestones*

In general, the Jurassic limestones are less consolidated than their Palaeozoic equivalents, retaining some primary porosity and intergranular permeability. The main Jurassic limestones in southern England are the Great Oolite, the Inferior Oolite (Cotswolds and Lincolnshire Limestone) and the Portland and Purbeck limestones. There are also many thin but extensive limestones including the Blue Lias, and the Beacon Limestone Formation, as well as the Fuller’s Earth Rock, the Forest Marble, the Cornbrash which are part of the Great Oolite Group, and the Osmington Oolite, which is part of the Corallian Group. The Corallian of Yorkshire and northern extensions of the Lincolnshire Limestone are located in the north of England.

Most of the larger abstraction boreholes in the Great and Inferior Oolites of the Cotswold Hills draw water from a deep confined aquifer, remote from 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 are likely to exist. A few large springs exist in the confined zone. These are likely to be in areas of incomplete cover or where there are collapse features and 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 geological structures (e.g. faults, etc.). These enhanced flow zones lead to karstic recharge.

The zoning procedure described in Section B4.2 can be applied to the Lincolnshire Limestone where karstification is known or suspected. In areas where there is no evidence of karstification, hydraulic capture zone delineation should be based on analytical or numerical modelling of Darcian flow, supplemented by local hydrogeological knowledge of the aquifer behaviour.

*Chalk*

Although caves appear to be fairly rare in the Chalk and surface karst features occur on a smaller scale than in classical karst aquifers, they can occur very frequently, and there is extensive evidence of karst in the Chalk. Karst features that have been identified include:

- 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;

- rapid, high volume 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.

The zoning procedure described in Section B4.2 can be applied to Chalk areas where karstification is known or suspected. If there is no evidence of karstification, then hydraulic capture zone delineation should use analytical or numerical modelling assuming Darcian flow, supported with local hydrogeological knowledge of aquifer behaviour.

The delineation of capture zones around sources in winterbourne catchments may cause problems. Winterbournes are streams that typically flow in winter when groundwater levels reach the elevation of the spring line feeding the stream, but in summer when the water table is below this level, the stream bed is dry. They are characteristic of the Chalk country of southern England. At high water level the abstraction catchment might be on the borehole side, but could equally be connected to a flowpath on the opposite side of the valley, and this in turn may or may not be connected to the flowpath supplying the winterbourne. Under low flow conditions, the abstraction might get water from lower flow horizons that pass under the dry riverbed, but equally could get water from the borehole side if that happens to be where the karst flowpath is developed. These uncertainties and variabilities will be the same for the time of travel zones as for the total catchment.

In determining SPZs for catchments that include winterbournes, a good conceptual understanding of the seasonal variations are required to determine which parts of the catchment to include. This may involve modification of hydraulic capture zones derived from model output to represent seasonal variations in catchment areas. It is noted that transient regional groundwater models should represent this change in catchment with time.

## B5. Kinematic porosity and sandstone sources

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

Tracer tests over relatively short distances (metres to tens of metres), suggest that flow in Permo-Triassic Sandstones is mainly intergranular, with kinematic porosities of 10–15%, but that fissure flow over hundreds of metres can occur (Ward et al., 1998).

Figure B.1 presents calculations of travel times and the size of 50 and 400 day zones for a range of fissure and intergranular kinematic porosities and shows that using porosity in the 10-15% range in thick aquifers can result in relatively small Inner and Outer Protection Zones.

Tellam and Barker (2006) note that an important consideration in the Permo-Triassic Sandstone is the extent to which fractures are interconnected over distance. They tentatively concluded that:

- fissure flow dominates over short distances of less than 10 m;
- both fissure and intergranular flow are present for distances of 10–100 m;
- intergranular flow dominates for distances of more than 100 m.

Investigations at 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 maybe via fissures and higher borehole yields are typically associated with fracture systems. This means that the use of a kinematic intergranular porosity, without considering fissure flow, could result in an underestimate of the 50 and 400 day time of travel zones.

The conventional conceptual model for these sandstone aquifers is that:

- contaminant migration to an abstraction is mainly through intergranular flow, but with some fissure flow;
- the significance of fissure flow will be greatest over shorter distances and most relevant to the 50-day zone;
- Therefore, although kinematic porosities of 10–15 % are appropriate at the wider scale, closer to the abstraction where fissure flow becomes significant, a lower porosity value may be appropriate for delineation of the inner protection zone.

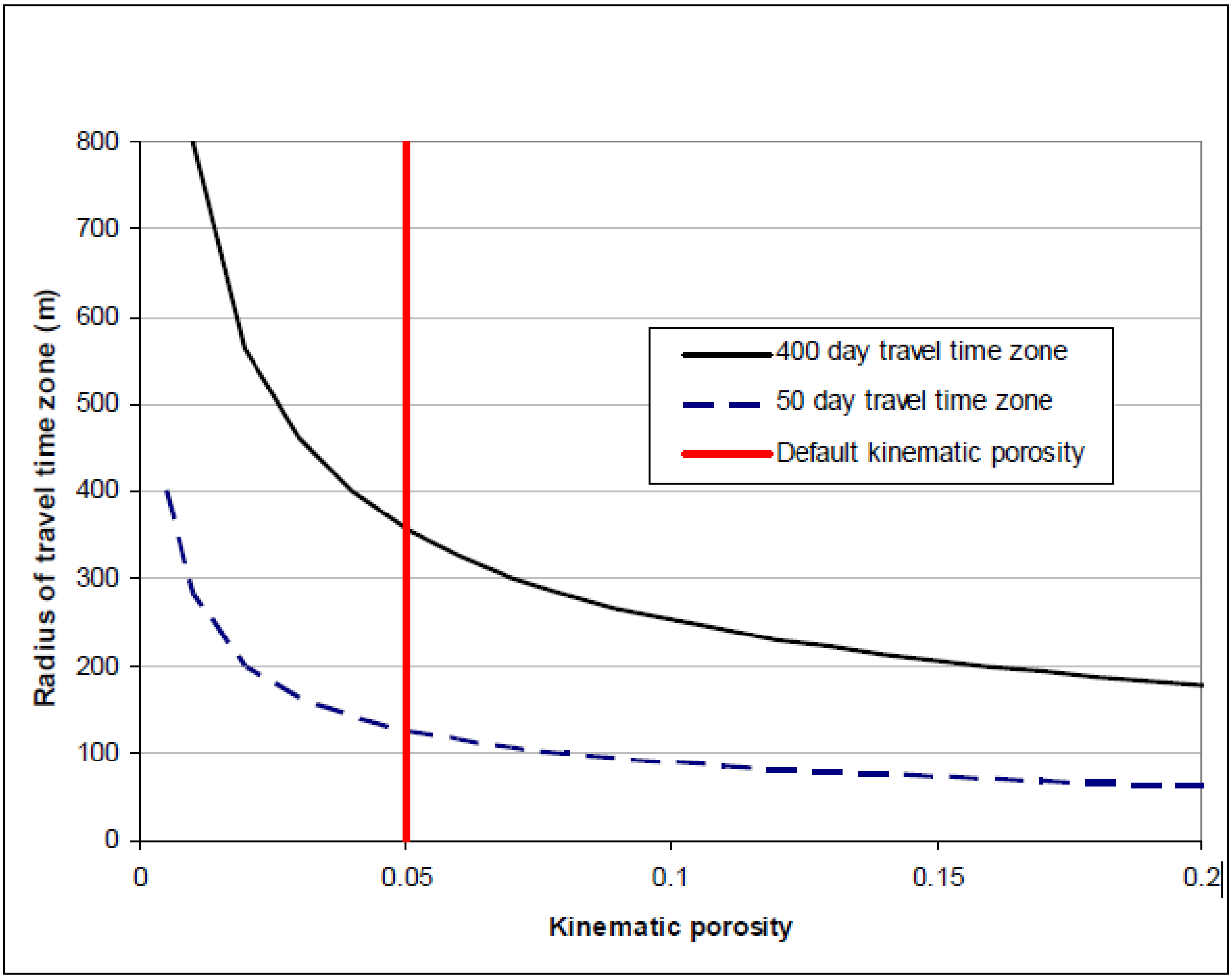



**Figure B.1 Radius of 50 and 400 day travel time zone dependent on kinematic porosity**

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

1. Collate data 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.

2. Develop a conceptual model of the flow to the abstraction taking into account recharge areas, flow directions and seasonal variations, and any potential boundaries to flow.

3. Calculate the area of the hydraulic capture zone:

- 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% to determine the 50 day and 400 day time of travel zones. The use of this value assumes that groundwater flow to the abstraction is a combination of fissure and intergranular flow. The relative contribution of fissure and intergranular flow is rarely known and this default value is a reasonable assumption based on scoping calculations. The details of these calculations were included in Appendix A of the previous version of this manual (Environment Agency 2009).
- Use a lower kinematic porosity value of 1–2% where there is good evidence (pollution event, turbidity data, bacteriological monitoring) of rapid flow to the abstraction borehole.

– Use a higher kinematic porosity value such as 10% where there is evidence (e.g. tracer test) that flow is intergranular only. In most cases, however, the use of a default radius will result in a larger protection zone.
– Record the justification for the selected value of kinematic porosity.

4. Determine Inner and Outer Protection Zones using the calculated areas and the conceptual understanding of the aquifer. Check for consistency with known pollution problems which demonstrate flowpaths in the aquifer to the abstraction. Record decisions made in the delineation process for future reference.

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

SPZ1 (Inner Protection Zone). Apply the 50 m default rule.

SPZ2 (Outer Protection Zone). Set minimum radii of 250 m or 500 m for sources with protected yields of <2,000 $m^3$/day or >2,000 $m^3$/day respectively. In either case, the radius should not extend outside the Catchment Protection Zone.

## B6. Heavily abstracted aquifers

In heavily abstracted aquifers, the combined SPZ 3 boundaries will cover a significant proportion of the recharge zone. As a result, SPZs could overlap, abut, or be separated by relatively thin slivers from their neighbours. There will be some uncertainty in the actual position of total capture zone catchment boundaries due to operational changes in the abstraction regime, seasonal fluctuations in catchment area, and the uncertainty in outputs from a model representing a complex system.

As the same groundwater protection policies are likely to apply to the whole aquifer area rather than to individual SPZs, in heavily abstracted areas, 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 we stopped defining individual SPZ3s in heavily exploited aquifers, 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. It is also useful to understand the catchment to individual abstractions in the case of pollution incidents, and also for the purposes of catchment management schemes and setting Safeguard Zones which deal with diffuse pollution.

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, and other source operators if required, individual SPZ3s are defined, making these available to the source operators. They are also available internally within the Environment Agency, but individual zones haven't been approved for access externally (see Section 5.1).

The shared SPZ3 should be defined when groundwater abstraction is 75% or more of the recharge for a specified area of aquifer. The specified area could be the scale of CAMS groundwater management units, WFD groundwater bodies, or the whole unconfined outcrop of the aquifer.

As illustrated in Figure B.2 the methodology for delineation of a shared SPZ3 for heavily abstracted aquifers is as follows.

- Determine the aggregate protected yield for the aquifer area by dividing the sum of the licensed annual quantities of SPZ abstractions in the area by 365. Restrictions placed on abstraction at individual sources by group licences should be taken into account.
- 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. Define individual SPZs, for specific sources, to be provided to source operators only.
- If ratio <0.75, define individual SPZ3s for publication.

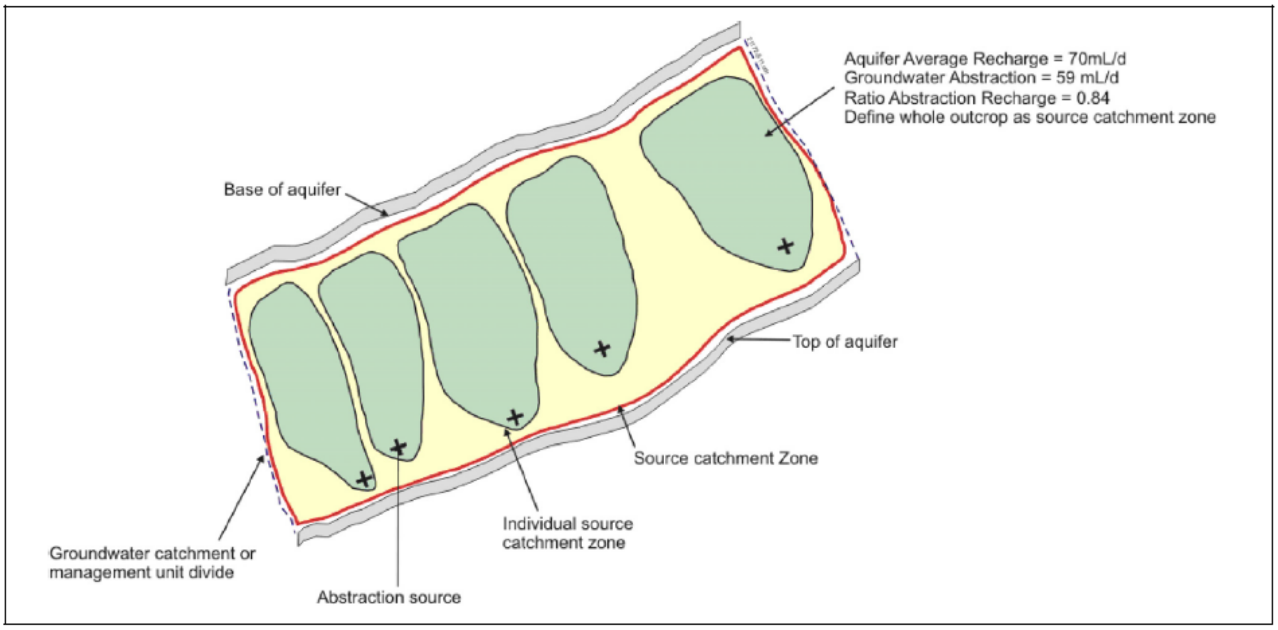



**Figure B.2 Application of the heavily exploited aquifer method**

## B7. Adits and other elongate sources

Historically horizontal tunnels or adits were added to wide diameter well abstractions to improve yield of a source. In England, adits are typically over 50 years old, and constructed into consolidated aquifers such as the Chalk, Magnesian Limestone or Sherwood Sandstone. They are typically unlined to allow infiltration, and can greatly increase vulnerability of an abstraction to pollution, especially where they are relatively shallow, and create issues with turbidity during high rainfall. For other elongate sources, for example lateral collector wells used to abstract from riverbank filtration systems, the same approach can be used.

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. In general the approach to SPZ delineation has been to adjust the zone to include the length of the adit as follows:

- 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 width on either side of the Inner Protection Zone and a minimum 250 m width on either side of the Outer Protection Zone are defined as illustrated in Figure B.3.
- 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 permeability representing the adit

to simulate the observed water level data. A more rigorous numerical approach to representing adits is given in Environment Agency (2001), which also shows that the approach of representing adits with high permeability zones is adequate in most cases. As previously noted, with technological advances in modelling techniques, the sub-model cell level of detail required to more accurately represent adits and other elongate sources could be achieved in future.

- 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.
- Comparison of water quality, rainfall, abstraction rate, and abstraction well water level data can be a useful way of identifying the contribution of different parts of a complex adit system to the abstraction. Water company operational staff may also have information on how the water quality changes under different rainfall / abstraction conditions.

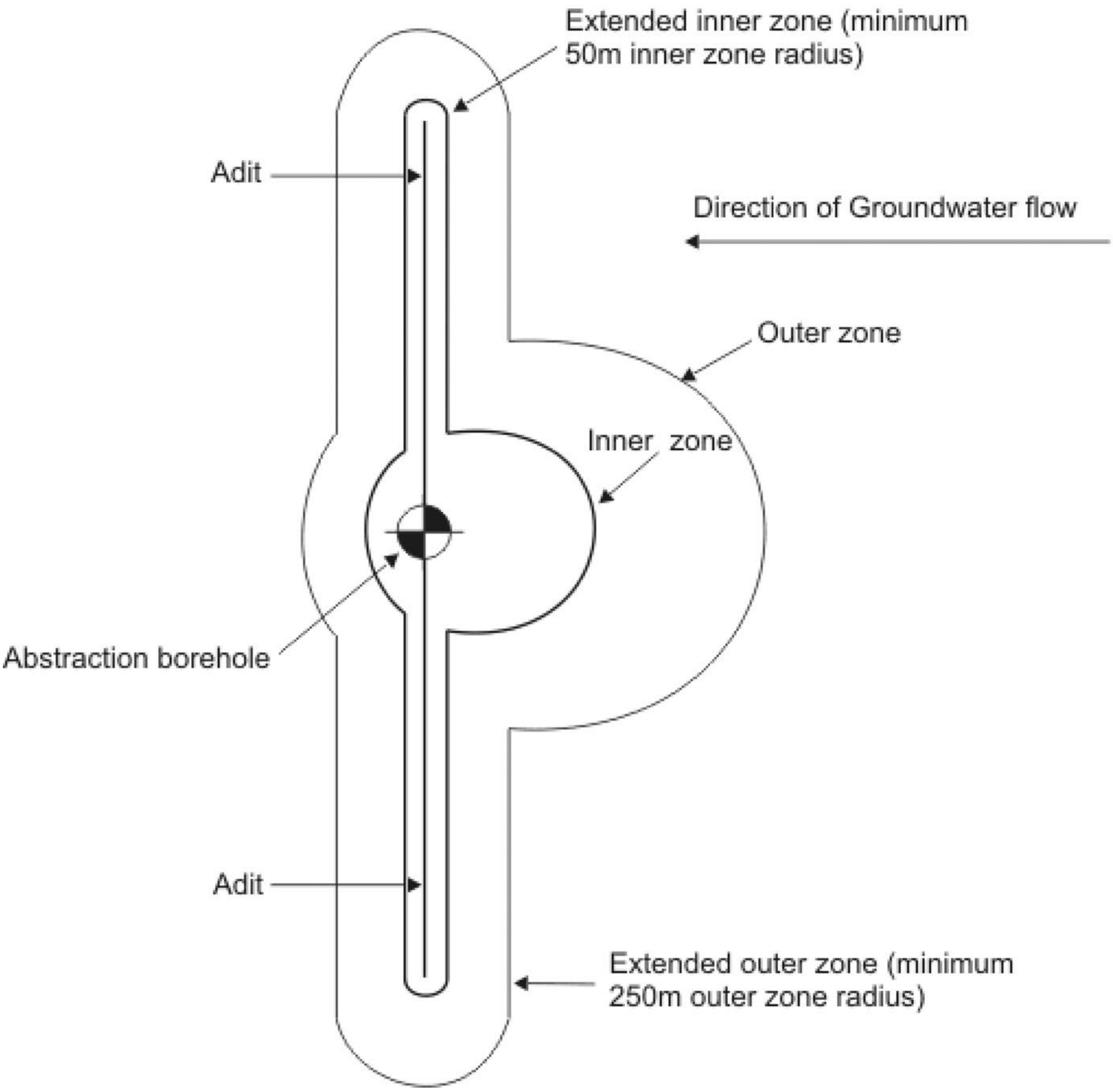



**Figure B.3 Minimum dimensions of zones around wells with adits.**

# Appendix C Defining hydraulic capture zones

The main basis for source protection zones (SPZs) is the definition of hydraulic capture zones. This appendix provides further technical detail in support of Section 3 of this guidance. Here we give brief background to previous cycles of SPZ delineation, and then describe methods that have been used for calculating hydraulic capture zones in the past ten years by the Environment Agency, from simple manual calculations supported by field observations, through analytical solutions (WhAEM), to numerical modelling techniques (MODFLOW, MODPATH and Flowsource).

Guidance is given as to the appropriate tools to use, but the final choice of methods is left for the user. 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 3.5). What is common to both manual and numerical modelling approaches is the importance of having an agreed conceptual understanding of the aquifer being modelled. Case studies on SPZ delineation where modelling has been used have been provided in Appendix D, one for a chalk source (case study 1), and one for a sandstone source (case study 2). Further case studies for manual delineation in Karst (case study 5), and for sources with limited information (case studies 3 and 4) are also provided in Appendix D.

## C1. Previous SPZ delineation approaches and modelling tools

### C1.1. Original approaches

The delineation of SPZs was first carried out in the early 1990s, driven by new duties for groundwater protection given to the National Rivers Authority, although in some areas of the country zones had already been created by the water authorities. SPZs were one of three approaches to groundwater protection, the others being mapping of groundwater vulnerability and nitrate vulnerable zones. Delineation of capture zones was mostly carried out using Flowpath, a two dimensional horizontal aquifer simulation model developed by Waterloo Hydrologic. WHPA, a precursor to WhAEM, was used in certain circumstances.

A second review of the zones was made which refined the models which SPZs were based on, and looked at uncertainty identified in the original models. This second review round identified zones of uncertainty based on the likely range of input data. Doing this meant that SPZs took greater account of changes to capture zones due to seasonal changes in groundwater levels and infiltrating recharge. Following on from this a third review was undertaken, with a lot of the work being done regionally, in some cases using the regional groundwater resource MODFLOW models that were being developed in the late 1990s. The following accepted methods were used for zone delineation (listed in order of simplest to most complex and increasing amount of data needed) and are still pertinent today:

- Hydrogeological mapping and field techniques
- Arbitrary fixed radius circles
- Calculated circular zones based on recharge and abstraction rate
- Analytical solutions based on simplified hydraulic assumptions
- Standardised shapes and semi analytical modelling
- Steady state numerical modelling
- Transient regional modelling

Hydrogeological mapping is the precursor to all other methods. Most of the zones delineated in England used steady state Flowpath models, and a large number of these zones are still used today. The main problems identified with Flowpath zones were that:

– Particle tracking leads to capture zones with long thin tails stretching over many kilometres but only 10s of metres wide. This was especially a problem for aquifers with high transmissivity zones (e.g. the Chalk) which do not produce large cones of depression in the aquifer, leading to long thin catchments, whereas in reality, water could come from a wider area. A solution was to cut catchment tails where they decreased to below 50m wide.

– The use of the fully licensed volume as the protected yield meant that in aquifers that had historically been over-licensed using the Flowpath steady state model is not possible. Instead abstraction rates were changed so that the source being modelled was set to the full licence rate whilst others were reduced to actual abstraction to allow the model to run, although this change has also been needed for MODFLOW models.

FLOWPATH has not been supported by the developer for at least a decade. In some cases, where a regional groundwater model exists, the conceptual understanding of the aquifer and abstraction management may have changed significantly. Therefore, the update and continued use of FLOWPATH models is not appropriate, and SPZs delineated using the model should be reviewed. That does not mean that the information used to build the FLOWPATH models is not useful, and this should be used to understand why there could be differences with newly delineated zones. Where the conceptual understanding of the aquifer has not changed and abstraction occurs in the same pattern as when the FLOWPATH model was built, there may not be a need to update the SPZs. The possibility of this being the case should be reviewed, and the benefits of updating the SPZs identified as opposed to carrying on with business as usual. Where possible the licence holders should be involved or informed of the decision to update SPZs.

### C1.2. Regional Groundwater Resource Models

Since the late 1990s, in response to the need to protect ecosystems and aquatic habitats from the effects of water abstraction, The Environment Agency has commissioned a number of transient regional groundwater models covering most of the principal aquifers in England. Most of the models in England are built using MODFLOW to simulate flow in the saturated aquifer, accompanied by a recharge model. The model design is based on a conceptual understanding formed from all of the available information on aquifer properties, surface water behaviour, and abstraction and discharges, and, most importantly, agreed with Environment Agency and water company hydrogeologists. The models are normally calibrated against observed groundwater levels and observed stream flow data, and can be used to simulate fully licensed (worst case) and recent actual (average of the last 5-6 years) abstraction scenarios using CAMS ledger abstraction rates.

At the time of writing, regional groundwater models should provide best available technology in that they describe the agreed conceptual understanding of aquifer behaviour. This means that they should be the best tool to use when delineating of capture zones to groundwater abstractions that are used for SPZs and Safeguard Zone delineation.

