NRA NATIONAL CENTRES 5

ENVIRONMENT AGENCY

Groundwater Protection For Small Sources

Volume I - Review of Available Methodologies and Existing Practice

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Statement of Use
This three-part document reviews the methods which have been employed in the UK and elsewhere to define capture zones around groundwater sources, evaluates their applicability to the need to safeguard small sources as part of the NRA's groundwater protection policy and makes selective recommendations on which should be adopted as standard techniques for protection zone delineation. Its primary purposes are to provide a technical guide to the subject, and as a policy development initiative by the NRA Groundwater Centre.

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SUMMARY

The protection of the catchments of small groundwater sources, here defined as those abstracting 250m^3/d or less, presents a number of technical and practical problems which distinguish them from larger abstractions. This study reviews the techniques currently available to define protection zones around such sources, the methods which have been used in the past in the UK and those which are being employed elsewhere in Europe and North America (Volume I).

Detailed descriptions of the techniques are exemplified by application to a number of real situations in various groundwater settings in England and Wales. Seven standard techniques are recommended for adoption, whose selection will depend on the data available, the complexity of the hydrogeological environment around the source, the importance of the source in terms of public health and the resources available for zone definition.

Worked examples (Volume II) are provided to help the user employ the recommended techniques correctly, and a compendium of standard zones (Volume III) is included to enable one of the standard techniques to be employed in the conditions which are typically encountered in aquifers in England and Wales.

CONTENTS

Symbols and Notation

A_d	Area of t_d (days) travel zone (m^2)
A_R	Source recharge area (m^2)
b	Aquifer thickness (m)
h	groundwater elevation (m)
h_g	ground elevation (m)
k	Aquifer permeability (m/d)
L_s	Spring leakage factor (m^2/d)
n	Aquifer porosity
q	Abstraction rate (m^3/d)
q_s	Spring discharge (m^3/d)
r	Radial distance from well
r_d	Radial distance travelled in t_d days (m)
r_o	Radius of influence of a well
r_R	Radius of recharge area A_R (m)
r_w	Radius of well or borehole (m)
R_e	Rainfall recharge (mm/a)
T	Aquifer transmissivity (m^2/d)
t	Time (days)
t_d	Travel time (days)
t^*	Non-dimensional time
V_d	Aquifer volume dewatered in t_d days (m^3)
w	Non-dimensional coordinate
x	Coordinate parallel to hydraulic gradient
x_d	Distance travelled in t_d days (m)
x_L	Distance of null point from well (m)
y	Coordinate orthogonal to hydraulic gradient
y_{max}	Maximum half-width of steady-state capture zone
z	Non-dimensional coordinate
Δ	Hydraulic Gradient
π	3.142

1 INTRODUCTION

1.1 In 1992, the NRA published the national policy document entitled "Policy and Practice for the Protection of Groundwater[1]" (GPP). The purpose of this new policy was to consolidate and standardise the practices inherited from the former Water Authorities, having regard to the duties imposed on the NRA by the Water Resources Act, 1991, because the earlier practices, although relatively successful, were based on differences in approach and technical foundations.

1.2 The delineation of protection zones around groundwater sources (GPZ's) is a key element of the GPP. Overall, it has been estimated that there may be up to some 90,000 groundwater abstractions in use throughout England & Wales, although many of these are very small. The GPP's source protection principles apply to all sources, but priority in defining protection zones has been afforded to the major public supply sources To date, protection zones have been defined around approximately 800 sources, covering over half of the existing major potable groundwater supplies in England & Wales[2] and it is anticipated that GPZ's will have been determined for all the remaining potable sources which abstract more than 0.5 Ml/d, by 1997.

1.3 Groundwater source protection zones were first proposed in the UK in a 1948 Ministry of Health memorandum which stated[3] : "Where a well or borehole is on or near the outcrop of strata from which water is drawn, it should be the routine duty of the water undertaker's staff to make regular and frequent inspection of the area within 2 miles of the site with a view to detecting possible causes of pollution". This standard was widely adopted by the water supply industry at that time.

1.4 The first regional GPP to be established in England & Wales was proposed by the former Severn Trent Water Authority[4] in 1976 , closely followed by the adoption of such policies by Anglian Water Authority (1977), Southern Water Authority (1978), and Yorkshire Water Authority (1982). Where protection zones were proposed in these policies, they were defined, in general, on pragmatic rather than on entirely scientific grounds, reflecting :

- the lack of knowledge about the (often) complex hydrogeological controls;
- the need to define zones which were neither conservative nor unreasonably restrictive, but would indicate to the Planning and Waste Disposal Authorities and potential developers, areas in which proposed activities likely to cause pollution would not be acceptable;
- the lack of readily available methods and resources for delineating source protection zones.