### C1.3. Manual Methods

There are large areas of secondary aquifer which are not covered by a regional groundwater model, and karst aquifers are to date not best represented by MODFLOW models. For some regions the groundwater models may not be considered of high enough quality for this work. Sometimes the choice of method, and the effort used to delineate the zones, need to be balanced with the importance of the source, and its vulnerability to pollution (Section A3). Therefore non-modelling approaches still need to be used for SPZ and capture zone delineation.

## C2. Manual methods for capture zone delineation

### C2.2. Conceptual Models

The first step in SPZ delineation, regardless of the method used, is the development of a conceptual understanding of the source and its catchment. Conceptual model development is covered in Section 3.3 of the guidance.

*Conceptual model of the catchment to the abstraction*

In general the conceptual model involves an understanding of how the aquifer behaves:

1. Where recharge of the aquifer happens - outcrop areas, run-off from less permeable areas to outcrop, river leakage, discharges to ground;
2. How groundwater flows in the aquifer - dominant flow mechanisms, any anisotropy in the flow in the aquifer matrix (caused by bedding, fissure flow, or preferential flowpaths), and the likely relative timing of flow;
3. How groundwater flow is controlled by barriers to flow (faults, rivers, change in geological strata), land-surface topography, or abstraction;
4. How groundwater levels change in the aquifer with summer and winter changes in recharge. If the change is significant then the catchment area could also change a lot with time.
5. How the groundwater exits the aquifer (locations where it feeds rivers, springs, wetlands etc., where it is abstracted and for what purpose).
6. Other catchment information that could be useful includes land use mapping and aerial photographs.

All of the above can be represented with descriptive text, supported by use of 3-D sketches / cross sections and figures (an example is shown below).

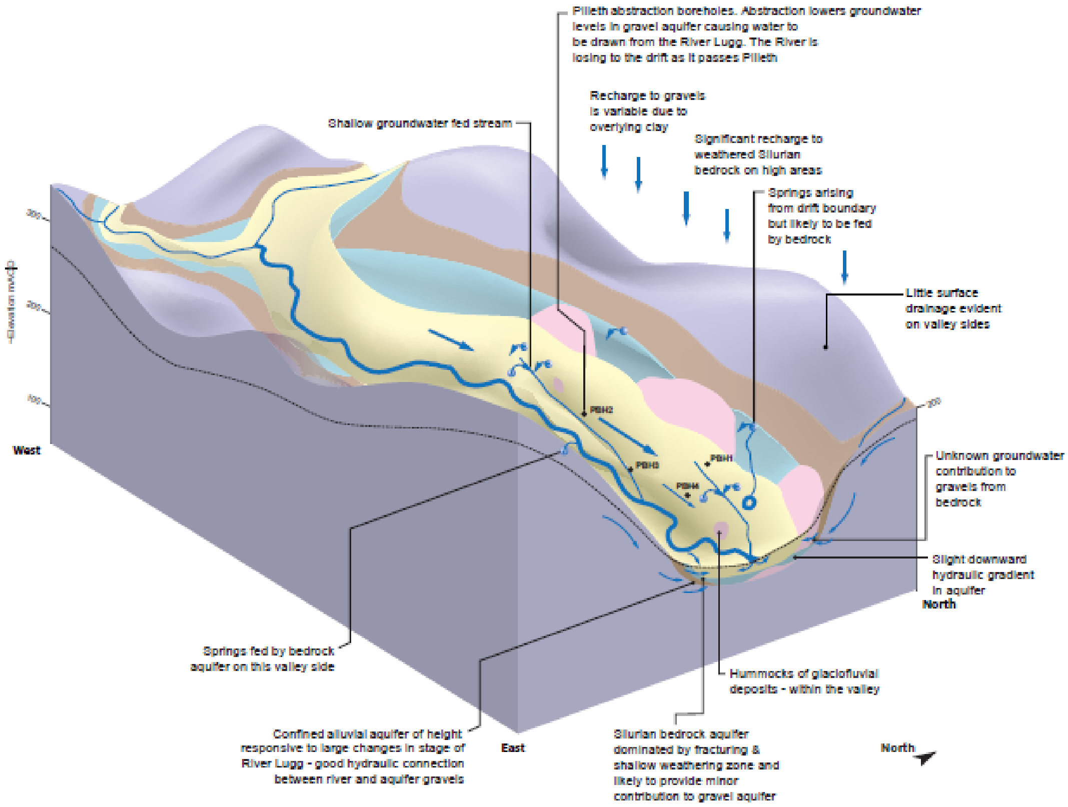



**Figure C.1 3D sketch figure of the conceptual understanding of groundwater flow to an abstraction**

*Conceptual understanding of the abstraction*

It's also important to understand how abstractions are operated. For example there could be several points (boreholes and wells) on one abstraction licence, but some points may no longer be used, or only used for emergency standby. The accuracy of the abstraction location should be confirmed, as quite often the licence might have a grid reference for one borehole, or the treatment works, rather than for every point. Knowing how the different abstraction points are used is very important in getting the shape of the capture zone correct, and clearly getting the location of the abstraction point right is essential.

Screen depth and the identification of inflowing fissure horizons, or even reported pollution events that have impacted an abstraction can help in defining capture zones. Fissure horizons can provide a rapid pathway for pollution which could mean that the capture zones should be enlarged. Similarly a pollution event that can be traced back to a source is another good way of confirming the extent of the capture zone, especially if a travel time can be estimated.

When developing the conceptual model, information on borehole and well location, and construction (depth, screen section depth, location of any fissure horizons encountered during drilling etc.) should be included. The operation of the source and the exact location of the points on the licence should be checked with the licence holder. The protected yield on which the calculations of the capture zone areas will be based should also be agreed with the licence holder where possible.

## C2.2. Where to get this information and how to present it

Spatial information is readily available for geological mapping, topography, abstractions and discharges, river and wetland locations, soils, land-use mapping and aerial photography. GIS should be used where possible to compare information and produce figures, and also to digitise the proposed capture zones. The licence file should hold all relevant information on drilling, pumping tests, and borehole construction.

The location of the boreholes and wells, and their typical operation should be checked with the licence holder. Where possible a site visit with the licence holder (or representatives) is a very useful way to confirm the findings of a desk based review of data sources. In most cases a description of the conceptual model should be accompanied by supporting figures.

## C2.3. Manual Methods and Analytical Solutions for calculation of capture zone dimensions

As listed in Sections 2.1 and 2.2 there are minimum zone dimensions which should be applied to capture zones when delineating an SPZ. Outside of these *de-minimus* areas, the shape and extent of the capture zones can be defined using the aquifer properties in simple calculations of circular hydraulic capture zones and more complex analytical solutions which 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

*Catchment protection areas*

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

$A_R$ = Protected Yield / $R_E$ (Equation C.1)

where:

protected yield of the source = groundwater pumping rate ($m^3$/year) (see Section 2.5).

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

If the regional piezometric surface is horizontal, the catchment to an abstraction source can be assumed to be circular, the radius of which can be calculated (Figure C.2). Although this situation does not normally occur in reality, it is still a useful approximation for aquifers for which there is no information on hydraulic gradient or the direction of groundwater flow. Equation C1 has been used to delineate catchment areas for sources for which there isn't enough data to justify the use of numerical models, with modifications to the circle made to take account of local geological and topographical boundaries.

Sometimes the interference between neighbouring 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 based on manual calculations can oversimplify the true geometry.

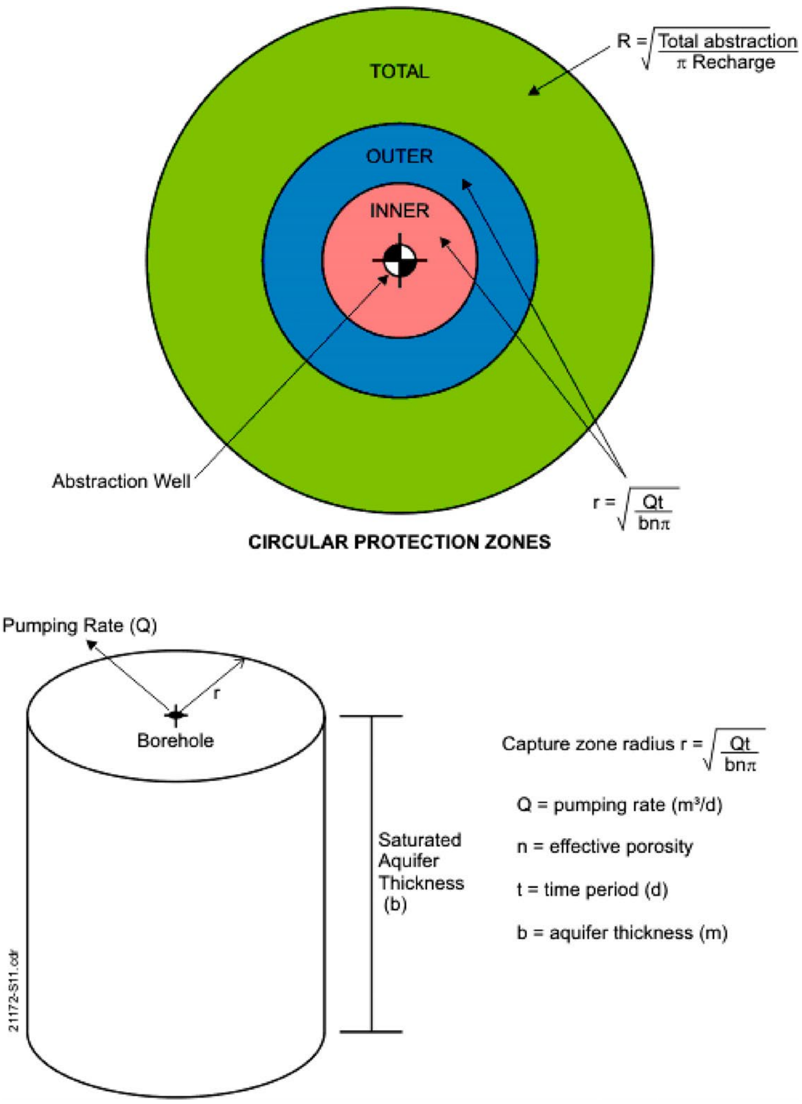



**Figure C.2 Protection zone delineation using volumetric flow method**

*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:

$A_d = Qt_d / b\eta$ Equation C.2

where:

Q ($m^3$/d) = either the protected yield ÷ 365 (for the calculation of 400 day capture zones) or the licensed maximum daily quantity (for the calculation of 50 day capture zones)

b = aquifer thickness (m)

η = effective porosity.

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

As noted before, with no information on the direction of groundwater flow, hydraulic capture zones may be assumed to be circular with radii calculated as illustrated in Figure C.2. 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.

Although these manual calculations make huge assumptions about the homogeneity of the aquifer properties, recharge etc., they are useful for checking the minimum size of SPZs in situations where lack of data means complex calculations are inappropriate.

*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 describing the boundary line (Figure C.3) of a hydraulic capture zone around a borehole in a confined aquifer of infinite extent with a uniform hydraulic gradient is given by (Bear and Jacobs 1965):

$$\frac{y}{x} + \tan\left(\frac{2\pi kbiy}{q}\right) = 0$$ Equation C.3

where:

q = abstraction rate ($m^3/d$)

k = hydraulic conductivity (m/d)

i = hydraulic gradient (m/m)

b = aquifer thickness (m)

x and y = co-ordinate directions (m).

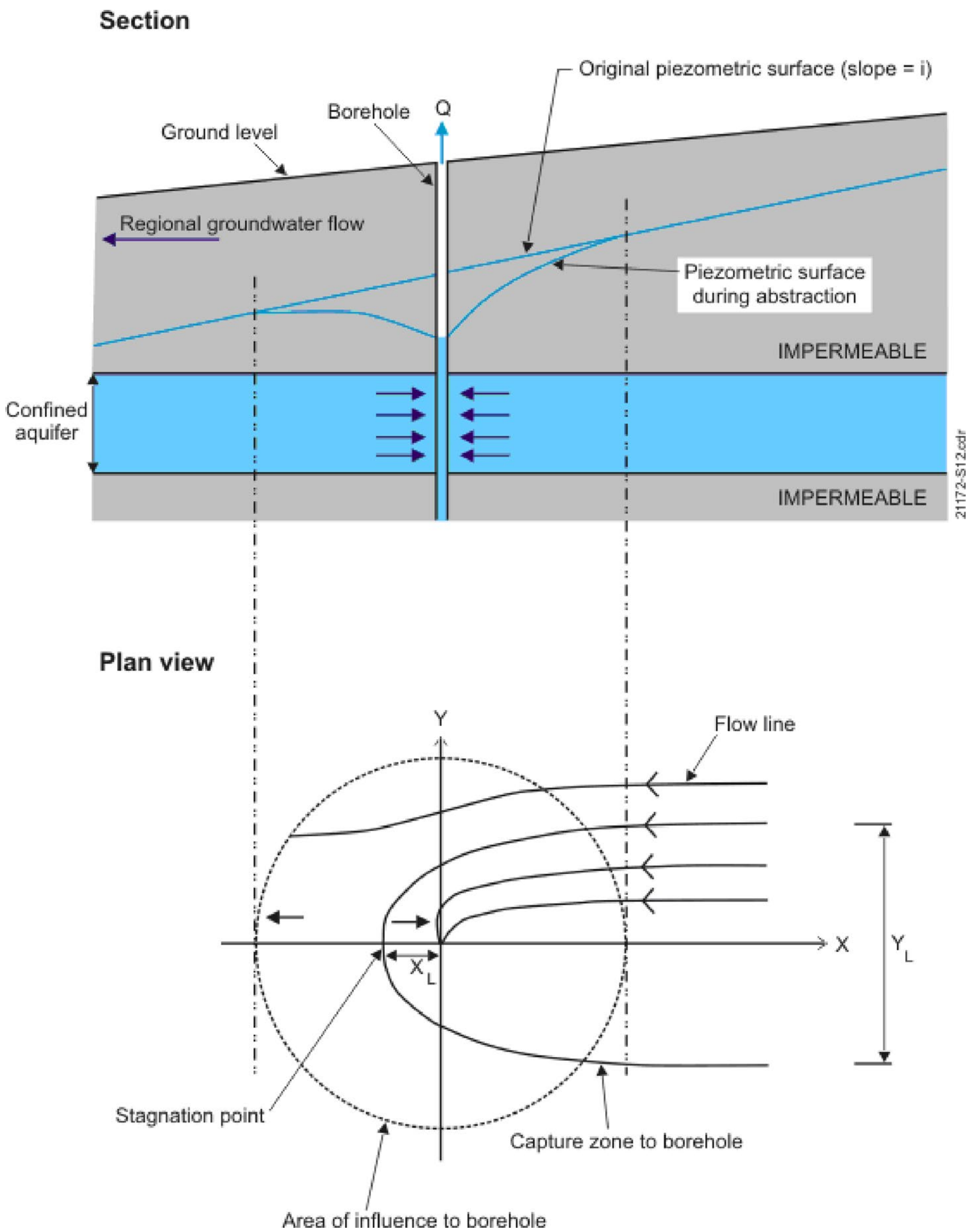



**Figure C.3 Capture zone to borehole located in uniform flow field**

Equation C.3 can be solved to give the maximum up-gradient width $Y_L$ of the hydraulic capture zone as:

$$Y_L = \frac{q}{kbi} \qquad \text{Equation C.4}$$

and $X_L$, the maximum down hydraulic gradient extent as:

$$X_L = \frac{q}{2\pi kbi} \qquad \text{Equation C.5}$$

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 is constant can be described by the following equation:

$$e^{-t^*} = e^{-z}\left(\cos w + \frac{z \sin w}{w}\right)$$ Equation C.6

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

$$z = \frac{x}{X_L},\ w = \frac{y}{X_L},\ t^* = \frac{kit_d}{nX_L}$$ Equations C.7

For points along the x-axis, the line passing through the borehole in the direction of regional groundwater flow, Equation C.6, reduces to:

$$t^* = z - \log(1 + z)$$ Equation C.8

The travel time from any point to the source can readily be calculated using Equation C.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).

These calculations can be made using a spreadsheet with aquifer properties and abstraction rates as input data to give a discretised analytical solution to the dimensions of the time of travel zones and total capture zones. Such approaches have been developed for Environment Agency staff by consultants to calculate the velocity of groundwater near wells, and to identify the likely shape of zones based on these calculations.

### *Simple groundwater velocity calculation for spring sources*

The analytical solutions described above (from Bear and Jacob's equation) are only suitable for pumped sources. For sources which are not pumped (i.e. springs and artesian boreholes), one option for estimating the up-gradient extent of the 50 and 400 day time-of-travel zones is a simple velocity calculation, derived from Darcy's law:

$$d = \frac{Kit}{ne}$$ Equation C.9

where:

d = up-gradient distance from source for a particular time-of-travel

K = hydraulic conductivity

i = hydraulic gradient

t = time-of travel

ne = effective (kinematic) porosity

Reference: Misstear, B, Banks, D and Clark, L (2006) Water Wells and Boreholes

The equation C.9 can also be used for pumped sources, but neglects the effect of increased hydraulic gradient in the immediate vicinity of the pumping well. Some worked examples are given below.

Example of spring catchment calculations for the Inferior Oolite

Inferior Oolite: Pump tests indicate a T value of typically 500 m$^2$d over an aquifer thickness approximately 50m.

Thames Conservancy groundwater levels for Maximum Inferior Oolite water levels indicate a hydraulic gradient of approximately 10 m per 1000 m = 0.01

Typical porosity = 20% (median value from Aquifer Properties Manual.)

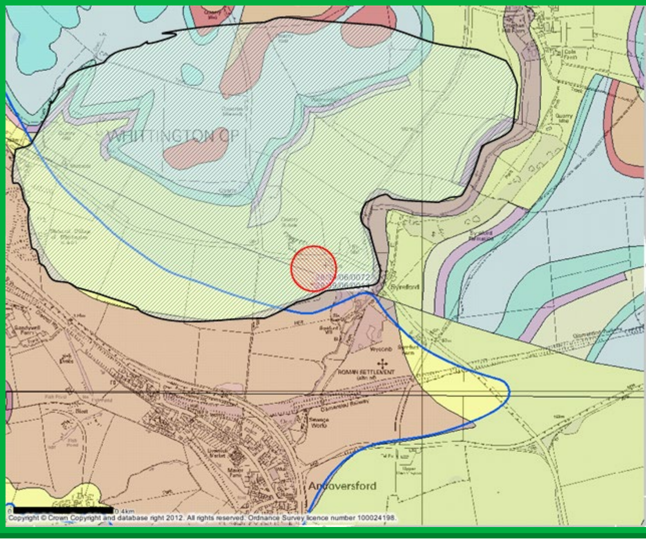
Velocity v = k.i / n

= 50 x 0.01 / 0.2

= 2.5 m/d

50 days travel = 2.5 x 50 = 125 m

400 days travel = 2.5 x 400 = 1000 m




## C3. Analytical element models

Analytical element models apply partial differential equations to the problem of modelling groundwater flow fields, using only boundary conditions as opposed to discretised volumes i.e. no model grid is required. As no model domain is identified, only boundary conditions, the numerical solution is calculated continuously throughout the study area, meaning there are no issues with grid size and numerical dispersion. The model can retain great accuracy in small areas, so that cones of depression around pumped wells are represented accurately, and particles backward tracked from pumped wells follow realistic paths. They can be set up relatively simply, and can include irregular boundaries and rivers. Multiple sources can be represented and particle tracking can be performed. Variation in aquifer thickness can be represented, but the models can become unstable if they become too complex. Multi-layered aquifers cannot be represented.

WHAEM (Well Head Analytical Element Model) has been used to delineate SPZs in the Hampshire Avon Chalk and also for some manually delineated sources for Natural Resources Wales (NRW). Other than these examples, the use of AEMs in SPZ capture zone delineation has been minimal. Instead the use of transient distributed groundwater models built in MODFLOW, with a combination of post-processing tools has been favoured as the main numerical approach to SPZ delineation.

## C4. Regional groundwater resource models

Over the past decade the main methods used to delineate capture zones to SPZs have either been manual approaches, or based on the use of regional numerical groundwater models with post-processing of the outputs to identify capture zones.

The main post-processing tools used involved particle tracking (MODPATH), and identification of the captured fraction of water from each model cell by specific model boundary conditions (i.e. abstractions) (MODALL or FlowSource). In this section the range of different ways the models can be set up is described. The ways in which the outputs are interpreted, and the representation of uncertainty are also discussed. A case study (Appendix D, Case Study 1) is also provided which demonstrates how the different outputs from the different models are used to delineate SPZs.

## C4.1. What is a Regional Groundwater model?

Most regional groundwater models in England are built using the MODFLOW software in some form. MODFLOW is the USGS modular finite difference flow model, used to simulate three-dimensional flow of groundwater through aquifers. The programme is capable of representing complex layered aquifer systems with significant heterogeneity, as well as a wide range of boundary conditions such as stream leakage or drainage (groundwater - surface water interaction), abstractions and discharges to ground and recharge to the aquifer (which is usually estimated with a separate recharge model). The models typically operate on a regular grid of around 200 m spatial resolution, and simulate a period of several decades, divided into "stress periods" usually of length 10 days to 1 month. Recently, a version of MODFLOW (MODFLOW6) has been released by USGS that can operate on an unstructured grid, allowing localised grid refinement in areas of particular interest (such as the immediate vicinity of abstraction boreholes).

Most regional groundwater models in England are set up with at least four different scenarios of abstraction: "historic" which represents the historic pumping regime and provides a platform for model calibration against observed stream flows and groundwater levels, "naturalised" which represents the aquifer flow with no abstractions or discharges, "recent actual" which represents the average pumping regime over the recent period (normally 5 to 6 years), and "fully licensed" which represents pumping at the maximum permitted rate (typically based on Catchment Abstraction Management Strategy (CAMS) ledger abstraction to represent any aggregate limits on licences).

As the models produce a large volume of output spanning periods of around 40 years or longer, it is useful to review the outputs based on the extreme conditions. Hence "dry", "wet", and "average" stress periods are normally defined, with the dry stress period reflecting historically extreme low groundwater conditions, and the wet stress period historically high groundwater levels. The average stress period may be selected based on professional judgement. The selection of representative periods can and does differ between models, due to variations in historical conditions between aquifers.

## C4.2. Protected yield adjustments for use in regional groundwater models

The requirements for protected yield are described in Section 2.5. The protected yield should be linked to: the amount of water the borehole can produce; any restrictions on abstraction rate due to environmental constraints; and where significantly lower than the licenced rate, should reflect the actual amount of water typically abstracted.

This suggests that licence abstraction rates (where derived from actual pump test data and therefore should be realistic) with any environmental limit (e.g. a group aggregate limit) and the actual operation of the abstraction should be used to define the proposed protected yield. In addition the planned and future use of the abstraction, or for individual points on the licence, should be included in the decision making process.

*Location of abstraction points and allocation of rates*

In a regional groundwater model the boreholes on a licence can be located in different model cells, especially satellite boreholes. Where the boreholes are close together, and location information is only given for the treatment works (this is common on National Abstraction Licensing Database (NALD)), then the placement of individual boreholes may be relatively arbitrary, and in some cases could be based on whichever configuration yields better calibration of the model. Where there are individual rate limits on the boreholes these can be used as a protected yield value, but where only one over-arching licence rate exists for boreholes in more than one model cell then this rate needs to be divided up to provide the right level of protection to the source.

The method devised for the former Anglian Region for protected yield division between boreholes for modelling purposes is shown in Table C.1. This might seem quite detailed, but the region were working through the update of over 400 zones, and therefore needed some structure to the process to deal consistently with the large volume of work. The values derived from this process were then reviewed with the Water Company or operator to make any changes based on their actual and planned future operation. This is also the stage at which the location of boreholes were checked, disused points removed and the

Water Company name for a site identified where different from the Environment Agency name (i.e. on NALD or the paper licence).

**Table C.1. Dividing the licenced rates between model cells with abstraction points per licence for proposed protected yield values**

| **Pattern of abstraction point distribution in model cells per licence** | **How to divide the licence between model cells for a proposed Protected Yield (PY)** |
|---|---|
| One borehole | Annual and daily licence rate with any aggregate limit |
| More than one borehole in one model cell | Annual and daily licence rate with any aggregate limit |
| More than one borehole in more than one model cell and all with individual rate limits | Annual and daily licence individual rate limit with any aggregate limit |
| More than one borehole in more than one cell with some individual rate limits | Annual and daily licence individual rate limit. Divide remaining licence amount between other abstraction points and reflect any aggregate limit |
| More than one borehole in more than one model cell with no individual rate limit | Annual and daily licence divided equally between points reflecting aggregate limit |

The overarching process followed in defining the protected yield in the former Anglian Region, and in updating the GPZ (groundwater protection zone) database of abstractions with a SPZ is shown in the flowchart below (Figure C.4). The key stages are:

- data collation and identifying sources requiring an SPZ;
- deciding on the split of abstraction between boreholes / model cells;
- review by EA staff and operators; and
- recording the process of agreement.

Proposed protected yields should be checked and approved by Water Companies so that operational use for the boreholes is protected. The reasons for any changes from the previous protected yield values should also be identified in discussion with the operator. Recent Actual abstraction rates should not be used for protected yield development as they are typically averaged over a 5 or 6 year period which can lead to misrepresentation for sites where an operational shut-down period has meant the recent actual rate does not reflect the current or future use.

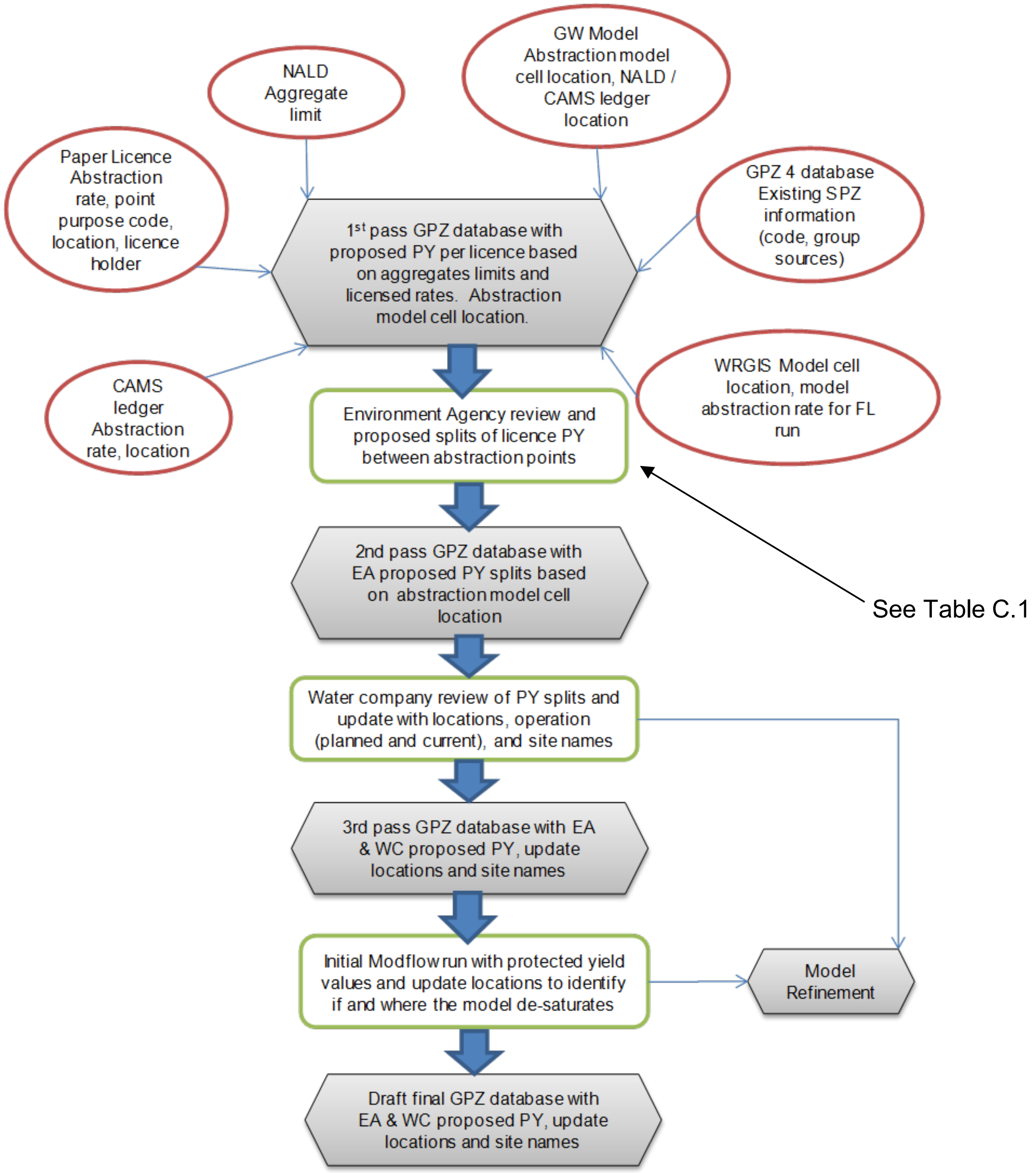
*Model Instability*

Finally it should be checked that the identified splits of abstraction between boreholes can be represented by the regional model without any instability (for example cells drying out and not rewetting). This can be done by running the regional groundwater model with the suggested protected yields, and checking the outputs for any cells that desaturate. In models run using "non-drying" MODFLOW, or any other adjustments to the code, the model output which indicates desaturation should be checked.

Where the model becomes unstable, sometimes this is due to recent changes in abstraction that have not been included in the model version being used. For example, an abstraction may have been out of use for years due to a pollution incident, but recently has come back on-line as treatment is in place. Emergency standby boreholes may now be the main duty borehole, again due to yield or water quality issues.

In cases where the groundwater model has several layers, the abstraction may be set in a layer that cannot provide the protected yield based on the aquifer properties that have been used. In such a case information on transmissivity in the area in question should be checked to see if there is justification for increasing this value from pumping test results or other investigations. Any changes to the model parameters can destabilise other parts of the model and have an effect on the calibration of the model, and therefore a check should be made on the nearest calibration point (normally a stream gauge) to make sure that the change is realistic. Ideally the changes made to the groundwater model to deal with any instability should be made prior to FlowSource and MODPATH modelling, in agreement with licence holders where deemed necessary.

**Figure C.4 Flowchart of protected yield derivation process in the former Anglian Region**




PY - Protected Yield, WC - Water Company, FL - Fully Licensed

*Setting up model runs for different capture zones*

For the delineation of SPZs the fully licenced and recent actual model scenarios are most useful. Clearly the most up to date version of the model in terms of agreed conceptualisation should be used. The models need to be set up to reflect the protected yield. It is recommended that the daily maximum licensed abstraction rate is used to define the 50 day time of travel capture zone. As continuously using the daily rate may mean that the annual licensed rate is exceeded, the daily rate can be set only for the stress periods running up to and including those that give the extremes of water levels, i.e. the "dry", "wet", and "average" stress periods.

For the 400 day and total capture zone calculations the annual licensed abstraction rate should be used. In some cases the annual licensed abstraction rate has been used as the protected yield to define both the 50 day and 400 day time of travel zones and total capture zones. For abstractions other than the sources for which the SPZ is being defined, recent actual totals can be used.

## C4.3. How Modpath works

MODPATH is a particle tracking model which uses the outputs of MODFLOW models. It works by interpolating the components of groundwater flow between model cells ('cell-by-cell' flows) to calculate a single flow vector for each cell through which released particles pass. Once calculated, this single vector is used to describe the pathway through the cell: no further interpolation is done until the particle crosses a cell boundary, at which time a new vector is calculated. Particles arriving at different locations along cell boundaries will clearly be assigned different interpolated velocities.

*Outputs used in SPZ delineation*

MODPATH can be used to define capture zones, including the time of travel capture zones, on which the SPZ 1 and 2 can be based. The total capture zone can also be estimated, but these tend to have long tails (see discussion of Flowpath above) and the outputs should be sense checked with the FlowSource outputs.

*Pros and Cons of using MODPATH*

Some aspects of MODPATH behaviour are worth noting:

- It is awkward to arrange backward particle tracking through transient flow fields, and the results may be difficult to interpret;
- It can give rise to long 'tails' which may be considered as unrealistic although these can be removed during the SPZ delineation process;
- It can be very sensitive to model grid size, such that back-tracking from relatively small abstractions can give thin 'cigar-shaped' zones, which again may be considered as unrealistic: this can be partially overcome by selecting an appropriate particle release radius;
- It is difficult to get MODPATH to properly recognize other external sources and sinks of water that are represented in the model, although their effect on the groundwater flow pattern is implicitly taken into account;
- It can be sensitive to the elevation of particle release, especially in multi-layer models and this has been addressed by releasing particles at three different depths for the SPZ particle tracks – see figure below.

Despite these apparent shortcomings, it is considered that MODPATH calculations are still worth undertaking, since they provide a useful check on other methods of Total Capture Zone (TCZ) estimation and can be used to calculate time of travel zones.

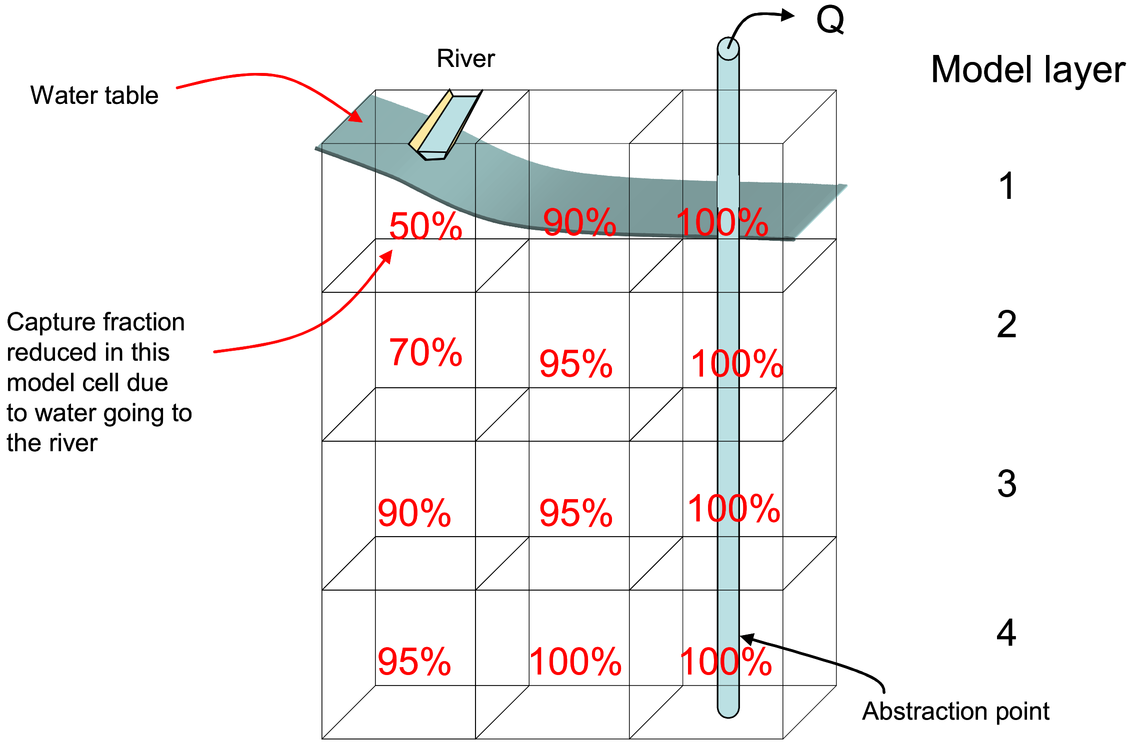
## C4.4. How Flowsource works

FlowSource is a post processing package that works by using the cell by cell flows (the flow between model cells) calculated for each stress period in a MODFLOW model. Each model stress period could be a day, a week, or month depending on how the MODFLOW model is set up, but is usually in the range 10 days to 1 month. For each stress period, FlowSource identifies how much of the water in each model cell is ultimately removed at a specified location (i.e. the location of an abstraction).

*Outputs from FlowSource*

A **capture fraction** is defined as the fraction of water passing through the cell which ends up being abstracted at the point of interest, and is calculated for all cells that contribute water to the well. A capture fraction of 1 (or 100%) indicates that all water passing through the cell is abstracted by the borehole, whereas a capture fraction of 0 means that there is no contribution from this cell (Figure C.5).

**Figure C.5 Conceptualisation of Capture Fractions in a Simple Model. Values Shown Are Likely Proportions of Water in Model Cells That Will End up at the Abstraction Q**




In simple terms, a capture fraction tells you where water comes from in a catchment to a borehole, and the proportion of water in any model cell going to any point you define in the model, for example an abstraction. However, it doesn't tell you how much water or how important different parts of the catchment are to the water quality at the abstraction.

This can become important in low permeability areas where the volume of groundwater flow is actually small, but the capture fraction may be quite high, suggesting that a high proportion of a small volume of water reaches an abstraction.

The volume of water flowing through each model cell is calculated using the capture fraction and the volume of the abstraction to give an absolute value. This absolute volume can be split up in terms of the source-pathway-receptor conceptual understanding of pollutant transport as:

- **Volume from** (the source of water to the model) can be defined as the volume of water flowing into any model cell in any layer from boundary conditions which will end up at the abstraction (Figure C.6). Although in theory this includes any boundary conditions that may be applied in the model, in practice it is usually dominated by recharge to groundwater and stream leakage. It does not include flow into the cell from neighbouring cells in the saturated zone. This output can also be summed across the layers of a multi-layered model, to give the amount of water flowing through a column of model cells to the abstraction, making it easier to summarise 3-D flow in a 2-D map.
- **Volume through** (the pathway of water in the model) can be defined as the volume of water passing through the faces of a model cell during any one stress period which ends up being abstracted at the well. This includes water entering the model cell from neighbouring cells in the saturated zone (Figure C.7);

- **Statistical analysis** can also be carried out on the capture fraction outputs to provide probabilistic values such as the "proportion of time" (of the whole modelled period) during which the volume of water going through a model cell to the abstraction is more than a percentage of the abstraction or a specified volume of water. The spatially plotted output for the probabilistic calculation is usually given as the proportion of time that the volume of water going through a model cell to the abstraction is >1 $m^3/d$ (or a locally agreed equivalent).
- **A time of travel calculation** from Flowsource has also been produced for the 50 day and 400 day travel times. Flowsource forward tracks a single particle released from the centre of each cell that contributes water to the abstraction borehole, then uses the same calculation as MODPATH to interpolate a single velocity vector for each cell that the particle crosses. Total travel time to the edge of the cell containing the abstraction is calculated and assigned to the cell at which the particle originates. This, therefore, gives a distribution of travel time to the borehole.

The time of travel or velocity of groundwater flowing to an abstraction depends on the kinematic (or effective interconnected) porosity of the aquifer. Variability in this parameter and its identification is discussed in Appendix B (Section B5), specifically for Permo-Triassic Sandstone sources. Here, the recommendation is to use a kinematic porosity value that reflects the potential presence of fissure flow for the 50 day capture zone. FlowSource can be set up to calculate times of travel using the MODFLOW model grid of kinematic porosity values for each model cell, or other user defined values. For the Chalk a value of 1% is normally used. The FlowSource time of travel outputs are a statistical analysis of the distribution of travel time of the whole modelled period, for each model layer. The output shows the percentage of time that a model cell lies within the 50 day or 400 day travel time envelope.

FlowSource can produce outputs as long term averages (the average values for model cells across the outputs from all stress periods) or for individual stress periods (e.g. "dry", "wet" and "average"). The time of travel calculations by default take into account all stress periods.

**Figure C.6 Conceptualisation of Flow From Output, i.e. the Water Originating in Model Cells Contributing to the Abstraction.**

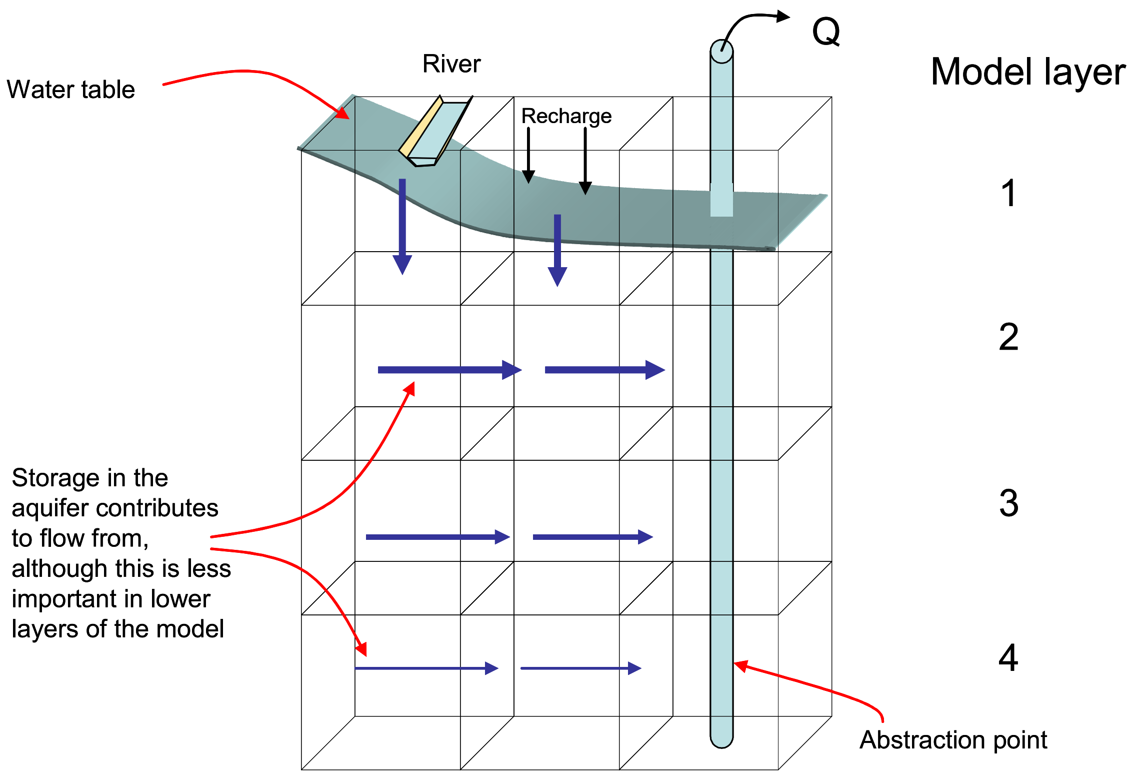
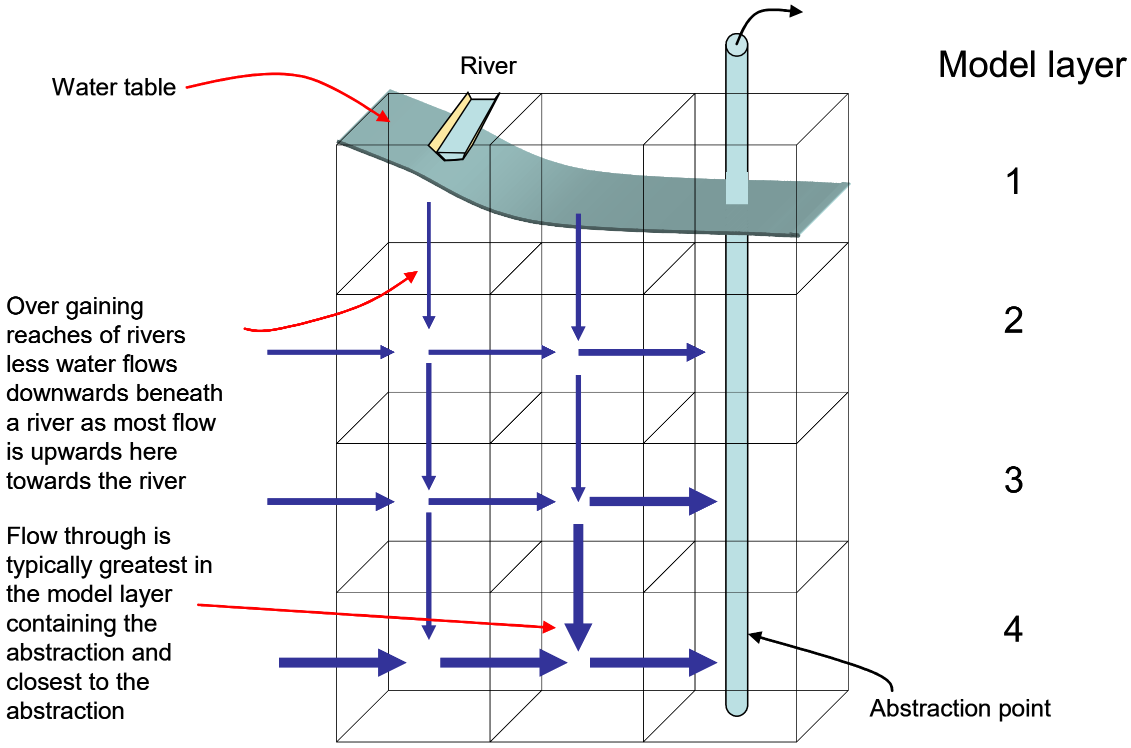


**Figure C.7 Conceptualisation of Flow Through Output, i.e. the Water Flowing Through the Faces of a Model Cell from Other Cells Contributing to the Abstraction**




*Outputs used in SPZ delineation*

The outputs from FlowSource are usually viewed in GIS, as rasters of values. The outputs can also be viewed in NGMS which has been configured for FlowSource functionality. The output can be provided for specified stress periods and time steps. Normally in SPZ delineation the extreme scenarios of the dry and wet stress periods are used, whilst other approaches focus on the "normal" situation described by the average stress period. Long term average outputs of volume from and through and capture fraction are also useful in delineating the total capture zone. Examples of these methods are shown in case studies 1 and 2 in Appendix D.

For total capture zones the main purpose of this task is to understand where water comes from for the abstractions of interest and how often this water ends up at the abstractions. To understand this the aquifer properties (transmissivity, hydraulic conductivity), groundwater flow regime (flow vectors, groundwater levels), recharge (4R or other recharge model output), abstraction rates and locations (sites layer), and grouped Flowsource and particle track outputs should be the focus. The grouped particle tracks and capture fraction output should also be reviewed to identify the likely capture area, and frequency of contribution to the borehole (grouped proportion of time volume through exceeds 1m$^3$/d).

*Drawing catchments based on FlowSource grid outputs*

There are different ways in which zones can be drawn around FlowSource outputs:

- Around model cells to include the outer edges of the model cells;
- Through the centre of model cells with a small capture fraction;
- Sawtoothed outline of the model grid to define a capture zone.

This last method which gives a "sawtoothed" shape to a SPZ should not be used. The recommended approach, especially for total capture zones, is to draw an envelope around the model cell centres as the location at which the value represented by the whole cell is most likely to occur.

*Pros and Cons of using FlowSource*

FlowSource, when used in conjunction with GIS based tools (e.g. ModelMap) and with a good knowledge of the regional model conceptual understanding, is an excellent tool for capture zone delineation.  In particular, being able to visualise where flow is coming from and going to within a regional model, is very useful for SPZ delineation and for Safeguard Zone identification.

The Volume From output can be used to identify the areas of catchment which provide the highest volumes of water, and that could therefore provide the greatest improvement in groundwater quality if catchment management action was focused there.  As this output tracks water flow from recharge boundaries, in combination with the Volume Through which follows pathways in the aquifer, it can be used to identify source- pathway- receptor conceptual models.