1.5 In 1985, Southern Water Authority reviewed its Aquifer Protection policy, and that revision[5] introduced the concepts of protection zones based on 50 day travel times. The 50-day zones were derived assuming abstraction took place from a source in an aquifer with a uniform hydraulic gradient[6]. However, hydrogeological uncertainty in respect of regional hydraulic gradients, permeability and aquifer thickness was recognized, and the resulting policy proposed "standard shape zones" derived from the computed zones but only dependent upon the nature of the aquifer and the abstraction rate although pragmatic extensions to the standard zones were proposed for springs and adits. Zones were defined around each of the Southern Water sources, and 1:50000 scale maps showing these zones, although primarily for internal use, were issued to all the Planning Authorities within the region.

1.6 Groundwater protection in Europe in the past has focused on the compilation of aquifer vulnerability maps, and the consequent recognition of the need to restrict many activities in areas in which there is a high risk of groundwater pollution. Many countries have now published aquifer vulnerability maps[41] (eg France, Spain, Belgium, Cyprus etc). In contrast, full coverage of England & Wales is not expected until 1997.

1.7 In addition, protection zones around public water supply sources have been enforced in Europe for many years[20], and they are often based on estimated time of travel to the well : typically the protection zones represent some 50 days travel time.

1.8 In 1987, the United States Environmental Protection Agency (EPA) published a review[7] of the methodologies in use, throughout Europe and the US, for delineating groundwater protection zones (wellhead protection areas or WHPA's in US terminology) and also recommendations for use. The methods examined ranged from simple "circular" zone definitions, based on abstraction rate and recharge, through semi- analytical methods based on travel time theory, including that adopted by Southern Water Authority) to the more complex numerical methods based on the computer codes available in the public domain at that time (e.g MODFLOW developed by the US Geological Survey).

1.9 In 1990 BGS[8] were commissioned by the NRA to advise on the proposed national groundwater protection policy, and as part of the associated studies compared a number of analytical[9] models and the readily available numerical[10] methods for computing groundwater capture zones. The latter study concluded that the best code available at that time for zone delineation was FLOWPATH, the 2-D steady - state horizontal aquifer simulation model from Waterloo Hydrogeologic Software[11].

1.10 To date, FLOWPATH has been used to delineate protection zones around some 70% of all the public water supply sources investigated by the NRA[2]. A second model, WHPA[12], a semi - analytical model for delineating wellhead protection areas developed by the US EPA, which was not available when BGS were comparing codes, has been used successfully on the majority of the remaining modelled sources.

1.11 While priority has been afforded by the NRA to GPZ delineation around the major public supply sources, (principally those abstracting at rates greater than 1 Ml/d), there is an emerging need to have available a consistent, technically valid methodology which is suitable for defining such zones around the smaller sources, particularly those in the Southwestern, Welsh and Northwest regions.

1.12 This report contains the results of an investigation into the suitability of the various currently available GPZ methodologies for defining zones around small sources, which for the purposes of the contract are taken as those abstracting less than 3 l/s (0.25 Ml/d). The technical brief from the NRA for this contract (NRA Contract Reference 124987) is given as Appendix 1 (in Volume 11).

1.13 The core activities of the contract are :

- A review & assessment of existing GPZ practice within the NRA
- A literature review to determine current international GPZ practices
- Comparisons & suitability assessments of the alternative methodologies which are now available.
- Recommendations of techniques to produce best available methodology

They are considered in the following sections of this report

2 REVIEW OF NRA REQUIREMENTS & EXISTING PRACTICE

Consultation with NRA Staff

2.1 In the Project brief, full consultation with those NRA staff involved with the day to day implementation of the Groundwater Protection Policy was proposed. This was in order to obtain details of current GPZ experiences and to provide the opportunity to discuss the regional requirements for the proposed methodology, in the context of a nationally consistent procedure which would be:

- technically valid
- robust when applied to both poorly- and well- documented applications
- simple and rapid to use.

2.2 Southern Science Ltd (SSL) addressed the needs for wide consultation by proposing regional meetings with key Hydrogeological staff, preceded by a questionnaire which would be distributed to a wider forum.

2.2 In the event, three meetings, at the Leeds, Reading and Solihull offices of the NRA were held on : 8, 9 and 11 December 1994 while the questionnaire (Appendix 2) was distributed to the hydrogeological staff within each area office. The objective of the questionnaire was to obtain details of current practice within each area office in respect of protection zone delineation, and to seek test data and/or case study data for the more problematic or complex hydrogeological situations which the proposed methodology would seek to address. The list of staff to whom the questionnaire was addressed, together with the names of delegates to the meetings, and notes of each meeting are given in Appendix 3.