The capture fraction and Volume Through, and the probabilistic outputs (i.e. where the capture zone is for a percentage of the modelled time period) support total capture zone (SPZ3) delineation.  Although FlowSource is affected by numerical dispersion, due to being based on the MODFLOW model grid, the outputs provide a huge improvement over the Flowpath particle tracking, with much wider more realistic zones.

The impact of numerical dispersion can mean that the delineation of smaller zones (SPZ1 and 2) is difficult, especially for smaller sources, where one or two model cells may be active.  In this case using FlowSource in combination with MODPATH, provides a more robust method of delineating the likely shape of the zone, and confirming its extent.

FlowSource can also identify interesting "issues" with the geometry of the underlying regional groundwater model.  For example, where layer numbers are re-used in different parts of the model (e.g. Cam and Bedfordshire Ouse groundwater model) then care should be taken in interpreting the outputs.  In some cases both particle tracking and FlowSource can both show that the solution the model is calculating is unexpected, with leakage from unexpected "impermeable" areas being of sufficient volume over the whole model period to be identified in the calculated outputs.  This is more of an issue for the long term average outputs from FlowSource which may suggest odd behaviour, but on deeper investigation may be related to events that only occurs in a few of the model timesteps, for example a river drying up. Where possible these issues should be flagged to the model builder, so that any issues can be understood and resolved.

An independent review of the FlowSource model as used for Source Protection Zones was commissioned by the Environment Agency (2015), and found that the model was useful for SPZ delineation, and compares well to other codes.

*Cut-off values in FlowSource*

Depending on how FlowSource is set up, the cut-off values used to exclude capture fractions which are getting close to negligible for an abstraction, can vary between 1% and 10%, depending on how much "noise" is expected in the underlying groundwater model (see section C5 on Uncertainty). This limit has varied in the past, depending on the modeller's understanding of the underlying regional groundwater model, although there is not much consistency in setting this limit.  The justification for varying this limit to exclude very low capture fractions is linked to the expected response of the underlying groundwater model and the aquifer.  A model for a highly transmissive aquifer like the Chalk may have more "noise" associated with it compared to a Sandstone aquifer model which has a slower response.  The decision to set a very low "cut-off" level may be taken to ensure that as much information on how the system behaves as possible is considered in delineating capture zones.

## C4.5. Access to FlowSource and MODPATH

*National Groundwater Modelling System (NGMS)*

FlowSource is now accessible for some regional groundwater models through the NGMS platform and can be used with regional groundwater model output to produce capture zone supporting outputs.  However, at the time of writing, the output is restricted to analysis of the three stress periods (normally wet, dry and normal conditions) that NGMS is set up to produce groundwater model output for.  Therefore long term average outputs used to identify the possible position of the capture zone through the whole model period is not possible at present.  Similarly, time of travel analysis is not possible in FlowSource.

The MODPATH programme (see section C4.3) is also not available on NGMS.

At the time of writing the functionality in NGMS is unlikely to provide all of the outputs required for robust SPZ delineation.  However, some relevant and useful information could be gathered to support manual approaches to delineation, if these were being used.

*Direct use of FlowSource and MODPATH by Environment Agency staff*

A small package of spreadsheet tools and executable files has been developed by Groundwater Science ©.  The spreadsheet tools are intended to assist the user with standalone MODPATH and FlowSource model runs and building the control files for these runs.  The spreadsheets allow the user to easily set up the control and input files for FlowSource and MODPATH, and also allow for post-processing of MODPATH outputs (i.e. cell by cell flows) in Python, so that they can be viewed as raster layers in ArcGIS. At the time of writing the tools do not work with the non-drying version of MODFLOW.

This approach gives the user the full functionality of both FlowSource and MODPATH. The groundwater model outputs were run by Groundwater Science © for Environment Agency area teams, with the model set up in a manner appropriate for SPZ modelling, and then the outputs were supplied for further processing by the area team.  The tools have been used by some Environment Agency areas to help delineate SPZs using regional groundwater model output.

# C5. Uncertainty in SPZ delineation

The delineation of SPZs as set out in the original version of this manual (Environment Agency 1996) 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. There is further uncertainty in Flowsource calculations due to numerical dispersion, but this is accounted for through the pragmatic selection of "cut off" values at the time of configuration of Flowsource (for example, a minimum value of, say, 1% capture fraction below which a cell's contribution to the abstraction is considered negligible), and is not further discussed here.  A two-step approach should be used for the uncertainty analysis that aims to address the uncertainty in parameter values and in conceptual understanding 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 C.2. The second step is explicitly included in the process to define the SPZs from the hydraulic capture zones as described in Section 3.5.

**Table C.2 Approaches for uncertainty analysis**

| Step | Method | Requirements |
|---|---|---|
| **1. Sensitivity analysis** | Three groundwater model runs based on best estimate model:<br>· decrease in recharge;<br>· increase in hydraulic conductivity;<br>· decrease in hydraulic conductivity.<br>One particle tracking run based on the best estimate model:<br>decrease in kinematic porosity | Parameter ranges have to be specified and justified before the start of modelling.<br>Recommended sensitivity variations are:<br>· recharge –15%<br>· hydraulic conductivity ±30%<br>· kinematic porosity –30%.<br>Any sensitivity variations should lie within the parameter ranges specified.<br>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. |
| **2. Hydrogeological judgement to modify best estimate hydraulic capture zones** | Part of the procedure for final SPZ delineation as set out in Section 3.6. | Reporting of changes is mandatory, together with any supporting information |

# Appendix D Case Studies

Case Study 1 Chalk example which demonstrates grouping of overlapping zones, nudging and modelling

Case Study 2 Sandstone example to demonstrate modelling in a Sandstone source and the development of a groundwater model specifically for SPZ delineation.

Case Study 3 Manual delineation of an SPZ demonstrating the approach to take when there is insufficient data (first example)

Case Study 4 Delineation of an SPZ demonstrating the approach to take when there is insufficient data (second example)

Case Study 5 Manual delineation for an SPZ in a Karst system, demonstrating a complex system including fast pathways and groundwater-surface water interaction.

# Case Study 1 Chalk, numerical model.

### What does this case study demonstrate?

Re-delineation of an SPZ using numerical models and manual methods, for an unconfined chalk abstraction. Grouping of SPZs with shared boundaries for neighbouring sources. The delineation for one licence is shown in detail and then grouping with other SPZs is described. The SPZ was updated in 2014.

### Aquifer / EA Area:

Cambridgeshire and Bedfordshire area – Rhee and Bourn catchment (unconfined Chalk) – Duxford sources, comprising 3 separate licences for individual PWS and private abstractions. Two of the licences are in an aggregate group licence, with an annual limit which is less than the full licenced rate.

## Justification for an SPZ / update of SPZ

Two abstractions original SPZs were delineated using Flowpath in 1997. Since that time, an additional licensed abstraction has been developed which requires an SPZ. The licensed abstraction rate at one of the original sources has reduced significantly since SPZ modelling, and the current SPZ is likely to overestimate the required protection area. The aggregate annual limit for the licences (from the CAMS ledger) is also lower than the annual full licence at one source and again the source protection area could be too big. The regional Cam and Bedfordshire Ouse Groundwater Model has been developed in the interim period, updating the conceptual understanding of the aquifer, and providing the best available technology for updating SPZs.

## Assigning the Protected Yield

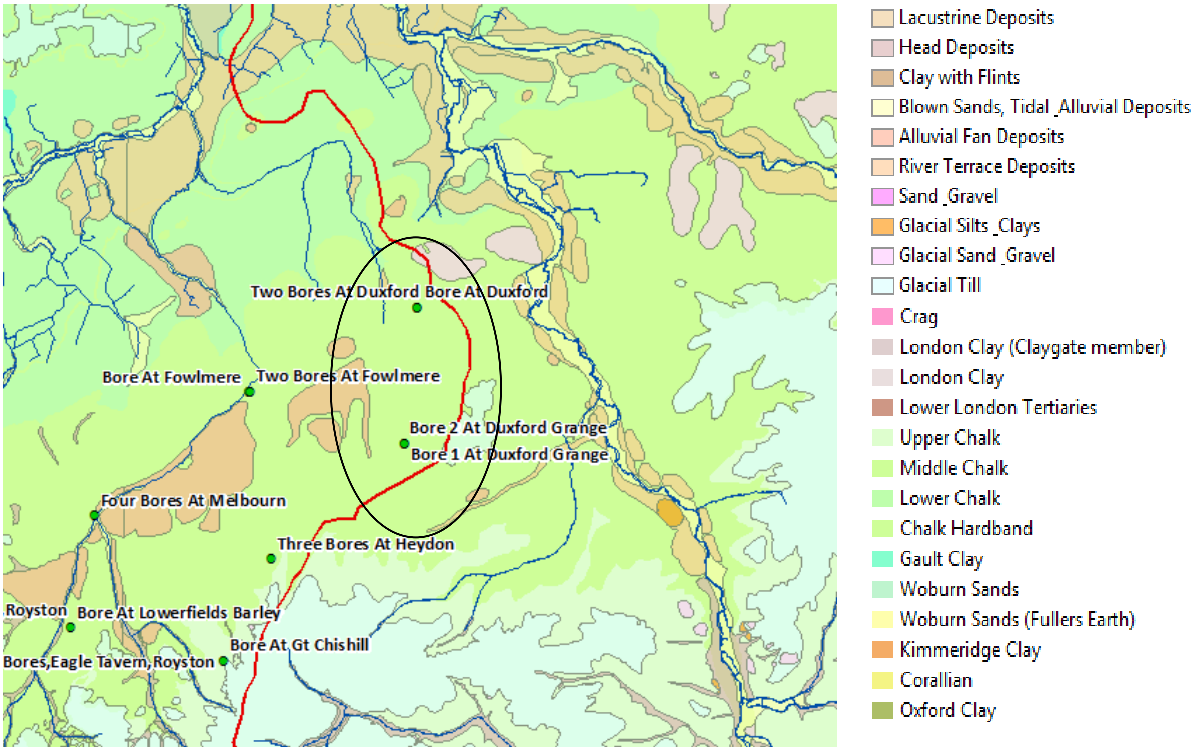
Protected yield was agreed with the licence holder (Anglian Water Services) and based on the licence annual and daily abstraction rates. A group aggregate licence was in place for this and several other neighbouring abstractions (i.e. an annual limit for a group of licences typically for environmental protection purposes). The aggregate limit for the individual abstraction, as identified from the CAMS ledger was used as the annual abstraction protected yield rate. This value was used in the delineation of the total capture zone and the 400 day travel time zone. The daily maximum abstraction rate from the licence was used to define the 50 day zone. Where there are multiple abstraction boreholes, including satellite sources, the division of the licensed abstraction was agreed with the water company, based on their actual or future likely reasonable use of the boreholes.

## Conceptualisation of the aquifer

GIS based model map was used to support the conceptualisation of the aquifer. The main outputs from the MODFLOW model including modelled transmissivity for the SPZ runs, horizontal and vertical groundwater flow vectors, infiltration and run-off recharge. Model input data was also reviewed including: bedrock and superficial deposit geology, historic groundwater heads and contours, model layer thicknesses, rivers network, groundwater and surface water abstractions, discharges to ground and surface water etc. Information from the previous proforma and schematic cross sections conceptualising the regional groundwater model were also reviewed.

Duxford abstracts from the Chalk, which forms the primary bedrock geology for the southern half of the Rhee and Bourne Reporting Area (Figure 1). The Chalk dips to the south-east, and in the upper reaches of the Reporting Area (to the South) the Chalk is overlain by Glacial Sands and gravels and glacial till margins. Chalk thickness reaches up to 180 m and T values over 1000 $m^2/d$ (Figure 2). The area is drained by the rivers Rhee and Bourne, and the tributaries that feed into these watercourses.

## Figure 1 Bedrock and Superficial Geology




## Figure 2 Transmissivity (model values) $m^2/d$

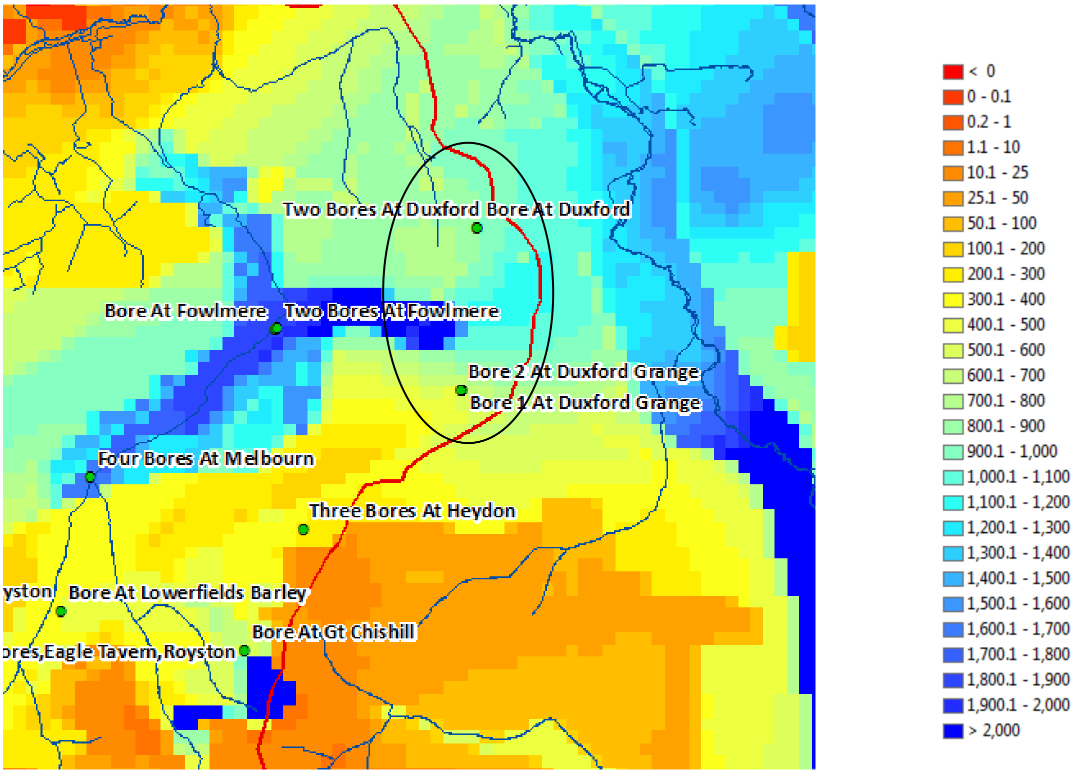


**Figure 3 Flow across the base of Layer 5 (highly transmissive upper part of Chalk) to Layer 6 (uniformly transmissive lower part of Chalk) (m³/d), horizontal flow vectors and groundwater contours (Dry Conditions)**

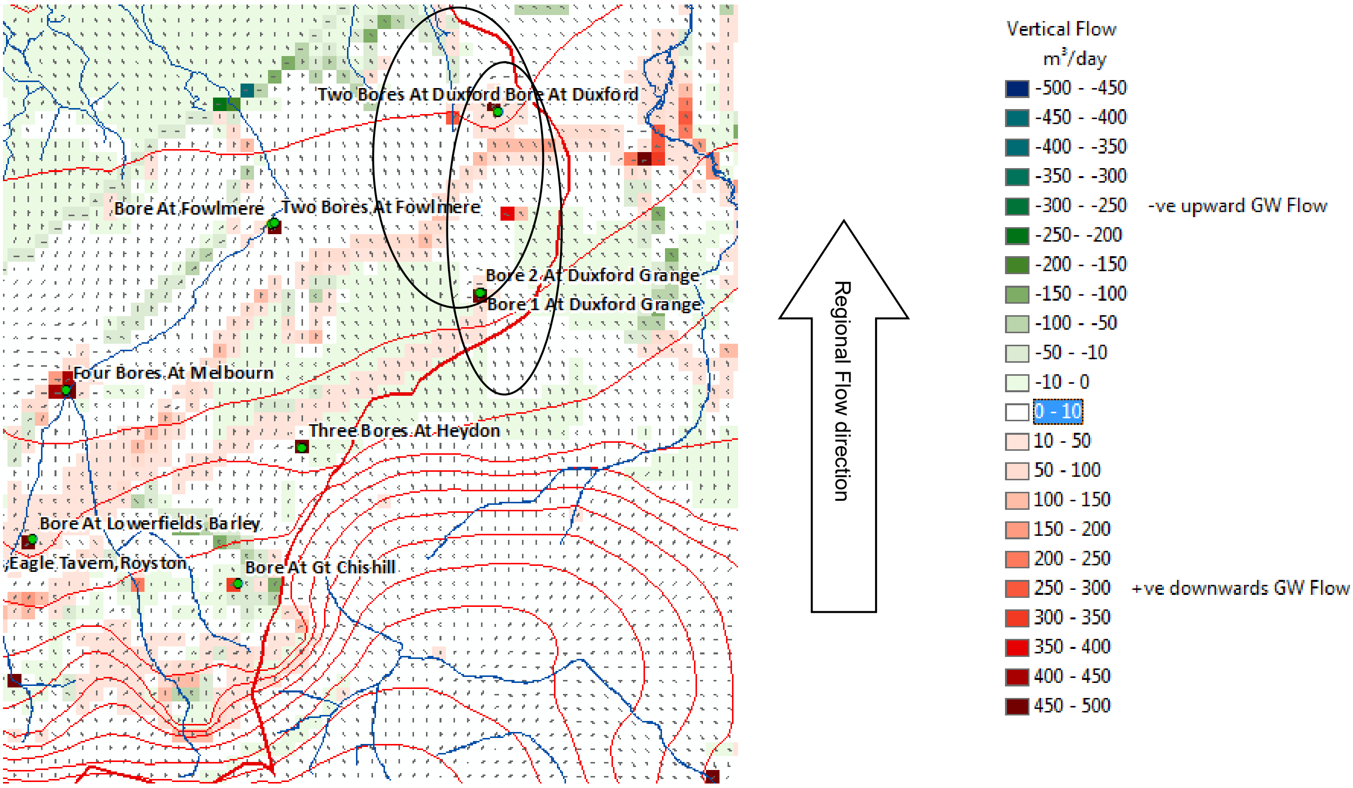



**Figure 4 Flow across the base of Layer 4 (Crag and other lithologies) to Layer 5 (Chalk) (m³/d), horizontal flow vectors and groundwater contours (Wet Conditions)**

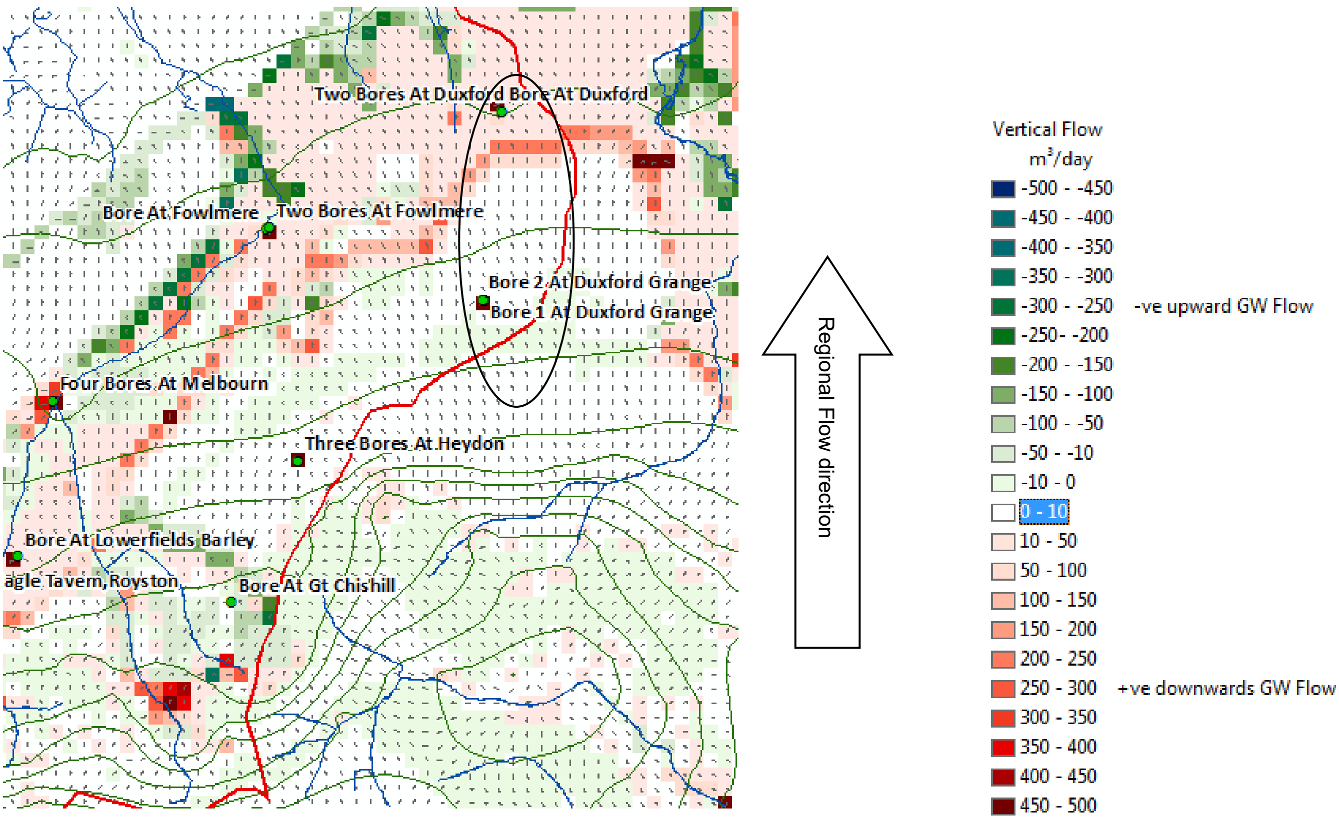
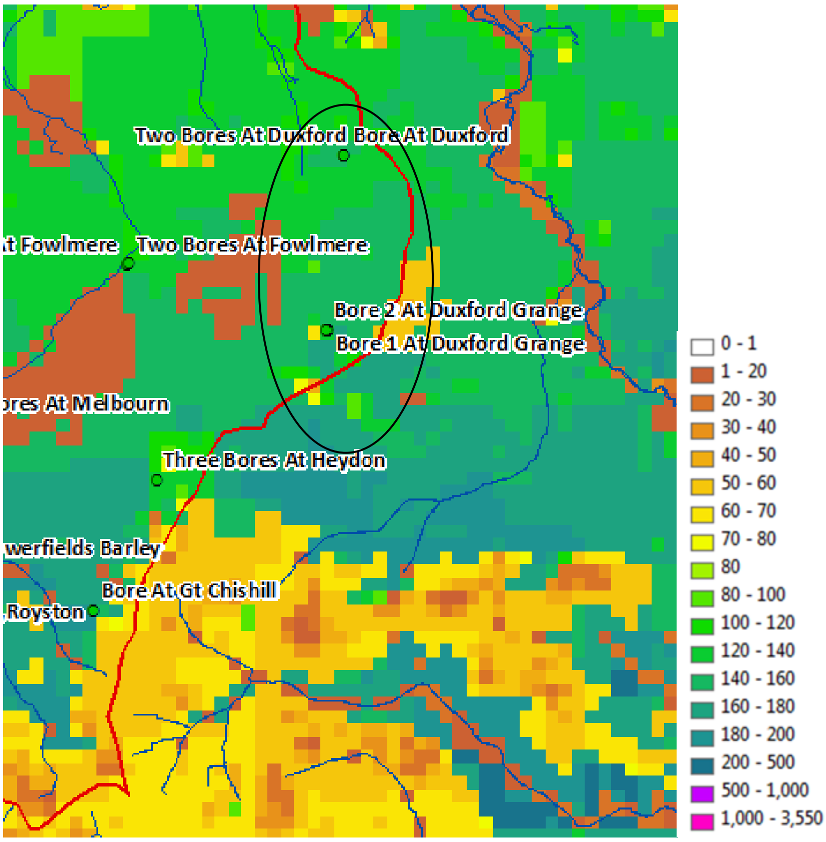


**Figure 5 Infiltration Recharge LTA mm/a**




Comparing dry and wet conditions, the upward flow of groundwater beneath river corridors is clear in wet conditions (Figure 3 and 4). Groundwater regional flow is towards the north and the hydraulic gradient is relatively flat around the Duxford area. The Duxford abstractions exploit an area of high transmissivity beneath the river in the neighbouring surface water catchment, and vectors indicate a significant flux of water from this area, particularly under dry conditions.