2.3 In all, some 30 questionnaires were sent out, and collective responses from each NRA regional office were received back, together with detailed information on many case studies. The returned questionnaires, and case study data are assembled, by region, in Appendix 2 (in Volume II)

2.4 The questionnaire sought to obtain data on the numbers and national distribution (in terms of aquifer and flow mechanism) of small sources, which for this study are defined as those abstracting less than 3 l/s (250 m^3/d), (cf. Technical Brief - Appendix 1, Volume II). The individual responses to this question, as received, are collated in Table 2.1.

2.5 The data are clearly imprecise, but nevertheless suggest that there are upwards of some 76000 small sources, many of which, particularly in the Northwest and Southwest regions, are located on aquifers which are non - darcian in character.

2.6 Classical groundwater flow theory assumes that aquifers respond as porous granular media (darcian aquifers), and does not describe flows in aquifers that are karstic or more generally, non-darcian in character. This has an impact on the methods which may be used to delineate capture zones around sources located in such aquifers. The analytical and numerical methods of capture zone delineation currently available are described in Section 3.

Review of Current GPZ delineation practices within the NRA

2.7 The questionnaires show a number of methods and practices are currently used by NRA regional offices, to delineate capture zones around groundwater sources.

North West

2.8 Current practice : Protection zones have only been delineated around the priority sources included in the first phase of the national GPP programme. Historically, each public water supply source has been examined as the need arose. The important pws sources are in the darcian aquifers

Northumbria

2.9 Historically protection zones defined around the major pws sources. It is now proposed to delineate protection zones around the minor pws, non-public sources such as those serving hospitals and private estates and the critical commercial supplies like spring/mineral water abstractions and breweries. Note that the Northumbrian Water Act (1981) frees NRA of the requirement to license sources < 1 Mga, and the need to maintain a register of such abstractions Thus the numbers and locations of the many small sources are unknown.

Yorkshire

2.10 Current practice is to delineate zones around the major pws sources (usually > 1Ml/d). However, a general planning response, in the Dales area, is to require soakaways and septic tanks to be located at least 50 m downgradient of any spring/borehole used for public supply. In the Southern area, with many small sources located on the Carboniferous rocks, the 50 m fixed radius circular zone recommended by MAFF, is imposed.

Welsh

2.11 Currently little data are available. A proposed contract seeks to assemble source data to enable GPZ's to be determined for the strategically important groundwater sources.

Severn Trent

2.12 Historically, the Severn Trent Water Authority Aquifer Protection Policy established 1 km fixed radius circular protection zones around public supplies and currently these zones are being reassessed as part of the national GPZ programme. The risks to sources other than major pws sources have been traditionally assessed on a case by case basis.

Anglian

2.13 Historically protection zones were established around the major pws boreholes, which are now being reassessed as part of the national GPZ programme. Current practice for protecting small domestic sources (Figure 2.1), involves delineating 50 m and 250 m fixed radius circular zones around them.

Southern

2.14 Historically, zones based on 50 days travel were established around the pws sources which are in major aquifers. These are now being reassessed as part of the national GPZ programme. Restrictions are placed on the siting of soakaways and septic tanks close to pws sources using an algorithm, based on distance, depth to water table etc, devised originally as part of the SWA Aquifer Protection Policy[5]

Thames

2.15 Historically Thames Water Authority[30] established capture zones based on 400 day travel times around the pws sources. Although the zones were initially derived from analytical solutions, they were modified manually to have regard to local features , e.g rivers, drift etc. Currently, zones around the pws sources, which are in the major aquifers are now being reassessed using semi-analytical and numerical models (WHPA, FLOWPATH and MODFLOW).

Southwestern

2.16 Protection zones around the pws sources in the major aquifers have been delineated as part of the national GPZ programme. Source protection areas (consultation areas) have been delineated around all pws in former Wessex Region in advance of detailed GPZ definition. Ad hoc methods have been used to define zones around small sources (cf 3.32)

Summary

2.17 In summary, groundwater protection zones are currently being established around the important pws sources, which tend to be in the major (darcian) aquifers. In general, small source protection is carried out on a case by case basis as the need arises. The 50 m circular zone around sources recommended by MAFF is imposed frequently, but its true value in providing protection in karstic aquifers for example, where flow paths may be unknown and travel times very fast, is unclear except in so far as it establishes sound hygienic practices around the site. In this respect, the 50 m arbitrary zone is analogous to the well head patio/courtyard area of a larger source

Figure 2.1 **NRA Anglian : Existing Small Source Protection Methodology**
(Reproduced from Regional Guidance Notes)

DERIVATION OF SOURCE PROTECTION ZONES FOR PRIVATE SOURCES - REGIONAL GUIDANCE

- Any private potable supply is entitled to protection; however, Source Protection Zones for private and industrial sources should only be defined where a dispute arises over a proposed development and the definition of a zone would aid in discussion.

- In cases of small private sources protection zones should be derived by manual calculation based on the average daily licensed abstraction, and set as follows:

  Zone I - radius of at least 50m

  Zone II - area equivalent to at least 25% of Zone III

  Zone III - area and radius defined by

  $$\text{area} = Q/R \qquad \text{radius} = (\text{area}/\pi)^{1/2}$$

  The minimum radius for Zone III should be 250m.

  Zones should be circular with the source at the centre, unless there is evidence to suggest otherwise. 1

- For unlicensed sources (less than $20m^3/d$), source protection zones should be set as follows:

  Zone I - 50m radius
  Zone II - 125m radius (25% area of Zone III)
  Zone III - 250m radius

  A circular zone of 250m radius will thus be set around all small domestic sources.

- In the case of spring sources, calculation of zones should be based on the spring discharge rather than the licensed abstraction. As springs are obviously directional, a semi-circular zone perpendicular to the direction of flow can be set rather than a circular zone. In this case, the minimum zone radius should be 350m to cover an area equivalent to that of a 250m circular zone. Spring sources cannot be easily modelled by Flowpath so a manual calculation is recommended.

Notes

1. For example, in "Karstic" situations development control should be on a case (or site) by case basis, taking into account max/mass permeability and structural controls (i.e. known factors)

Consultation Meetings

2.18 In all some 24 NRA staff, representing all regions, attended the three meetings. Notes were taken at these meetings by SSL staff, and the key points of the discussion recorded. These notes are reproduced in Appendix 3 (Volume II).

2.19 It is not proposed to discuss all the issues which were raised at these meetings, which may be found in the minutes, but among the main points arising were :

- the difficulty of defining protection zones in areas with little or no relevant data, or in the minor aquifers which are non -darcian in character,

- there was broad agreement for a reactive rather than proactive response to the designation of protection zones

- protection zone *versus* consultation zone - there was widespread agreement for designating large areas of aquifer as "Consultation zones" rather than trying to delineate very small protection zones - particularly so in the non-darcian environments. However no clear consensus emerged on what should constitute a consultation zone, and it is clear that further discussion is needed at a national scale to agree on its possible role in groundwater protection.

- protection zones should be based on scientific, rather than pragmatic factors where possible to ensure robustness in the public domain. The necessity to refine existing zones should additional data be obtained; possibly by applicant developers, was also accepted.

Literature Review

2.20 Literature searches, using the British Library Science Reference & Information Service (SRIS) facilities, through the Aqualine, Georef, Geobase and Water Resources Abstracts databases have been carried out for this study on key words associated with "Groundwater Protection". In addition, Conference Proceedings and Journal catalogues have also been searched for relevant articles. Appendix 5 lists the abstracts obtained through this process. Of necessity, the lists are edited - the original search through the databases for example, supplied over 300 titles. Those in the lists, therefore, have been selected for inclusion on the basis of the apparent relevance of their title only. It should be noted that one of the key articles in capture zone hydraulics[6] : "On the movement of water bodies injected into aquifers" ,would not have been identified by this process.

Overseas Consultations

2.21 The list of overseas organisations initially contacted for information on the application of groundwater protection policies in their respective countries is given in Appendix 4. To date, contact has been established with the following Institutions and personnel:

- US Environmental Protection Agency
- D Segar, Norwegian Geological Survey
- J Stockmarr, Danish Geological Survey.
- Dr A Dassargues, University of Liege : Faculty of Applied Science, Belgium
- Dr J Risler, European Commission, Brussels
- Dr E Simmelink, Rijks Geologische Dienst, Holland

2.22 Overall, the response to date has been disappointing, although we are continuing to pursue outstanding leads and follow up contacts as they become established. Developments in Norway and Denmark, on which we have received information, are outlined below.

2.23 Recent developments in Norway have focused on the use of numerical methods to delineate protection zones around public supplies. The only organisation working in this field at present is the Norwegian Geological Survey (NGU). In the most recent study[35] carried out, MODFLOW & MODPATH were used to delineate the capture zones around the public supply sources in Lillehammer, which draw their water from Quaternary deposits of mixed glacial and fluvio-glacial origin. Three protection zones were subsequently designated : Zone 1, based on 60 day travel time, a value recommended by the Norwegian State Institute for Public Health, Zone 2, representing the recharge area of the sources, and Zone 3 representing the surface water catchment area. No information on the historic methods of zone delineation in Norway have been obtained.