At Duxford Grange infiltration recharge is low beneath the Glacial Till and high at outcrop (Figure 5).

## Numerical model set up and outputs

Regional Groundwater Model (MODFLOW), FLOWSOURCE and MODPATH, combined with manual calculations are used to check on the geometry and extent of the delineated SPZ. The following settings were used for these models:

MODFLOW:

To represent groundwater flow conditions under the protected yield conditions (annual to represent the 400 day and TCZ, and maximum daily rate for the 50 day zone) the regional groundwater model was run twice using the recent actual model run (where the model represents the typical situation over the most recent 5 year period of data) as the baseline:

- 400 day and TCZ: All abstractions to be modelled as an SPZ are set to the protected yield based on the annual abstraction rate, as a flat rate throughout the whole modelled period.
- 50 day zone: All abstractions to be modelled as an SPZ set to the annual / 400 day abstraction rate, as a flat rate throughout the whole modelled period. In the two months prior to and including the dry, wet and average stress periods of the model, the abstraction rate is set to the daily rate for the abstraction.

For multiple boreholes the rate is divided equally between the boreholes (i.e. so the overall daily rate is not exceeded).

FLOWSOURCE:

Using the groundwater model outputs from the 400 day and TCZ run, FLOWSOURCE was used to derive:

Proportion of time that the time of travel is 50 days or less

Proportion of time that time of travel is 400 days or less

Time of travel to the abstraction

Volume from (dry, wet and average stress periods) $m^3/d$

- Volume through (dry, wet and average stress periods) $m^3/d$
- Proportion of time that the volume through a model cell exceeds 1 $m^3/d$

MODPATH:

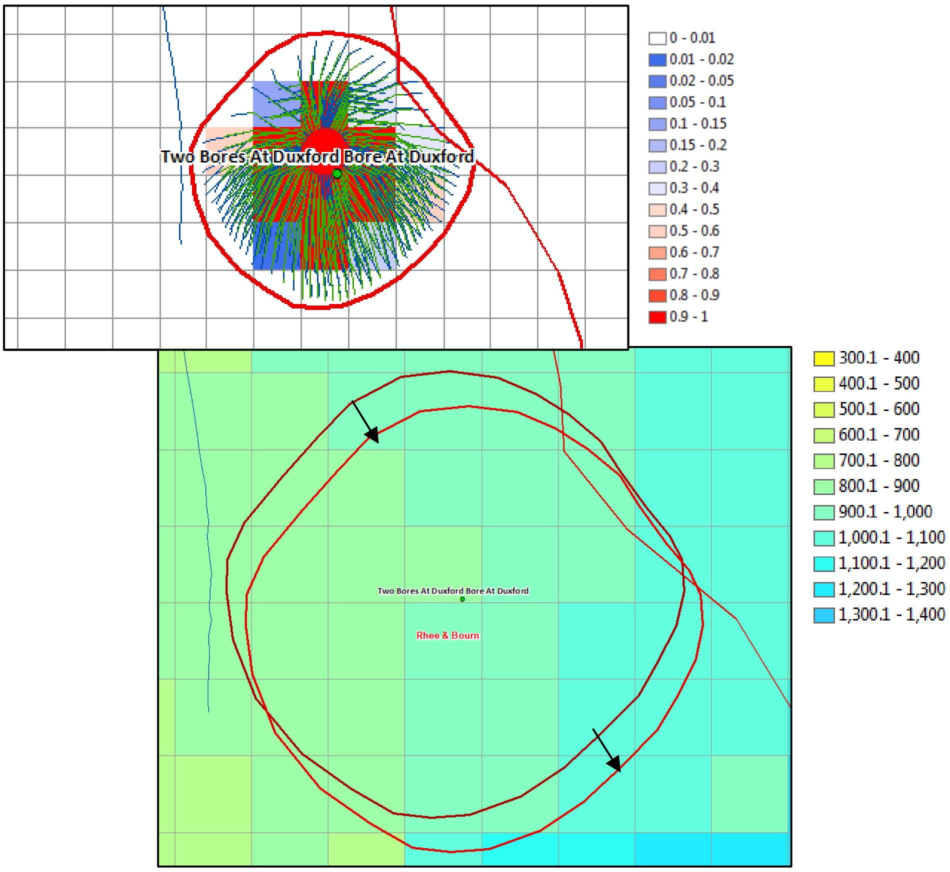
Using the groundwater model outputs from the 400 day and TCZ run, MODPATH was used to derive a time of travel zone for the 400 day and TCZ. The 50 day model run was used to calculate the 50 day time of travel particle tracks. Particles were released from the borehole in the active part of the aquifer, and backtracked through the aquifer to 50 days, 400 days or to a recharge boundary for the TCZ.

## Interpretation of numerical model outputs and conceptualisation – Two Bores at Duxford

### *SPZ 1 Delineation*

Set back radius is 50 m i.e. smaller than model cell (250 m x 250 m). SPZ 1 boundary nudged south-east to account for the location of the boreholes in the south east corner of the model cell (Figure 6).

**Figure 6 SPZ 1 Delineation (top) using FlowSource and MODPATH, and nudging of shape for borehole location in model cell using T values (bottom)**

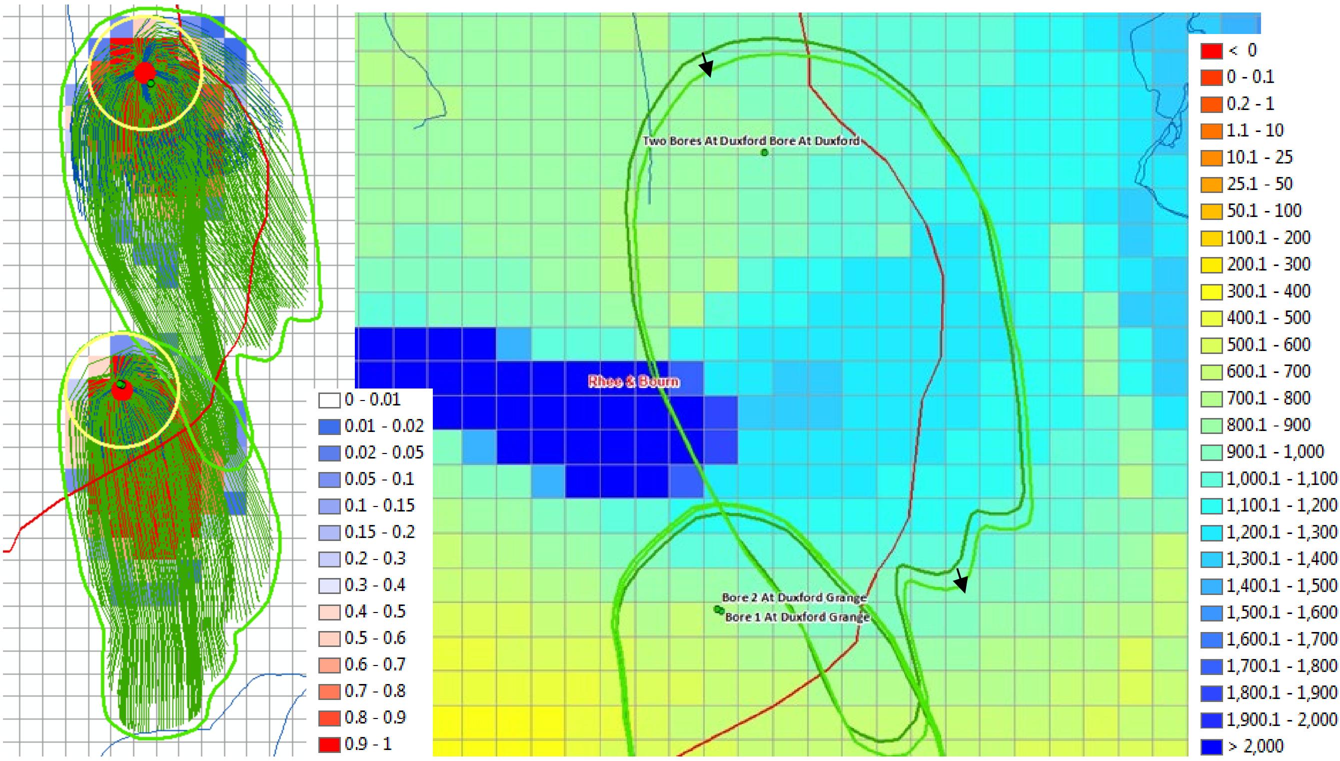


## SPZ 2 Delineation

All of the numerical model outputs are centred on the centroid of the model cell, but the abstraction is likely to be located elsewhere in the model cell. The shape has to be nudged to account for this difference whilst taking into account potential changes in transmissivity.

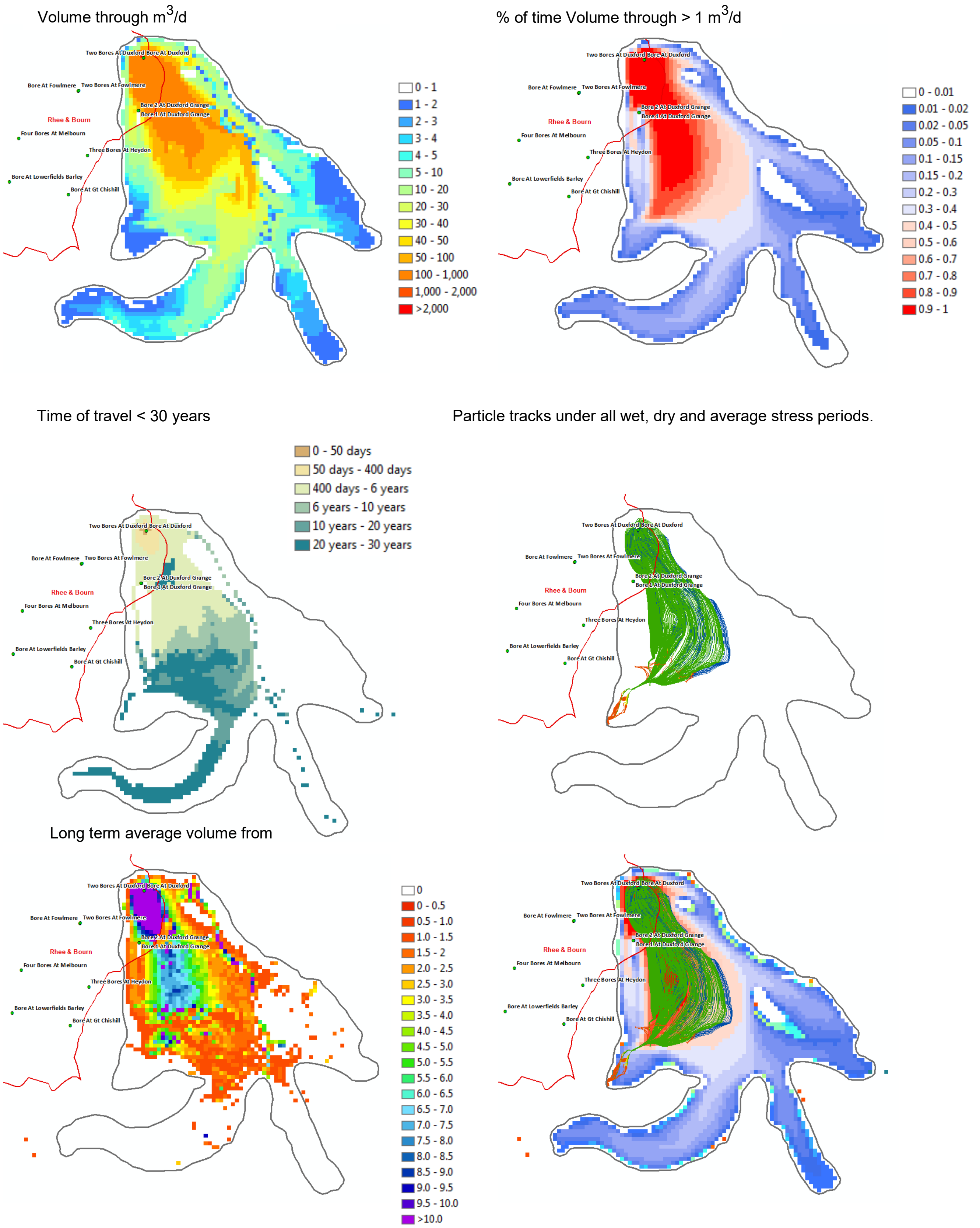
Two Bores at Duxford SPZ2 has been “nudged” from the cell centre to the site of the abstraction, moving the SPZ2 south-east. Average stress period transmissivity ($m^2$/d) suggests that nudging the SPZ 2 candidate boundary to the south-east to reflect abstraction location in the model cell moves the shape into an area of higher transmissivity and so no adjustment is made to the boundary. If the move was towards lower transmissivity area, the shape would be stretched to retain the area of higher transmissivity covered by the original extent.

**Figure 7 SPZ 2 Delineation (Left) using FlowSource and MODPATH, and nudging of shape for borehole location in model cell using T values (Right)**



## *SPZ3 delineation: base outline on all long term average outputs*

**Figure 8 Using all model outputs to delineation SPZ3**




**Final Zone: Individual 'lone' Volume From (VF) and time of travel cells not included**

Conclusion:

Include the Volume Through (VT) > $1m^3/d$;

Include the % of time VT >$1m^3/d$;

Check to see if water less than 30 years old is included;

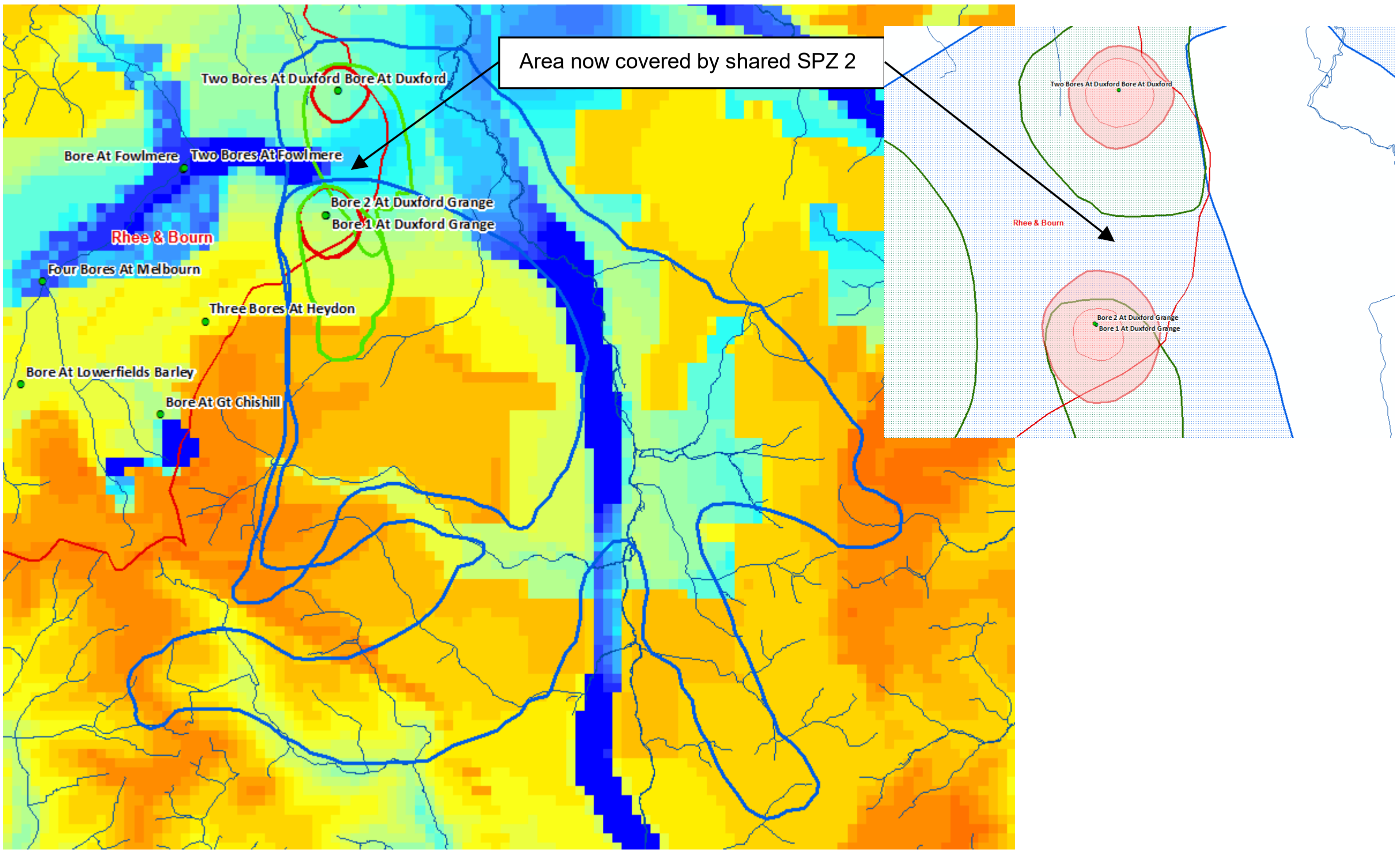
Check all particle tracks are represented;

Check if all VF is included (individual ‘sparse’ cells have been kept out of the delineation).

## Merging overlapping zones

Two bores at Duxford and Duxford Grange have overlapping SPZ2s. These were combined, but SPZ1s were left as separate boundaries. SPZ3 becomes merged as part of a shared public face boundary for the whole of the chalk outcrop. The boundaries are retained for internal purposes such as development / catchment management.

**Figure 9 Merging zones that overlap (inset shows previous zones)**




SPZ1s are now bigger than previously (despite the reduction in abstraction) and for Duxford Grange, extends outside of the current SPZ2. The shared SPZ2 area is new and needed to be communicated to internal and external stakeholders. All public facing zones were signed off by the water company.

# Case Study 2 Building a groundwater model for SPZs, Sandstone

## What does this case study demonstrate?

Delineation of an SPZ using numerical models and manual methods, for an unconfined sandstone abstraction. The SPZ was first created in 2015.

## Aquifer / EA Area:

Cumbria and Lancashire area: – Ehen catchment (unconfined St Bees Sandstone). The South Egremont sources are under a single licence for abstraction from multiple locations.

## Justification for an SPZ / update of SPZ

The SPZ was required as these were new sources drilled in 2010 and licensed in 2015. It was decided that to give the best confidence in the zones a numerical groundwater model for the sandstone aquifer was constructed specifically to model the catchments to the SPZs.

## Assigning the Protected Yield

The value was based on the licence annual and daily abstraction rates, and which of the abstraction boreholes (4 in total) were in use. The source has a licenced abstraction rate of 11 Ml/d and 365 Ml/yr. and there are no nearby licenced abstractions.

The protected yield and its division between boreholes, was agreed with the licence holder (United Utilities), based on their actual or future likely reasonable use of the boreholes as follows:

For the 50 day zone (SPZ1) a protected yield of 11 Ml/d was used split across 4 boreholes: BH A, B, C 3 Ml/d and BH D 2 Ml/d.

For the 400 day zone a protected yield was set at 365 Ml/yr.

# Conceptualisation of the aquifer

The study area lies on the western edge of the Lake District, Cumbria. The geology of the upland area of the Lake District comprises metamorphic and igneous rocks of Lower Palaeozoic age. These are surrounded by younger unconformable sedimentary rocks that dip away from the centre of the Lake District. Quaternary deposits unconformably overlie this sequence with variable thickness and composition. In the study area, the Permo-Triassic St Bees and Calder Sandstones dip westwards towards the sea, and unconformably overlie rocks of Silurian and Ordovician age, although in the north of the area they overlie the St Bees Shale and Carboniferous rocks.

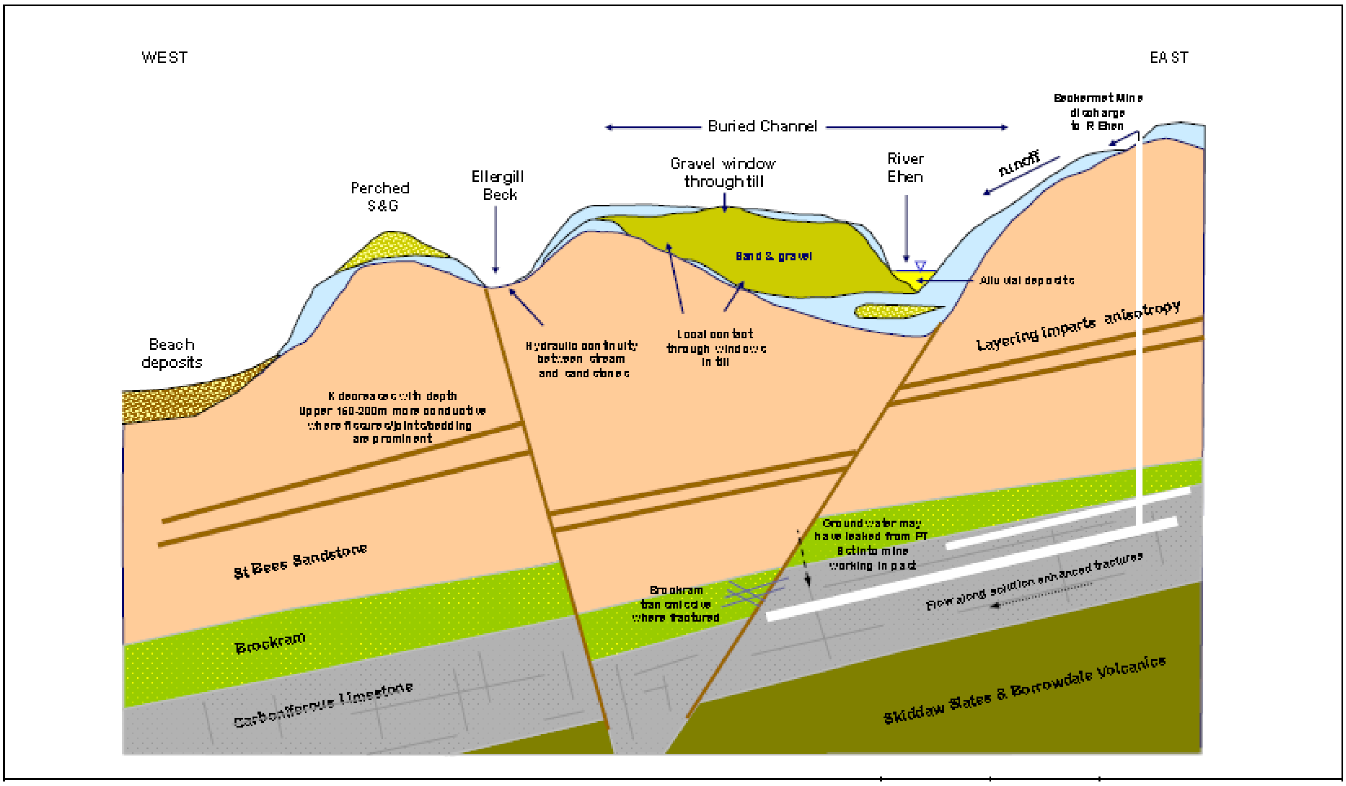
In West Cumbria the Permo-Triassic, Sherwood Sandstone Group is designated as a Principal Aquifer, and is the main aquifer present. It predominantly comprises the St Bees Sandstone, a fine grained and strongly cemented sandstone, with lower intergranular permeability than some other Permo-Triassic Sandstones in the same region (e.g. the Penrith Sandstone of the Eden Valley). As a result, groundwater flow mechanism is fracture-dominated and borehole yields are generally poorer than in the Penrith Sandstone. The St Bees Sandstone is generally more permeable in the upper 150-200 m, where fissures, joints and bedding plane fractures are more common. The sandstone is a layered formation, particularly in its lower portion, and this imparts significant vertical anisotropy, which can lead to the development of large vertical head gradients. The aquifer dips to the west but is disrupted by frequent sub vertical faults, with a predominant north west-south east orientation. The effect of these faults on local compartmentalisation of the aquifer is unclear. In previous work, certain fault zones were identified as separate hydrogeological features. Geological properties and the distribution of groundwater salinity suggest that the large fault zones compartmentalise the groundwater by forming barriers to flow, but create open fracture networks adjacent to them. This is a common feature of the Permo-Triassic Sandstone in the north west of England.