2.24 Water supply in Denmark is almost entirely based on groundwater. The aquifers consist primarily of glacial sand and gravel, Tertiary sand and limestone (i.e Chalk). There are some 400 municipal waterworks, over 3000 small private waterworks and approximately 140,000 private sources in rural areas. Groundwater management and protection policies date back to legislation passed in 1926, (Danish Water Supply Act), which established two protection zones : A narrow circular zone of 10 m radius surrounded by a fence to protect against hazardous waste, and a wide. circular zone of 300 m radius to protect the well from infiltrating wastewaters. In recent years additional national guidelines and recommendations for siting waste disposal sites and other point pollution sources, uses of fertiliser, handling of hazardous waste etc have been drawn up to meet current environmental standards. Numerical methods of protection zone delineation are to be examined as part of the recently established "Danish Environmental Research Programme"

Table 2.1 Regional Distribution of Small Sources : q < 3 l/s (250 m³/d)

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
Anglian	Central	Lower Greensand Chalk & Drift	d	1212	1500 - 2500
		Jurassic Limestone	k		
	Eastern	Crag, Sand gravels & Chalk	d	Essex: 450 Suffolk: 2500 Norfolk: 5000	
	Northern	Chalk, Sand & Gravel	d	> 100	
		Jurassic Limestone	k		

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
Severn Trent		Drift Triassic Sst Carboniferous Sst	d	100 954 587	NR
		Carboniferous Lst Jurassic Limestone	k	10 13	

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
NorthWest		Millstone Grit Coal Measures	ndnk	15000 - 20000 estimate from EHO survey	
		Glacial deposits	d		
		Yoredale sequence	nd		
		Carboniferous Lst Jurassic Limestone	k		

Table 2.1(Continued)

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
Thames		Gravel Chalk Lower Greensand	d	250	NR
		Great & Inferior Oolite	k		

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
Southern		Chalk Folkestone Beds Hythe Beds Tonbridge Wells Sands Ashdown Beds Ferruginous Sands River Gravels	d	>320 1100	NR 1250

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
Welsh		Drift Triassic Sandstone	d	3500	10000 - 15000
		Old Red Sandstone	nd		
		Jurassic Limestone Coal Measures Millstone Grit Silarian Limestone Igneous & Metamorphic	ndnk		
		Carboniferous Limestone	k		

Table 2.1 (Continued)

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
Northumbria & Yorkshire	Northumbria	NR		90	NR
	Dales	Sherwood Sst	d	1390	NR
		Millstone Grit	ndnk		
		Carboniferous Lst Magnesium Lst Corallian Lst Jurassic Lst	k		
	Southern Yorkshire	Chalk Sherwood SSt	d	602 boreholes 216 springs	NR
		Coal Measures Millstone Grit Carboniferous Lst	ndnk		
		Magnesian Limestone	nd		

NRA Region	Area	Aquifer Name	Flow Classification	No of small sources	
				Licensed	Unlicensed
South western		Permo-Triassic Sst Chalk	d	8000	20000 - 30000
		Carboniferous Lst Great & Inferior Oolite	k		
		Fissured Palaeozoics	ndnk		

Abbreviations used in Table :

d	darcian flow
k	karstic flow
nd	non-darcian flow
ndnk	non-darcian & non-karstic

3 REVIEW OF CAPTURE ZONE DELINEATION METHODOLOGIES

GPZ Delineation Criteria

3.1 Following the enactment of legislation (Safe Drinking Water Act) in the United States in 1986 proposing a nationwide programme to protect groundwater resources (which supply some 75% of public water supplies nationally and over 90% in rural areas), State Wellhead Protection Programmes were established for the purposes of "protecting wellhead areas within their jurisdiction from contaminants which may have an adverse effect on the health of persons". One of the major elements of this national programme is the determination of *Wellhead Protection Areas* (WHPA's). Since the establishment of the Federal programme, the United States Environmental Protection Agency (EPA) [13,14,15] and many States[16] have published guidelines to increase public awareness of the importance of groundwater, the needs to protect and conserve resources and methods of groundwater protection.

3.2 In 1987, the EPA[7a], which is responsible for the programme, published "Guidelines for Delineation of Wellhead Protection Areas". This report, which has recently been republished[7b], contains a review of international practice in the field of groundwater protection and describes the methods available for defining protection areas around groundwater sources. This document contains perhaps the most comprehensive review of the available methods, but they are principally for use on aquifers to which classical (darcian) groundwater theory applies (porous granular aquifers). More recently, however, the EPA[17] and others[18] have published the results of comparisons of available methods for delineating protection areas around wells in fractured rocks. This work however is not finalised, for the investigation of flow in fractured aquifers is a relatively new field of study.

3.3 The EPA identified 5 criteria which may be used to establish protection areas around groundwater sources :-

- Distance
- Drawdown
- Time of travel
- Flow boundaries
- Assimilative capacity of the aquifer

3.4 The extent to which protection areas could be delineated using these criteria clearly depends upon many factors including : the implementation time and associated costs, the availability of hydrogeological data and the availability of expert staff to interpret the data, the geological complexity of the site etc. In this section, the use of these factors as a basis on which to define protection areas is reviewed and the advantages and disadvantages outlined.

Distance

3.5 The use of a "distance" criterion is usually regarded as a first step in defining protection areas, and it has been used where there is a need to establish such areas rapidly and at minimal cost, for instance as part of a regional programme, or in the complete absence of data at a specific site or where there is a need to establish good practice around small sources. However, zones based on arbitrary distances clearly do not have regard to the local environment or aquifer hydraulics and cannot be technically defended, or indeed recommended.

3.6 Examples of the use of arbitrary "distance" or "radii" around the source as a zone delineation criterion include :

- Ministry of Health[3] : 2 Mile
- Severn Trent Water Authority[4a,b] : 1 km
- Ministry of Agriculture, Fisheries and Food[19] : 50 m
- United States Environmental Protection Agency [14] : 0.5 - 1 mile
- Anon[16] : 1750 ft (Rhode Island),
- Anon[16] : 1000 ft (Arkansas),
- Anon[16] : 100 ft (Vermont)