In the Egremont area the Permian aged Brockram (a sedimentary breccia) lies between the St Bees Sandstone and the underlying Carboniferous Limestone. Both the Brockram and the Carboniferous Limestone are classified as aquifers, but their interrelation with the Sherwood Sandstone Group is unclear.

Superficial Deposits are variable and range from thin till to the north to thick sequences of mixed material infilling a buried valley to the southeast. The role of superficial deposits in allowing or limiting recharge is variable.

Groundwater flow within the Sherwood Sandstone is predominantly towards the coast. However, there is some flow towards the main streams, and this indicates discharge into these streams or the associated buried valleys.  The main surface water features are the River Ehen, Ellergill Beck, Pow Beck, River Calder and River Mite. These flow generally south westward and southward over the Permo-Triassic Sandstone to the sea.

Figure 1 Conceptual Cross-Section (taken from Hyder Consulting, 2015)

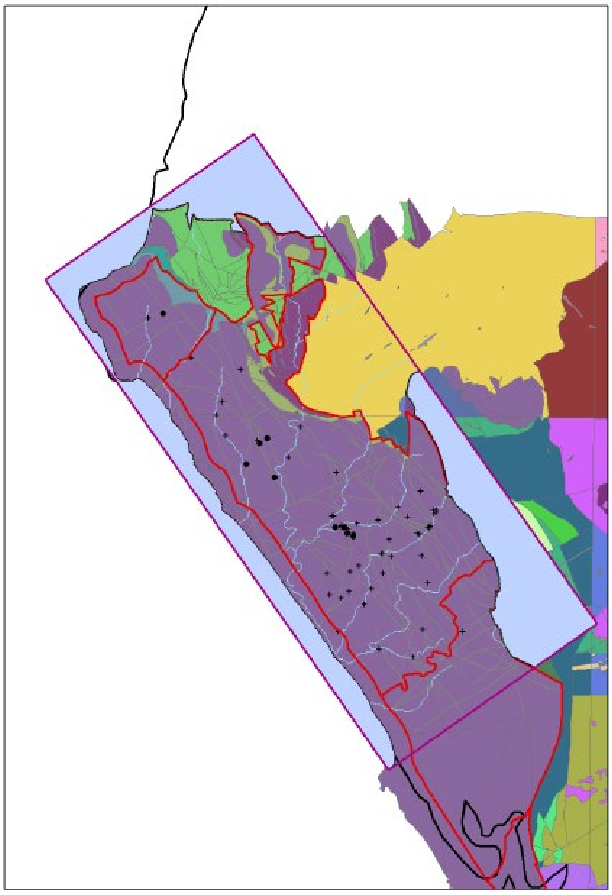



## Numerical model set up and outputs

A numerical groundwater model was built in MODFLOW96 for the abstraction by Groundwater Science (2015).  This covered a large proportion of the Sherwood Sandstone aquifer in West Cumbria, the outcrop of which is relatively well defined (Figure 2).

The model area was larger than that required to simulate the capture area of the South Egremont boreholes covering the entire Ehen/Calder and St. Bees Groundwater Management Units (GWMUs). A wider area was used so that the model could be used for other purposes. As the Calder Sandstone Unit is elongated NNW-SSE the model grid was rotated to reduce the total simulated area.

**Figure 2 Model Area**



*Notes: rectangle is model boundary, blue-grey area is inactive (coast or low permeability units), purple is sandstone and limestone, red polygons are Groundwater Management Units, BGS derived faults mapped in green, simulated rivers in light blue, abstractions are black dots.*

A smaller than usual model grid consisting of a 20 x 20 m cells was used to mitigate issues of numerical dispersion; to better represent rivers; and to permit representation of faults. The effect of extensive faulting across the sandstone on the local hydrogeology is uncertain. As uncertainty associated with faulting was likely to affect the delineation of capture zones three separate versions of the model were created with differing structural conceptual set-ups, as follows:

- Baseline, which assumes no faulting and is consistent with typical models constructed for SPZ delineation. The model has homogeneous, isotropic parameterisation for the igneous and metamorphic peripheries of the model. The sandstone was parameterised as a heterogeneous aquifer constrained by local groundwater level and spot-flow stream accretion gauging;
- Faults as conduits for flow.
- Faults as partial barriers to flow.

Each of the models was first calibrated under steady-state conditions, and was then developed as a transient model, run for monthly stress periods 1965 to 2011, with a single time step per stress period.

To aide SPZ delineation, post-processing was undertaken on each abstraction for the protected yield rates for SPZ1, SPZ2 and SPZ3 using FlowSource (v 6.13) and MODPATH (3). The faults-as-barriers model was not developed further as it did not provide a good representation of groundwater flow.

MODFLOW:

To represent groundwater flow conditions under the protected yield conditions (annual to represent the 400 day and TCZ, and maximum daily rate for the 50 day zone) each groundwater model was run twice (see Figures 3a-d and 4a-d):

- 50 day zone (for SPZ1): Abstractions were modelled at the 50 day protected yield rate.
- 400 day (for SPZ2) and TCZ (SPZ3): Abstractions were modelled based on the annual abstraction rate, as a flat rate throughout the whole modelled period.

FlowSource:

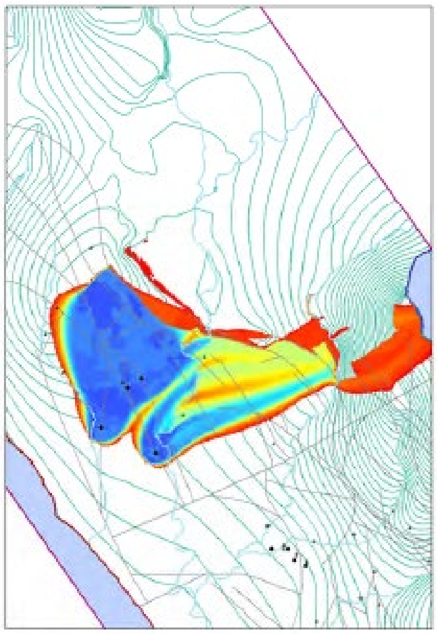
Using the groundwater model outputs from the 400 day and TCZ model run, FLOWSOURCE was used to derive:

- Flow Through;
- Time of travel to the abstraction;
- Volume from $m^3$/d;
- Volume through $m^3$/d.

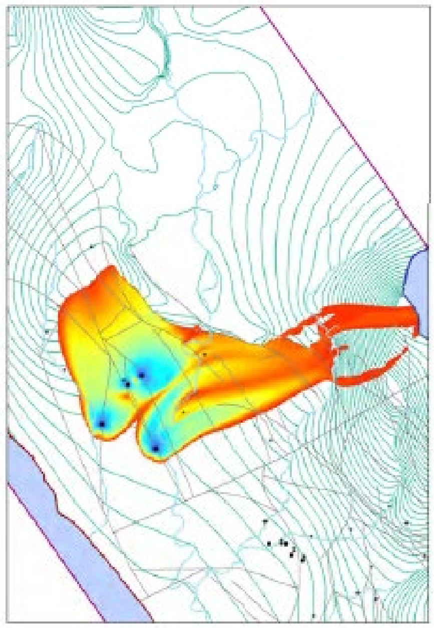
MODPATH:

Using the groundwater model outputs from the 400 day and TCZ run, MODPATH was used to generate a time of travel zone for the 400 day and TCZ. The 50 day model run was used to calculate the 50 day time of travel particle tracks. Particles were released from the borehole in the active part of the aquifer, and backtracked through the aquifer to 50 days, 400 days or to a recharge boundary for the TCZ.

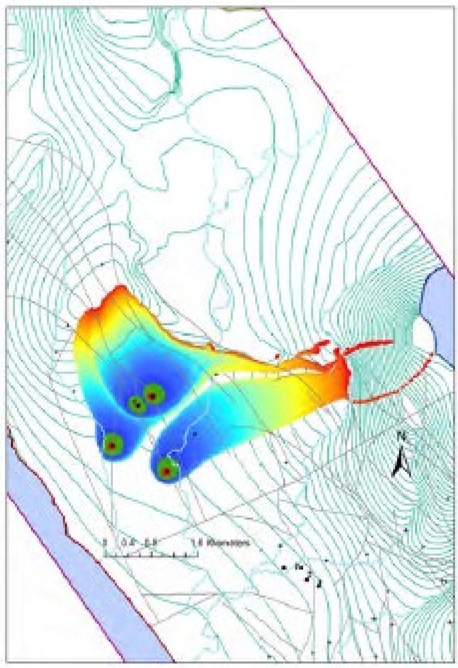
**Figure 3 FlowSource and MODPATH output for the 'No Fault' scenario (a) FlowSource 'Volume From' (b) FlowSource 'Volume Through' (c) FlowSource-travel-time (d) MODPATH-travel-time**



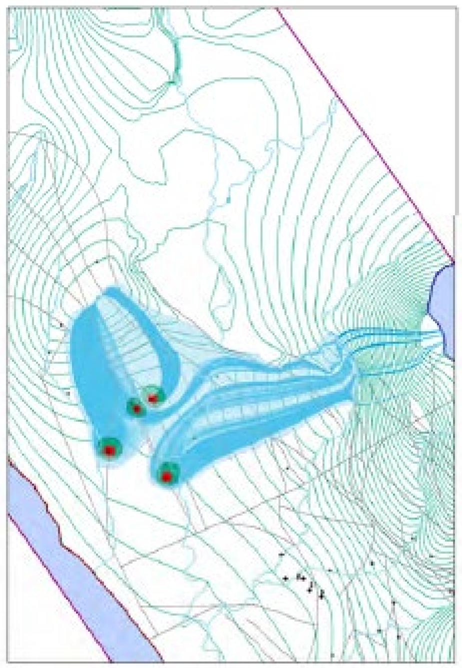
(A)



(B)



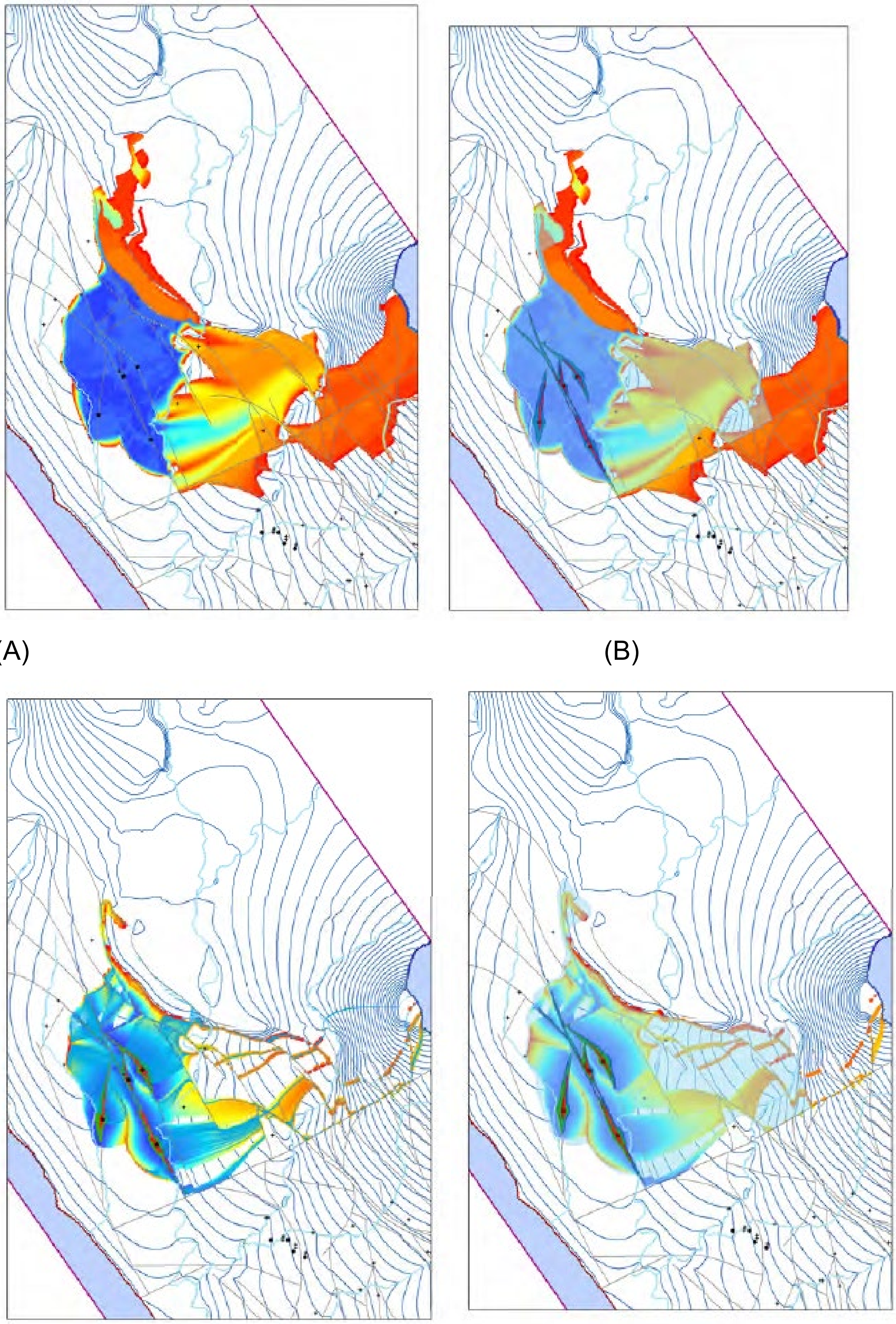
(C)



(D)

Note: The zones visible within the main capture area (blue) result from the heterogeneous recharge zonation. Red areas represent flow volumes which are negligible relative to the total abstraction rate and beyond model precision (and calibration accuracy)

**Figure 4 FlowSource and MODPATH output for the 'Faults-as-Conduits' scenario (a) FlowSource 'Volume From' (b) FlowSource 'Volume Through' (c) FlowSource-travel-time (d) MODPATH-travel-time**



(A) (B)

(C) (D)

Note: The zones visible within the main capture area (blue) result from the heterogeneous recharge zonation. Red areas represent flow volumes which are negligible relative to the total abstraction rate and beyond model precision (and calibration accuracy)

## SPZ Delineation

### SPZ 1 Delineation

SPZ1 was defined by the 50-day travel-time areas using both MODPATH and FlowSource.

### SPZ 2 Delineation

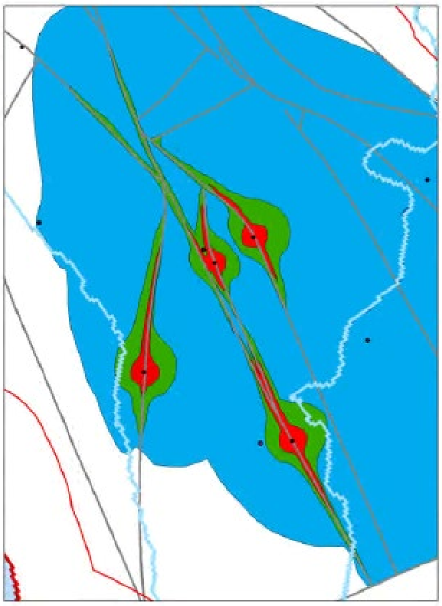
SPZ2 was defined by the 400-day travel-time in both MODPATH and FlowSource, although the shape was adjusted to include flow paths between areas within the 400 day limit and the TCZ that were not time dependent.

### SPZ 3 Delineation

The FlowSource 'Volume Though' (abstraction pathway) and 'Volume From' (abstraction source zones) outputs were principally used to delineate these zones. On the basis that they encompass the area simulated to represent where water enters the groundwater system and the most significant pathways for that water on route to the abstractions.

SPZs were generated for the two most likely scenarios: the 'no faults' and 'faults as conduits' scenarios. The two sets of SPZs are independent of one another and either could have been selected based as the most probable hydro-geological conceptual setup.  However, given the uncertainty, a combined single SPZ3 was established.

**Figure 5  Combined SPZs for the 'No Faulting' and 'Faults-as-Conduits' configurations (SPZ 1- red, SPZ 2 - Green, SPZ 3 - Blue)**



## References


Hyder Consulting.  2015.  West Cumbria Groundwater Assessment.  Report for the Environment Agency.

Groundwater Science.  2015.  St.Bees-Calder Sandstone Groundwater Model and South Egremont Source Protection Zone Report

# Case Study 3 Manual SPZ delineation with insufficient data

## What does this case study demonstrate?

An approach that was taken when there wasn't enough data for numerical modelling of the source. Instead expert judgement, field walkover, and manual methods were used.

## Aquifer / EA Area:

Harlow Hill Sandstone and Warley Wise Grit, Yorkshire area

## Justification for an SPZ / update of SPZ

Harrogate Spring Water Limited has two abstraction licences for the purpose of bottling water with no existing SPZ.

## Assigning the Protected Yield

There are three boreholes in total: Boreholes 1 and 2 are on the factory site and abstract water from the Harlow Hill Sandstone; Borehole 3 is approximately 700 m to the northwest and abstracts water from the Warley Wise Grit. The protected yield was set at the maximum daily licensed quantity (335 $m^3$/d for BH1 and BH2, 1080 $m^3$/d for BH3) and annual licensed quantity (23,666 $m^3$/yr for BH1 and BH2, and 106,109 $m^3$/yr for BH3).

## Conceptualisation of the aquifer

The conceptualisation of the source and the aquifer used available data including: borehole construction details and borehole logs; groundwater levels; results of pumping tests; topographic and geological maps; source operational information (abstraction returns); and rainfall and river gauging. These were used to create a hydrogeological conceptual model for the source. The conceptualisation of the source was carried out in collaboration between Harrogate Spring Water and the Environment Agency (EA). We discussed the best way to designate source protection zones for the boreholes to safeguard the groundwater quality. The EA agreed that if a hydrogeologist was appointed by HSW to delineate SPZs for the three boreholes in line with EA guidelines, the EA would review and adopt the resulting SPZs. This was also discussed and agreed with EA National Groundwater. An Environmental Consultant, Rick Brassington, was hired to undertake a review and delineate source protection zones for the boreholes using the best professional judgement. Rick Brassington has been working with Harrogate Spring Water since 2000 on environmental issues associated with the site. Several meetings were held where the approach to be taken was discussed, and the Environment Agency provided advice and guidance on the methods for delineation. The EA provided Rick Brassington with the 2009 guidance document (EA, 2009). The EA then took the report and used it to produce an SPZ document and map layers.

The water bottling site is located on outskirts of Harrogate. The topography is higher to the west of the site and slopes down to the east. The land use west of the site is agriculture, with the urban area of Harrogate to the east of the site. The Oak Beck is the main stream in the area and flows in a north east direction to its confluence with the River Nidd north of Harrogate.

Superficial deposits consist of patches of glacial till deposits which consist of a mixture of clay, sand and gravel. Bedrock consists of layers of mudstones, sandstones and occasional limestone of Carboniferous age. The sandstone and limestone beds form the main aquifers in the vicinity. There are numerous aquifer units separated locally by siltstones and mudstones. Groundwater flow is through fractures and joints associated with folding and faulting.

There are several faults in the area, mainly trending southwest to northeast, the main fault is the Harrogate fault. The rocks in the area have been folded into the Harrogate Anticline, which forms a significant structure on a regional scale. Borehole 3 is located on the northern limb of the anticline. The rocks at this location are heavily fractured as a result of the folding.

The stress associated with folding increased fractures which increased hydraulic conductivity along the bedding planes, resulting in strong directional flow. The hydraulic regime is also influenced by the hydraulic gradient which in turn is controlled by topography.

Boreholes 1 and 2 are located within the Harlow Hill Sandstone which is a coarse-grained sandstone located close to the line of the Harrogate fault. The aquifer is overlain by low permeability material.

Borehole 3 abstracts water from the Warley Wise Grit which is a coarse grained sandstone with some thin siltstone beds. There is approximately 31 m of low permeability material located above the grit at this location. The Warley Wise Grit is classified as Secondary Aquifer.

The Warley Wise Grit aquifer and the Oak Beck surface water body interact as follows: Upstream of Oakdale Bridge the aquifer discharges to the stream; Downstream of Oakdale Bridge, groundwater is not in continuity with the beck due to the overlying low permeability material.

The Harlow Hill Sandstone outcrops at Harlow Hill and the Warley Wise Grit outcrops from Skipton Road on the northeast side of Harrogate (SE 307 563) for approximately 5 km to the southwest to Pot Bridge (SE 269 543). This area contains the Oak Beck Valley. The aquifers are recharged from rainfall falling on the exposed rock outcrops located at Harlow Hill and the Oak Beck above Oakdale Bridge.

Groundwater flow direction and hydraulic gradients are affected by structural features and topography. The groundwater flow occurs through factures which results in strong directional flow.

Groundwater discharges to springs in the Harrogate area.

## SPZ delineation

### SPZ 1 Delineation

Due to limited reliable groundwater level observation data, the information on structural controls on flow direction, and interaction with surface water was used for manual delineation. The manual method was supported by analytical calculations of the minimum area required for the sources based on the likely effective rainfall.

SPZ 1 for Boreholes 1 and 2 have a radius of 50 m which is the minimum set back radius for these zones. Borehole 3 was assigned a radius of 150 m to account for increased velocities associated with the fracture system at this location. The fracture system creates anisotropic conditions so the location of the SPZ1 was offset relative to the borehole.

### SPZ 2 delineation

SPZ2 for boreholes BH1 and BH2, were assigned the de minimus radius of 250 m for abstractions which are less than 2,000 $m^3$/day. The SPZ2 for BH3 was made slightly larger to accommodate the larger SPZ1. The shape of the SPZ was drawn as an ellipse to represent the anisotropic conditions.

### SPZ 3 delineation

SPZ3 was delineated by professional judgment taking into account the interactions between topography, surface water drainage, geology, aquifer geometry, runoff and recharge. The shape of the source protection zone 3 was derived as the topographically high ground surrounded by the Oak Beck valley. This area includes the outcrop of the Harlow Hill Sandstone and Warley Wise Grit aquifers where they lie in the catchment of the Oak Beck plus the catchment area from which the surface runoff can drain in to the aquifer.