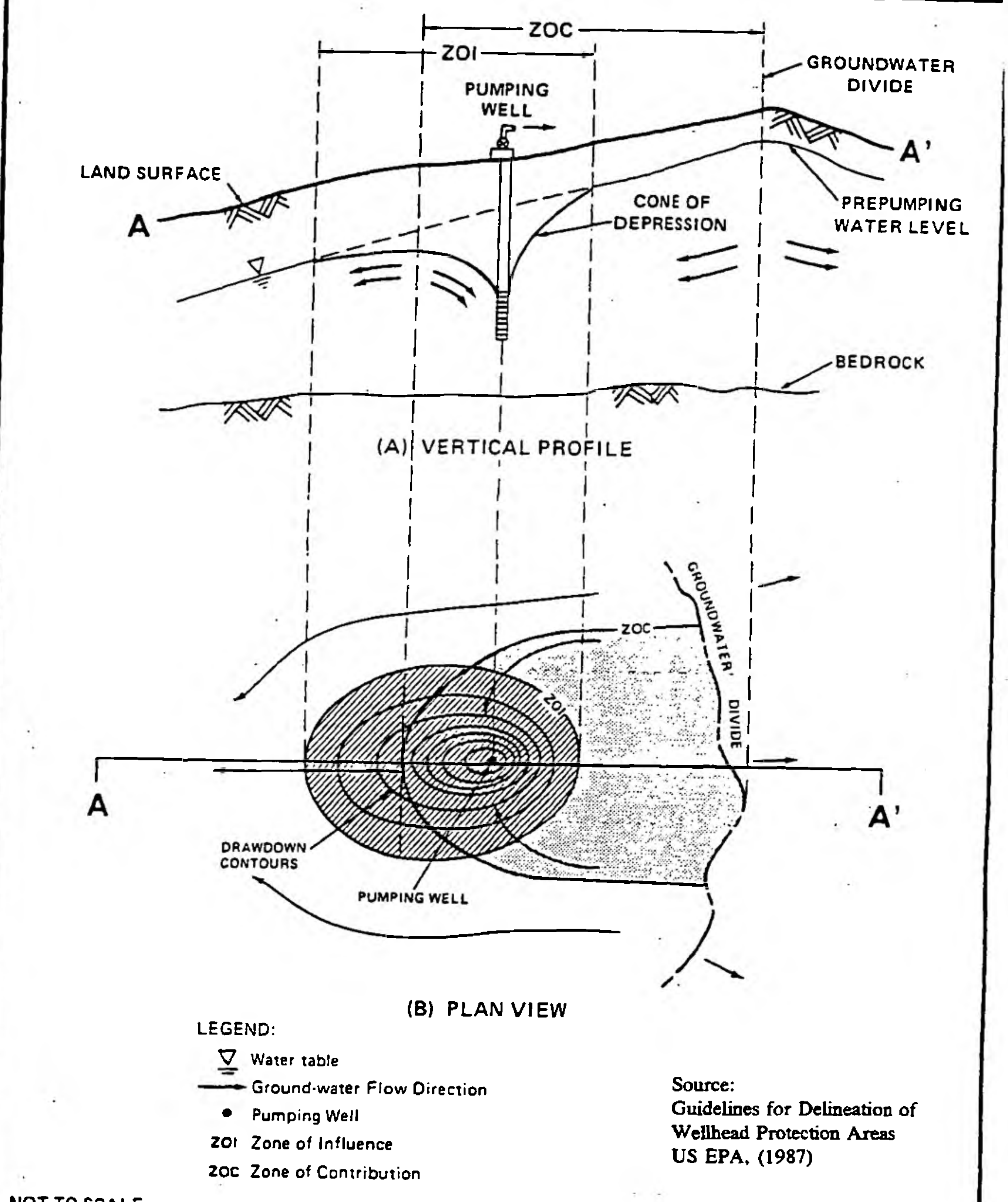
Drawdown

3.7 The use of "drawdown" around a source as a guide to the extent of a protection area would not appear to have been used within the UK, although such measures have been adopted in the past in the US[7]. The determination of drawdown requires either observations from a pumping test or estimates of the local aquifer parameters. The extent of the cone of drawdown is then calculated from the Theis equation or the Jacob equation and the approximate value of r_o, the radius of the cone of depression, (or radius of influence) used to define the zone boundary. The principal limitation of the method is that if abstraction takes place from an aquifer with a sloping hydraulic gradient, then the cone of depression and the capture zone will not be coincident, and errors in delineating the required protection area will arise. Figure 3.1 illustrates this point.

Time of Travel

3.8 "Time of Travel" criteria are now used extensively throughout the US and Europe when defining groundwater protection areas[1,4a,20,21] although the time used varies significantly : 50 and 400 days in England & Wales[1]; 60 days in the Netherlands[22], Norway[35] and Belgium[22]; 50 days in Germany and Austria[22] and 10 days in Switzerland[24].

Figure 3.1 Borehole Capture Zones



Source:
Guidelines for Delineation of Wellhead Protection Areas
US EPA, (1987)

3.9 In 1982 BGS[25] evaluated reported case histories of groundwater contamination by pathogens. The authors of the study concluded that the passage time between the borehole or spring and the proven source of pollution was equivalent to no more than the distance travelled by groundwater in 20 days, despite the fact that pathogens can survive in such environments for up to 400 days and viruses potentially for even longer. The value of 50 days, which conformed to existing practice in many countries, was therefore considered to be a *reasonable basis* on which to define protection zones.

Flow Boundaries

3.10 The use of "Flow boundaries" to define protection areas recognises the importance of such features in controlling the flow to the source. Examples of such features include : geological boundaries, groundwater divides, rivers , canals (?) and lakes etc., lithological (facies) changes too are also important. Flow boundaries are particularly important for defining protection areas in small aquifer systems where the travel time to the boundary may be relatively small.

Assimilative capacity of the aquifer

3.11 The "assimilative capacity" criterion applies the concept of using the ability of the saturated and/or unsaturated zones of the aquifer to attenuate the concentrations of the contaminants to acceptable levels before they reach the source. However the physical and chemical processes which affect the rates of attenuation of specific contaminants within aquifers are different and little understood, although much work has been carried out in Europe on the fate of nitrates[26] for example. Some contaminants, for example chloride, are conservative, whilst others are readily adsorbed within the rock matrix. Overall, the EPA[7] concluded that the attenuation mechanisms were too complex, and contaminant specific to assist in delineating protection zones against the "universal contaminant".