**Figure 1 SPZ1 and 2 for Harrogate Bottled Water**

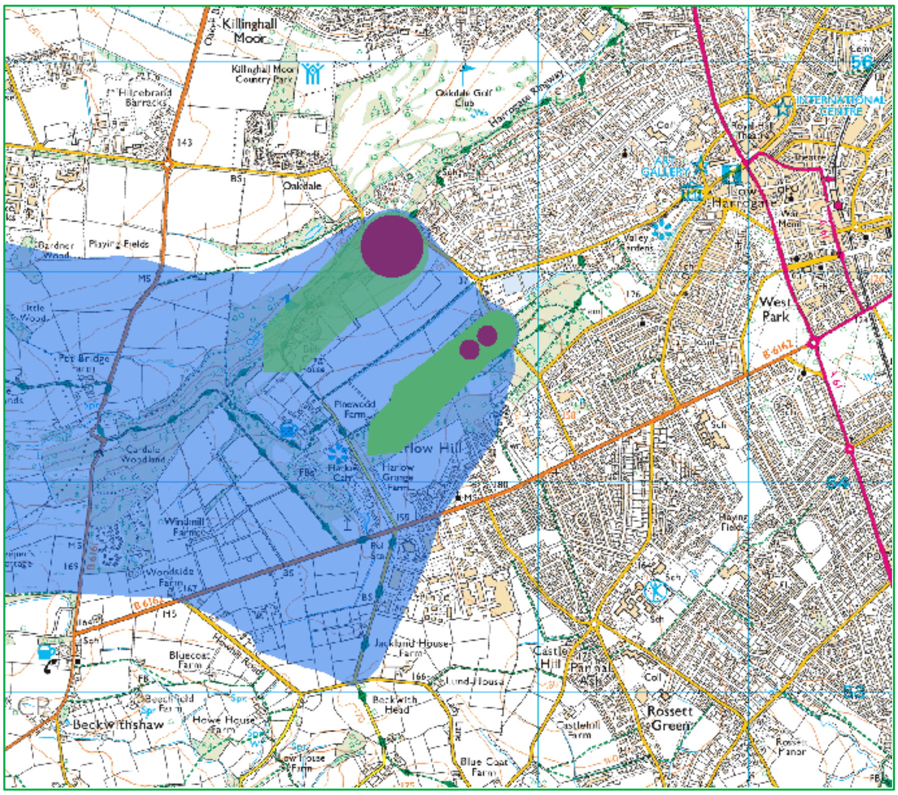
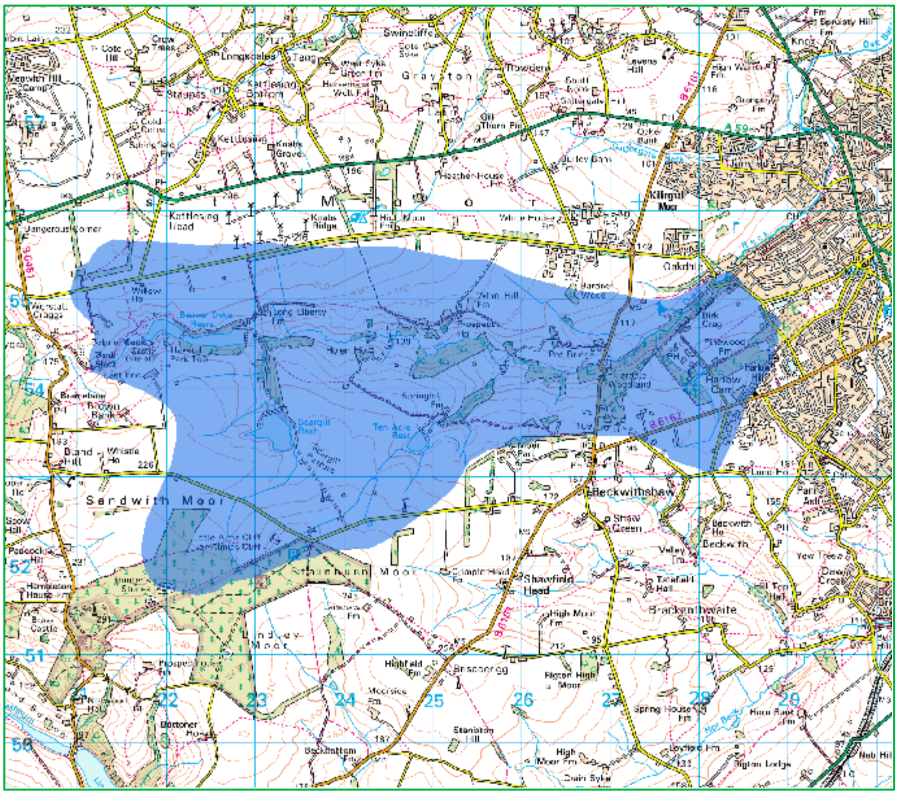



**Figure 2 SPZ3 for Harrogate Bottled Water**



# Case Study 4 Manual SPZ delineation with insufficient data

## What does this case study demonstrate?

An approach that was taken when there wasn't enough data for numerical modelling of the source. Instead expert judgement, field walkover, and manual methods were used.

## Aquifer / Area:

Glaciofluvial Deposits and River Terrace Deposits in Cwm Rheidol. Natural Resources Wales

## Justification for an SPZ / update of SPZ

The Lovesgrove (LGV) source is a public water supply consisting of three separate boreholes (LGV1, 2, 3) set along the Afon Rheidol valley. There was a previous SPZ that was derived using analytical modelling techniques.

## Assigning the Protected Yield

The protected yield was agreed with the licence holder (Dwr Cymru Welsh Water – DCWW). As a conservative assumption, and based on abstraction returns, the protected yield was set as the maximum daily and annual licensed quantity and applied to each abstraction borehole in turn.

## Conceptualisation of the aquifer

The conceptualisation of the source and the aquifer used the available data sources, which included: borehole construction details and borehole logs; groundwater levels; results of pumping tests; topographic and geological maps; source operational information (abstraction returns); rainfall and river gauging. These were used to create a hydrogeological conceptual model for the source.

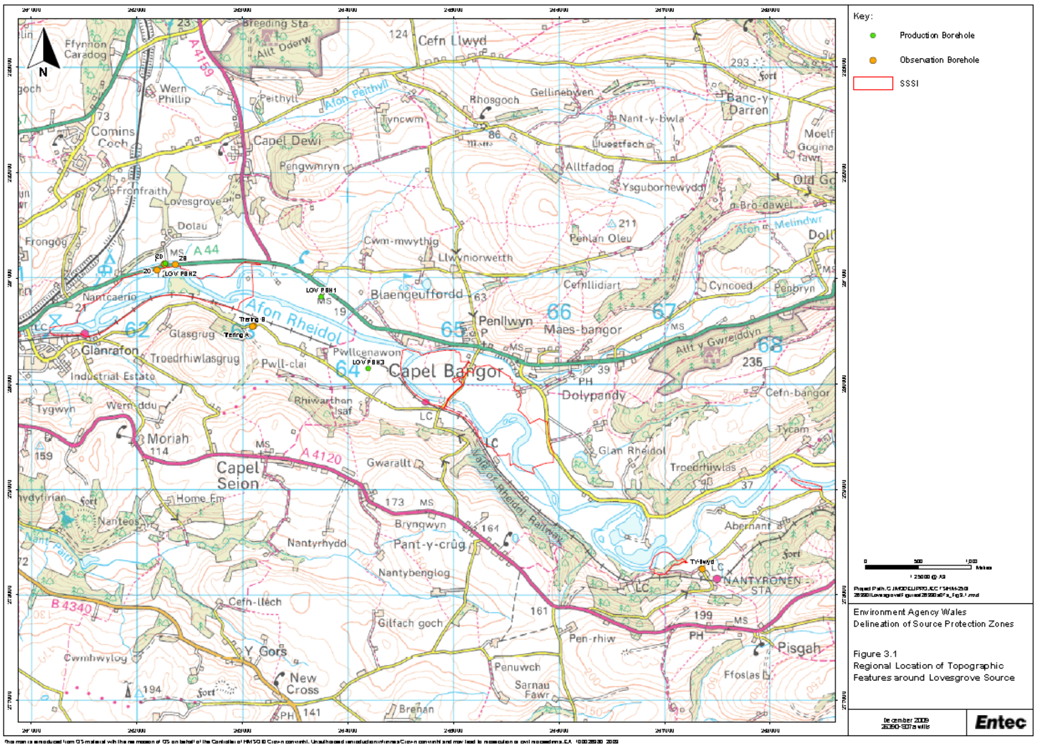
Lovesgrove abstraction lies in a valley bottom setting (Figure 1 and 2). The valley bottom is infilled with Glaciofluvial Deposits and River Terrace Deposits that form the aquifer from which abstraction takes place. Silurian bedrock beneath the Glaciofluvial Deposits and River Terrace Deposits and on the valley sides comprises well-cemented formations with low primary porosity and limited hydraulic conductivity. Minor flows from the bedrock may support the abstraction by providing flows to springs feeding streams, drains and ditches draining valley sides and the valley floor to Afon Rheidol; and through lateral groundwater movement at the valley sides. However, the bedrock was largely considered to be a non-aquifer, although now classified as a Secondary aquifer.

The Afon Rheidol was thought to interact with the Glaciofluvial Deposits and River Terrace Deposits aquifer. River flows and groundwater levels were compared but it was not possible to quantify the extent of interaction between the river and groundwater.

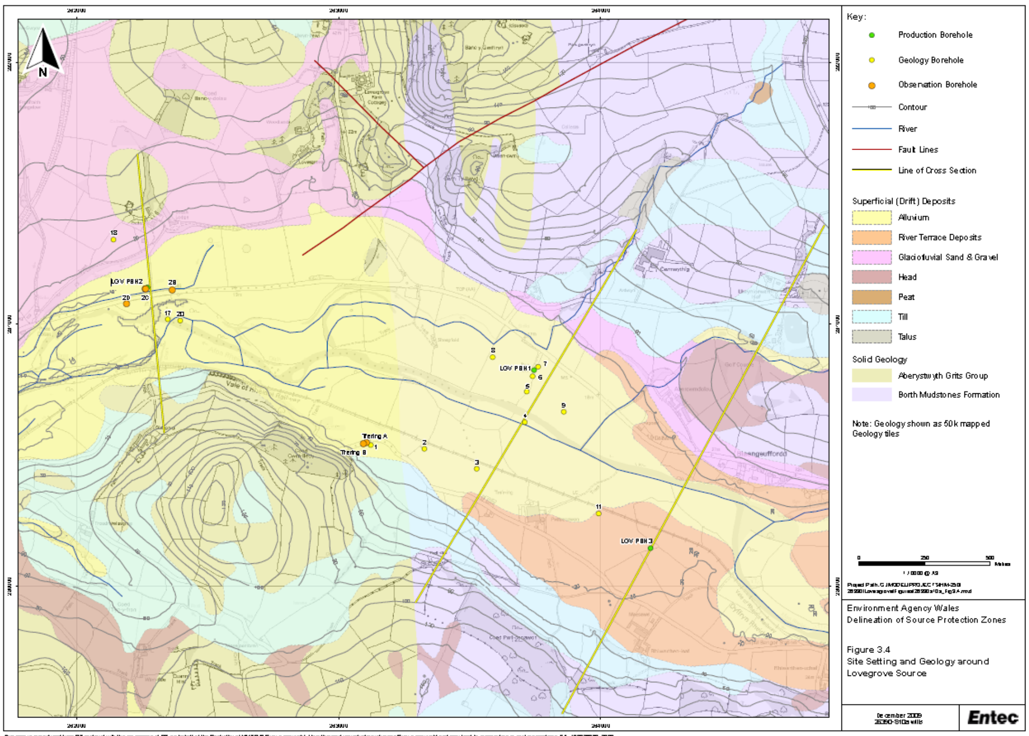
Recharge to the gravels was estimated as the difference between average effective rainfall and actual evapotranspiration between 1991 and 2000 for MORECS squares 122 and 133.

The data were used to construct a conceptual model which is illustrated on cross-sections and a three-dimensional figure showing the relationship between the abstraction and the aquifer (Figures 3 and 4).

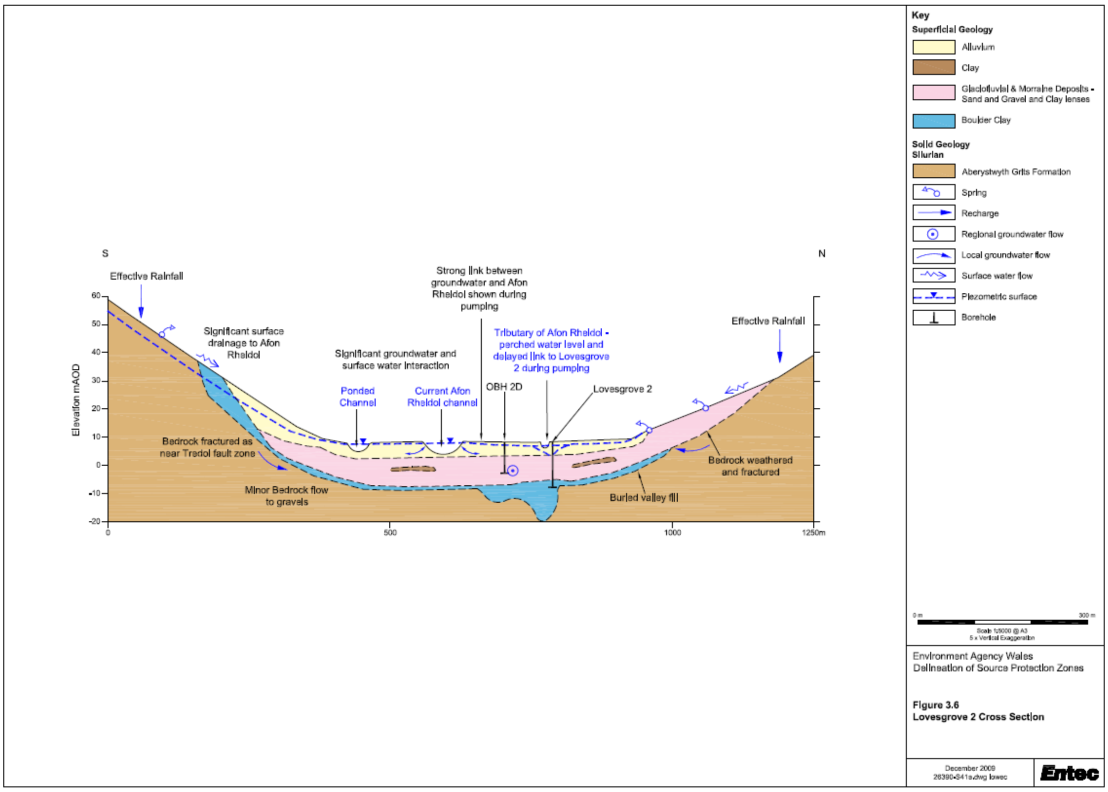
## Figure 1 Lovesgrove site setting

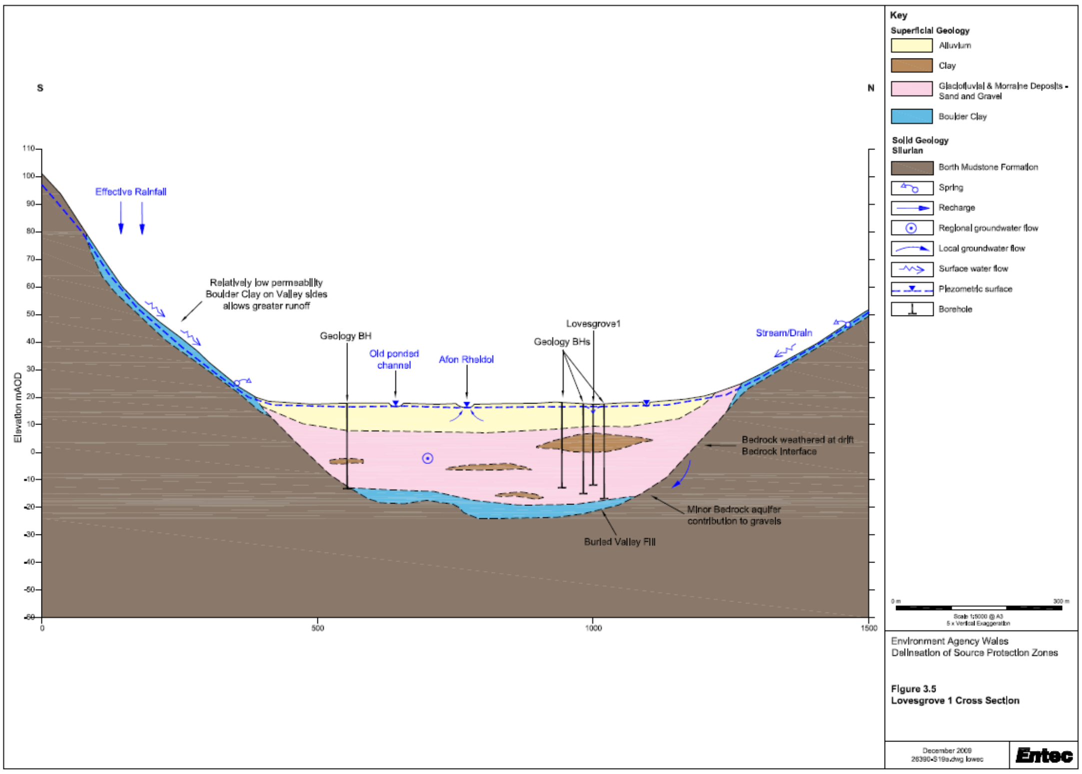



## Figure 2 Geology around Lovesgrove

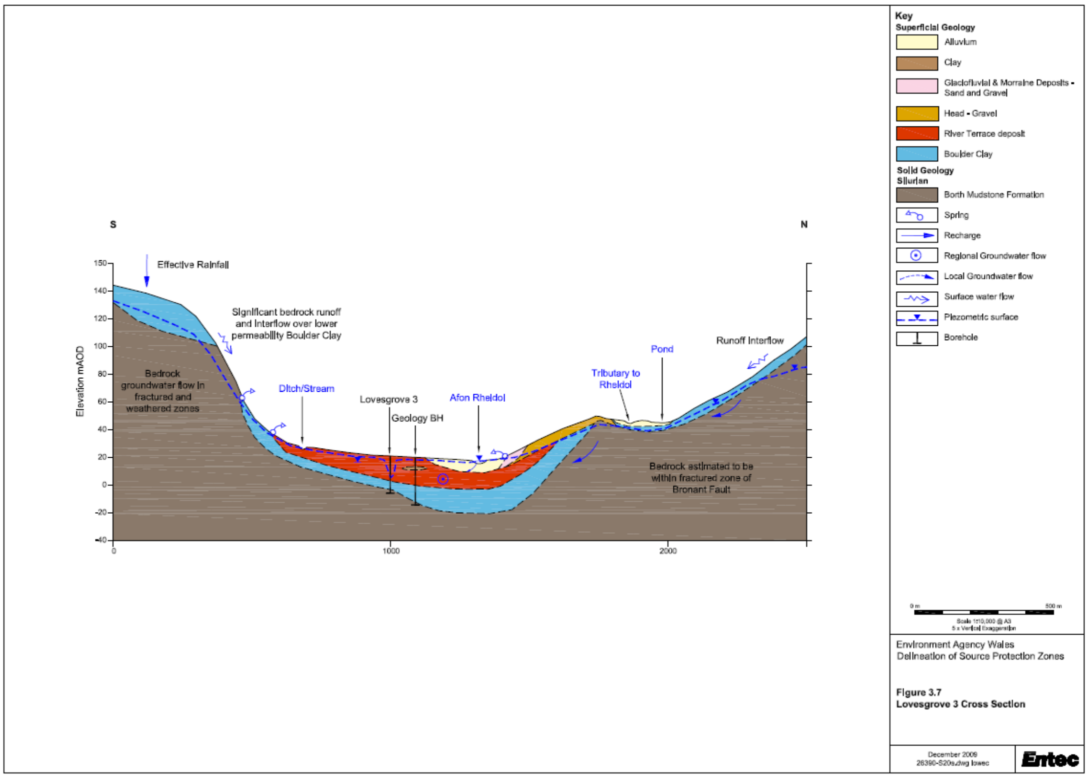


## Figure 3 Cross sections for each of the Lovesgrove Boreholes

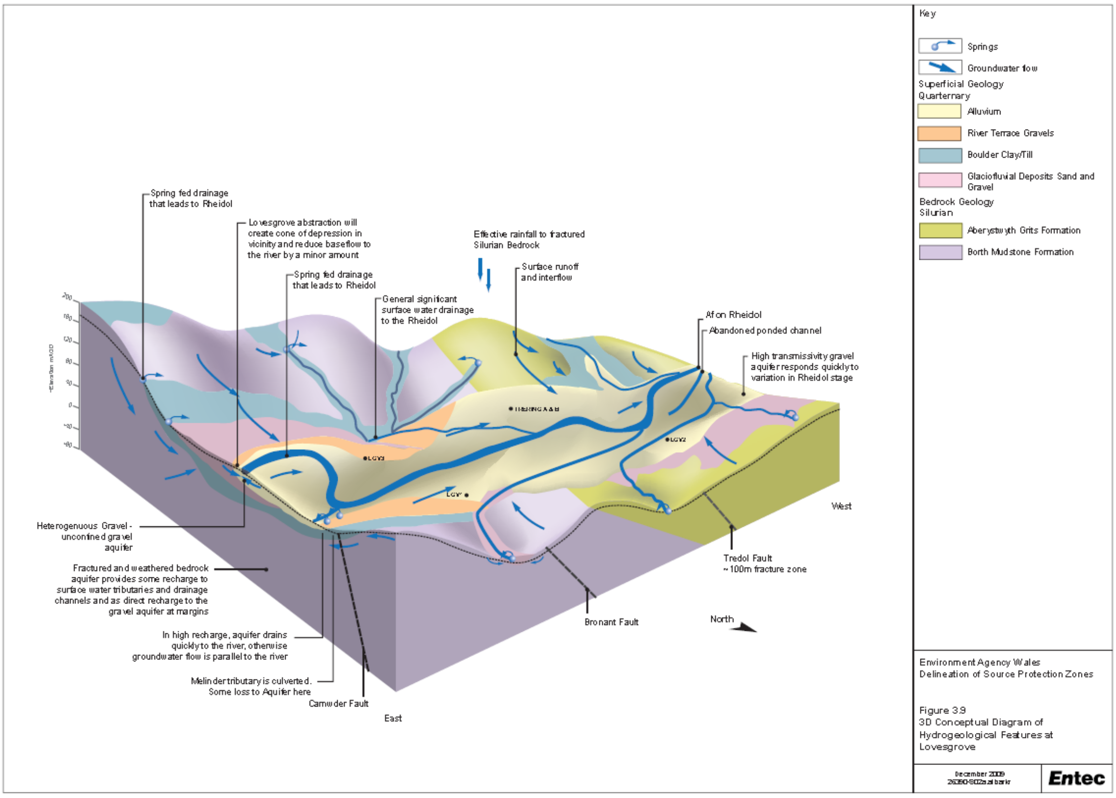


## Figure 3 cont'd Cross sections for each of the Lovesgrove Boreholes




## Figure 4 3D conceptual diagram of the Hydogeological Features at of Lovesgrove



## SPZ delineation

Due to limited reliable groundwater level observation data and the anticipated high, but unquantified, degree of interaction between the abstraction boreholes and the Afon Rheidol, manual delineation was the preferred approach. A numerical model approach was not used due to concerns that it would lead to widely differing zones, depending on the degree of river-aquifer interaction specified. The manual method was supported by analytical calculations of the minimum area required for the sources based on the likely effective rainfall. This approach was recognised to under-represent the degree of river-aquifer interaction, but was conservative in terms of the SPZ area around the sources.

The protected yield defined for each abstraction was used to estimate the area of time-of-travel capture zones for 50 and 400 days (SPZ1 and SPZ2), and the total recharge area of the source catchment (TCZ and SPZ3) using analytical methods. These estimates were used to define the minimum area and shape for manually-defined SPZs. In addition, the maximum down-gradient extent of the hydraulic capture zone was calculated (XI, the 'stagnation' point), along with the maximum up-gradient width of the hydraulic capture zone (YI). These were used to define the maximum down-gradient extent of the manually defined SPZs and the minimum width of SPZ3 respectively.

Zone delineation was iterative from SPZ3 to SPZ1 to reflect (i) topography; (ii) modelled piezometry, (iii) geological boundaries and iv) any additional site-specific issues identified in the conceptualisation.

The parameters input to the analytical calculations, that were used to give minimum areas for the three SPZs and shape factors to guide the delineation are shown in Table 1.

**Table 1 Parameters used in Analytical Calculations for SPZs**

| Parameters | LGV1 | LGV 2 | LGV 3 | Data Source |
|---|---|---|---|---|
| **Aquifer Thickness (b)** | 25 | 11 | 25 | Previous interpretation; Borehole logs |
| **Transmissivity T (m2/d)** | 4500 | 3700 | 825 | Pumping Test |
| **Hydraulic Conductivity K (m/d)** | 180 | 180 | 33 | Pumping Test |
| **Effective Porosity** | 0.05 | 0.05 | 0.05 | SPZ guidance |
| **Recharge (mm/a)** | 1230 | 1230 | 1230 | Calculated from MORECS |
| **Hydraulic Gradient** | 0.003 | 0.005 | 0.005 | Estimated from groundwater levels, topographic maps and and borehole datums |

A summary of the calculated and defined SPZ areas is given in Table 2.

The porosity value used in the above calculations is considered as being low and conservative. The area of a time of travel zone is inversely proportional to the aquifer porosity, such that a doubling of porosity leads to a halving in area. The consequence of adopting a different, likely higher, porosity value for the areas defined as SPZ 1 and SPZ2 can therefore easily be seen.

**Table 2 Results of Scoping Calculations**

| SPZ | Minimum Calculated Area (km2) | Delineated Area (km2) | Delineated Area as % of the Minimum Area |
|---|---|---|---|
| **SPZ1 - 50 day travel time** | | | |
| **LGV 1** | 0.20 | 0.33 | 165% |
| **LGV 2** | 0.45 | 0.51 | 113% |
| **LGV 3** | 0.20 | 0.34 | 170% |
| **SPZ2 - 400 day travel time** | | | |
| **LGV 1** | 1.14 | 2.63 | 231% |
| **LGV 2** | 2.59 | 2.63 | 231% |
| **LGV 3** | 1.14 | 2.63 | 231% |
| **SPZ3 Total Capture Zone** | | | |
| **LGV 1** | 1.06 | 2.63 | 208% of each source individually<br>83% of combined min value |
| **LGV 2** | 1.06 | 2.63 | As above |
| **LGV 3** | 1.06 | 2.63 | As above |

### *SPZ1 Delineation*

The proposed SPZs for the Lovesgrove sources are shown on Figure 6. Using the areas in Table 2 the SPZ1 for each abstraction borehole was increased from the calculated areas to extend the zone beyond or alongside the Afon Rheidol. In addition, the SPZ1 for Lovesgrove 1 was extended further upstream to merge with SPZ1 for Lovesgrove 3. The limited pumping test results indicate a hydraulic gradient parallel to Afon Rheidol and this was used to inform the shape of SPZ1. The SPZ1 for Lovesgrove 2 is 10-15% greater in area than the minimum calculation. The area was extended in the upstream direction along the Afon Rheidol to reflect the relationship between the boreholes and the river suggested by test pumping. Laterally the zone extends to the full extent of the aquifer.

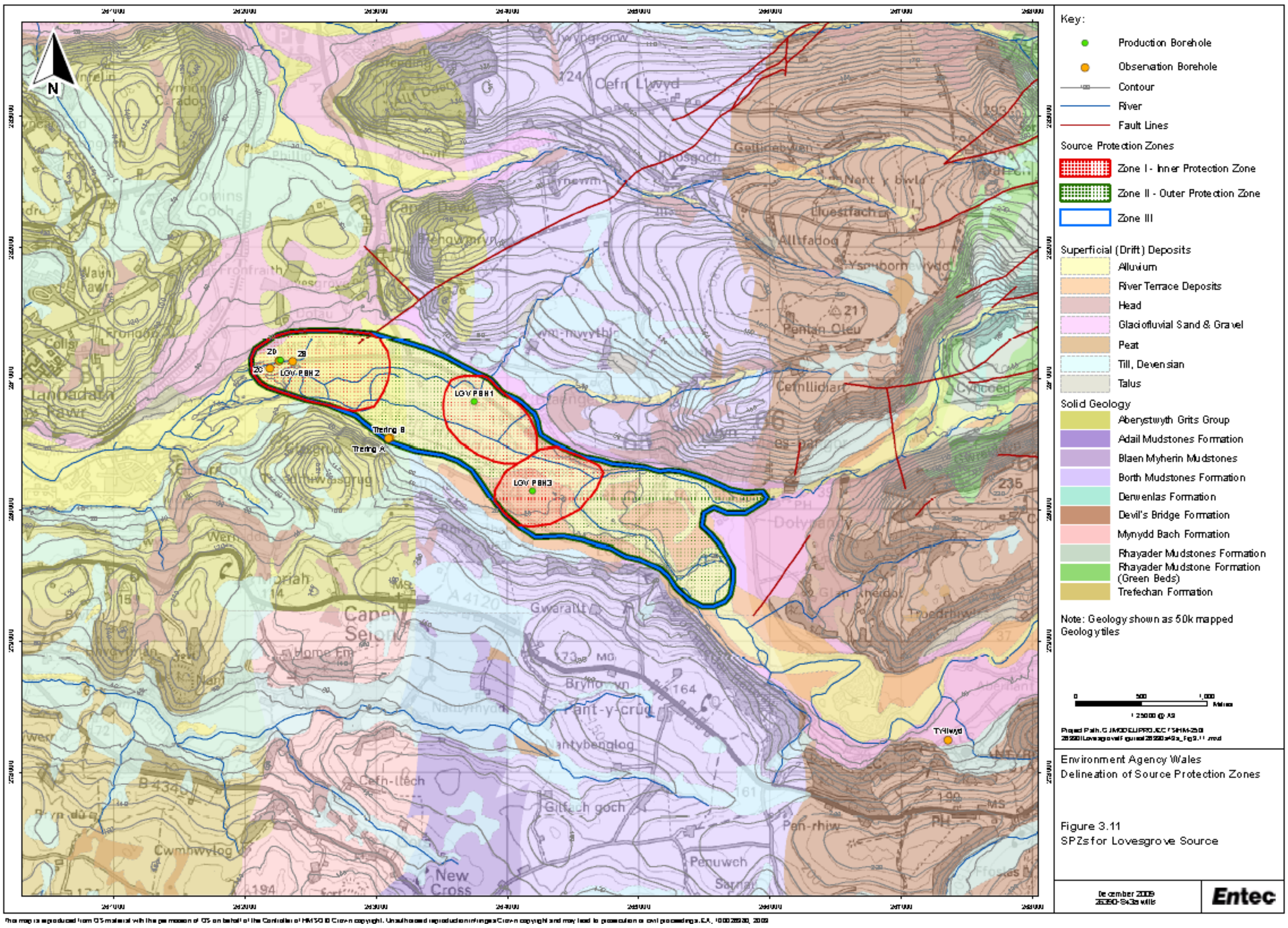
### *SPZ2 Delineation*

SPZ2 areas for Lovesgrove 1 and Lovesgrove 3 of 1.14 $km^2$ were calculated using a conservatively low (for a gravel) porosity value of 0.05. A larger SPZ2 area of 2.59 $km^2$ was calculated for Lovesgrove 2 due to the lower thickness of the aquifer around that borehole.

### *SPZ3 Delineation*

SPZ3 areas of 1.06 $km^2$ were calculated for each of the Lovesgrove 1, 2 and 3 to individually support the 1300 Ml/a abstractions with a recharge of 1230 mm/a. However, the SPZ2 area was larger than the SPZ3 area due to the low porosity. As a result, the outer SPZ2 boundary has been used for both. The resulting SPZ is shown on Figure 5.

## Figure 5 SPZ for Lovesgrove



# Case Study 5 SPZ Delineation in a Karst Catchment

## What does this case study demonstrate?

The approach to be taken for a source in which flow in karst features is important. The approach uses a combination of local knowledge, expert judgement and manual methods.

## Aquifer / EA Area:

Corallian Limestone Aquifer in the River Derwent catchment south of Scarborough

Yorkshire

## Justification for an SPZ / update of SPZ

The existing SPZs for the Scarborough abstractions were defined using a MODFLOW groundwater model of the eastern part of the Corallian aquifer. However, the majority of flow in the aquifer is through solution-enhanced fissures, and so using a numerical model that assumes uniform porosity is not appropriate for SPZ definition.

SPZs were derived for four licences making up the Scarborough abstractions group, which take groundwater from the Corallian Limestone Aquifer in the River Derwent catchment, south of Scarborough. Three of these abstractions are for public supply, while the fourth supplies a food-processing factory. The abstractions are the sole drinking water supply to Scarborough. The Corallian Limestone Aquifer has high groundwater velocities, which means that the risk of pollution to the drinking water supply is high.

## Assigning the Protected Yield

The protected yield was agreed with the licence holders (Yorkshire Water and factory owner). As a conservative assumption, and based on abstraction returns, the protected yield was set as the maximum daily and annual licensed quantity and applied to each abstraction borehole in turn.

## Conceptualisation of the aquifer

The conceptualisation of the abstractions and the aquifer used available data sources including: borehole construction details and borehole logs; groundwater levels; results of pumping tests; tracer test results; topographic and geological maps; source operational information (abstraction returns); rainfall and river gauging. This information was used to create a hydrogeological conceptual model for the source.

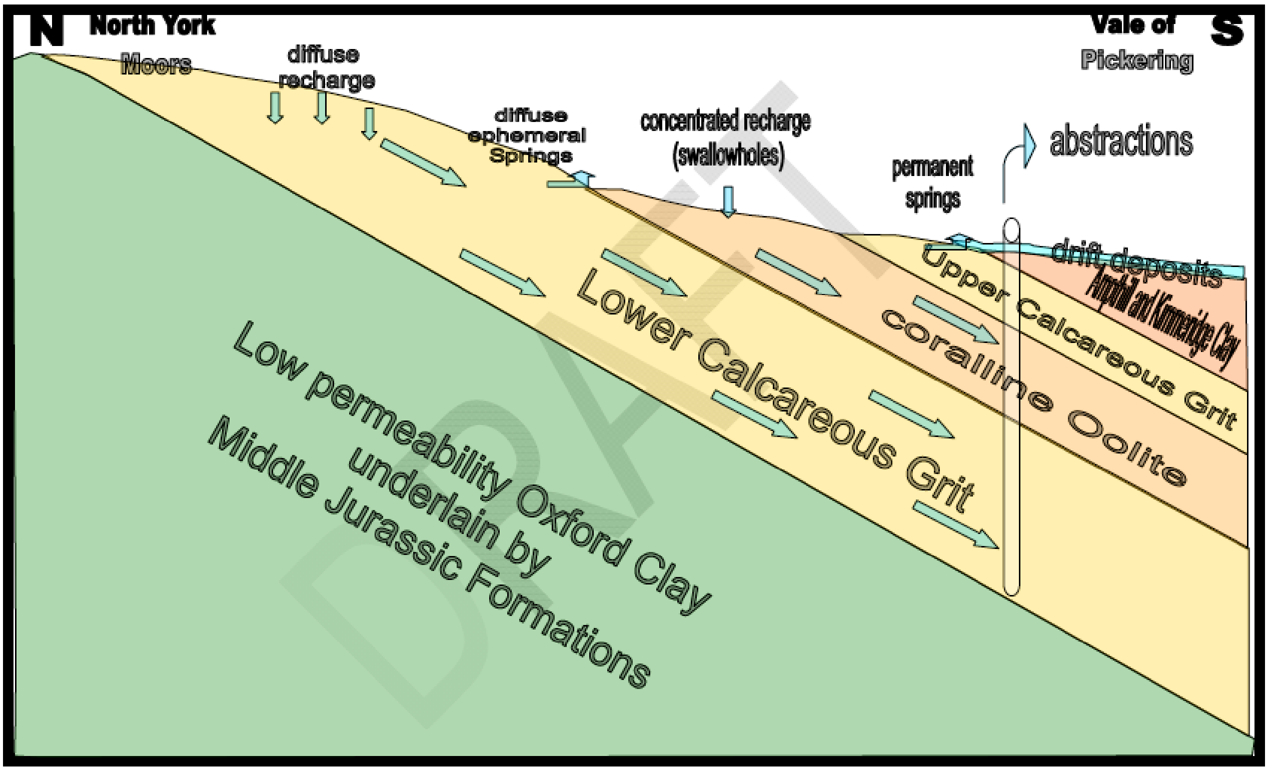
The Corallian Limestone is a fissured aquifer which outcrops in North Yorkshire between Sutton Bank in the west and Scarborough in the east. The aquifer is bound by two low permeability formations:

- Oxford Clay Formation which underlies the aquifer to the north; and
- Ampthill Clay and Kimmeridge Clay Formations which overlie it to the south.

The beds within the aquifer dip to the south. The land falls away to the south towards the Vale of Pickering. The Vale of Pickering is underlain by the Ampthill Clay and Kimmeridge Clay Formations, which are covered by low permeability till. This combination of low permeability strata means that the land is naturally heavy and water logged. The Corallian Limestone Aquifer outcrops mainly on the slopes of the Vale of Pickering and is characterised by naturally well drained land which is open to recharge.

Groundwater discharges naturally at a spring line along the interface with the confining Ampthill Clay and Kimmeridge Clay Formations (Figure 1). In the eastern part of the aquifer, north-west to south-east running faults divide the aquifer into blocks and encourage flow in a broadly north to south direction. These faults have also influenced the location of surface watercourses. Springs are also found at the base of north-south trending valleys. The position of these springs in the valleys change in response to the quantity of water in the aquifer. After periods of prolonged recharge, the spring line moves up the valley.

**Figure 1 Conceptual model of geology and hydrogeology**




The Corallian Limestone Aquifer is classified as a single aquifer but it can be divided into two principal rock types, oolite and calcareous grit. The oolites contain a higher proportion of calcium carbonate while the calcareous grits contain more sandy material. This means that the oolites are more prone to dissolution and the formation of rapid flow paths than the grits.

Karst features are present across the aquifer as caves and swallowholes. In places, particularly after periods of low rainfall, rivers can go dry, with all the river flow going to ground. The position of these karst features within the aquifer helps to understand how groundwater flows through it, and how and where surface and groundwater interaction occurs. The faults are generally orientated from north west to south east. Recharge to the aquifer is predominantly via the exposed Corallian on the hillsides to the north, either as direct recharge or as runoff onto the outcrop. Where rivers cross the aquifer upgradient, to the north and west of the abstractions, there is the potential for some river water leakage to the abstractions.

The north west to south east orientation of faults was considered likely to influence the shape of hydraulic capture zones.

A series of tracer tests were carried out at swallowholes to the northwest of the abstractions. The tracer test results have shown a rapid connection between the swallowholes and the abstraction boreholes. The Irton boreholes closest to the swallowholes (within 2 km) showed the shortest travel times, with first detections of tracer occurring within three hours. This demonstrates a direct and rapid hydrogeological connection between the swallowholes and the boreholes at Irton.

Tracer arrivals to the other boreholes further to the east were also rapid, although only small quantities of tracer were recovered. The tracer tests suggest that Irton derives a large proportion of its water from rivers implying that the river network up-gradient of the swallowholes needed to be included in SPZ1.

## SPZ delineation

Due to the karstic nature of the aquifer manual delineation was the preferred approach. Although there is a groundwater model for the aquifer, a numerical model approach was not used because the model treats groundwater flow in the aquifer as intergranular. The manual method was supported by local knowledge and expert judgement. The model outputs from previous SPZ modelling were used to inform the overall size of the SPZ and to help identify the likely width of the groundwater flow field towards the abstraction.

The delineation of SPZs considered the aquifer and its catchment for a series of conditions related to the structure of the aquifer and the nature of drainage. These were:

- The catchment of the River Derwent. The high proportion of river water at the abstraction at the Irton source meant that there are potentially fast pathways to Irton from the entire river catchment, including a large area to the north located on the underlying Ravenscar Group ;
- Southern boundary of main block. The aquifer here is confined by the Ampthill Clay and Kimmeridge Clay Formations. Only limited flow from the south was anticipated;
- Northern boundary of main block followed the outcrop of the Corallian Limestone.
- Western boundary of main block within the confined aquifer.
- Eastern boundary of main block within the confined aquifer.
- Hackness Hills block. This is an outlier of the Corallian Limestone to the northeast of Scarborough. It does not have a groundwater connection to the abstractions but has a potential surface water connection to the River Derwent, which runs along the western boundary of the block. As a result, the area was included in SPZ delineation. There is potential for rapid groundwater flow from the Corallian Limestone outcrop to the River Derwent across this block.

### SPZ1 Delineation

For SPZ 1 the primary consideration was the potential for rapid flow via surface water into sinkholes. The general approach was to apply default 50 m buffers around surface water features with connections to groundwater and also across outcrop limestone where sinkholes are potentially present. SPZ1 was also extended to include the flowpath from outcrop to the abstractions within the southern confined part of the aquifer as flow in this part of the aquifer was known to be rapid, but there was uncertainty regarding the properties of the overlying superficial deposits. The western and eastern boundaries were specified as flow lines that represented the limits of groundwater likely to flow towards the abstractions.

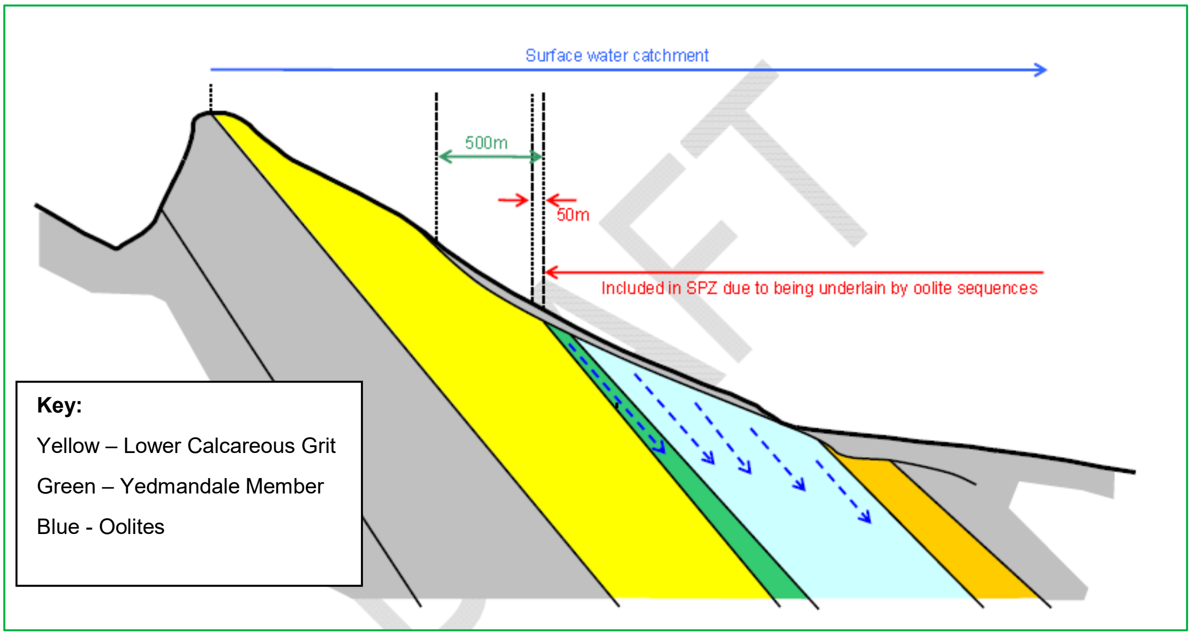
### SPZ2 Delineation

Due to the size of SPZ1 and the limited evidence for travel times, SPZ2 was not delineated for surface water features. In addition, applying a default 500m buffer to the surface water catchment would have included large areas of low permeability rock (Figure 2). SPZ2 was delineated for the more karstic oolite outcrop, which is also in SPZ1, and was extended, using a buffer of 500m, uphill from the northern boundary of the outcrop. SPZ2 was not delineated to the east and west in the confined aquifer as the SPZ1 was cutoff along flow lines and therefore no inflows from these boundaries was expected. Figure 2 demonstrates the use of the 50m and 500m buffers for SPZ1 and 2.

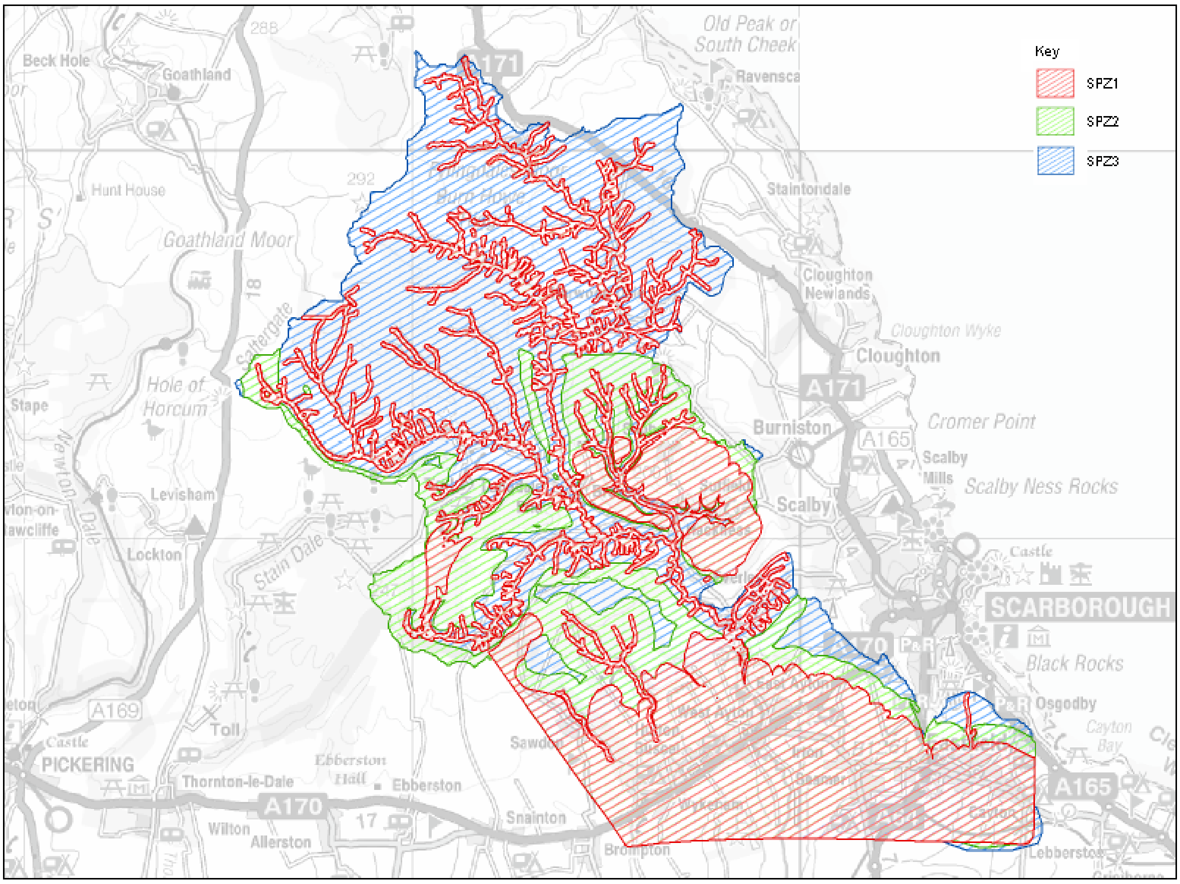
### SPZ3 Delineation

The SPZ3 was set as the surface water catchment in areas where rapid flow via surface water into sinkholes was the primary concern. It was extended beyond the surface water catchment in areas where the groundwater catchment (based on the outcropping limestone) went outside the surface water catchment. It was also extended upgradient of SPZ1 where flowlines were anticipated to continue upgradient.

## Figure 2 Schematic illustrating the use of buffer zones




## Figure 3 Combined SPZs



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