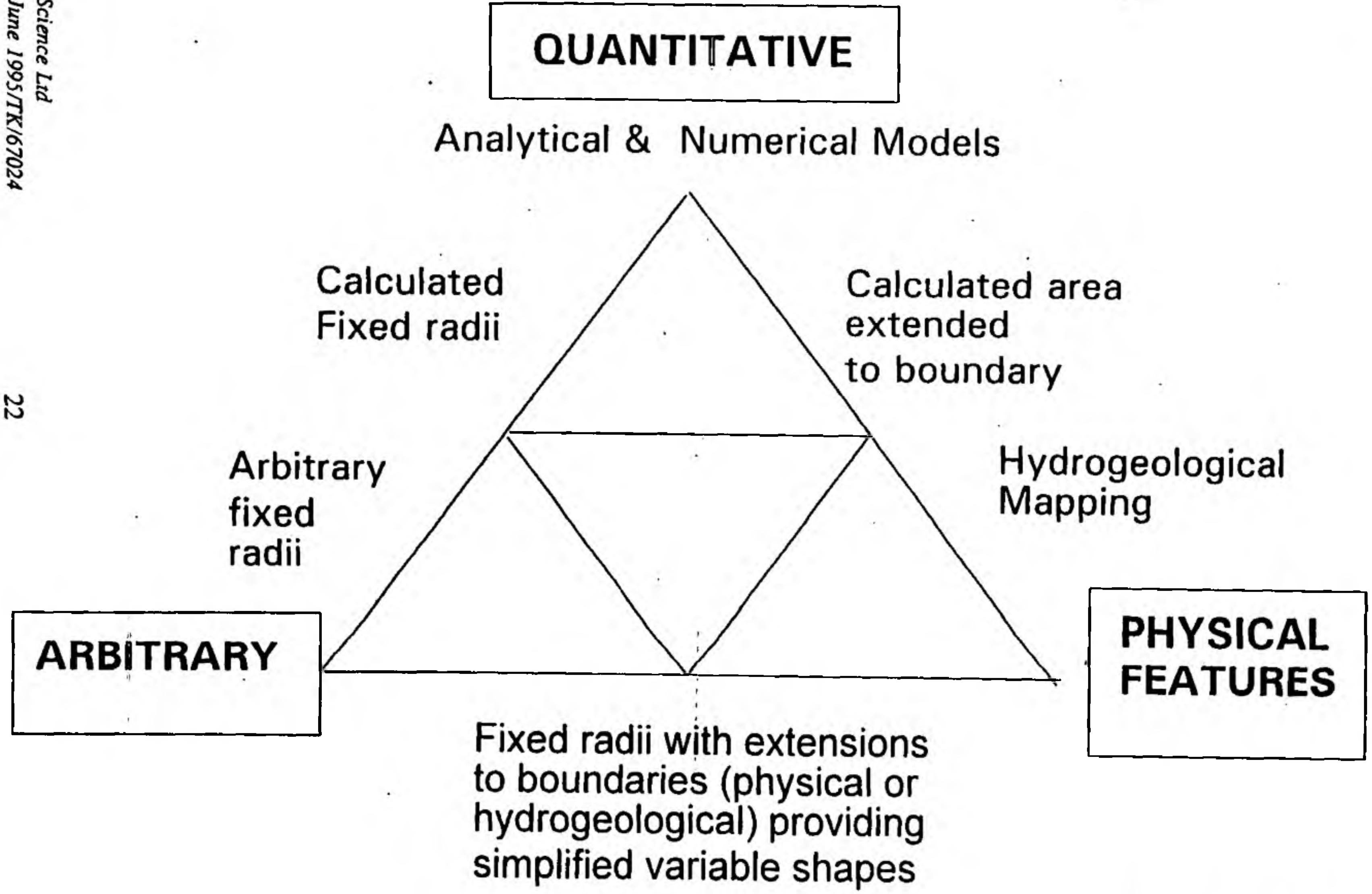
Methods of Delineating Protection Areas

3.12 The EPA[7] classify the methods for delineating Well Head Protection Areas, in increasing order of technical sophistication, as follows:

- Arbitrary fixed radii
- Calculated fixed radii
- Simplified variable shapes
- Analytical methods
- Hydrogeological mapping
- Numerical flow/transport modelling

3.13 Figure 3.2 shows the interrelationships between these methods which are described in detail below. The derivation of "protection zones" based on simplified variable shapes and/or computational methods has hitherto been based on the assumption that flow within the aquifer could be described by classical (darcian) groundwater theory. The application of such methods to aquifers which are distinctly non-darcian in character is clearly inappropriate. However, the characterisation and subsequent numerical modelling of flow systems in such aquifers is a relatively new field of study[17,18] and is "aquifer" dependent. Thus, the possibility of delineating borehole capture zones in many non-darcian aquifers is remote, (cf 3.48 below)

Figure 3.2



After US EPA (1987)

Fixed Radii Methods

3.14 The simplest form of protection zone is a circle of arbitrary radius centred on the well or borehole. Such zones may have value as "consultation zones for planning purposes" i.e. by requiring referral of possible developments within the zones from the appropriate Planning Authorities. However, without regard to the local geological or hydrogeological conditions such zones, unless they are very small, (for example: when protecting the immediate vicinity of the source) are unlikely to be technically defensible in public and therefore cannot be recommended (cf. 3.5 above).

3.15 As an example, an "Inner Protection Zone" (or Zone 1) of 10 m radius immediately around each public water supply source is enforced in Germany[21] within which pedestrians, vehicles and agricultural practices, for example, are prohibited, but the basic protection zone surrounding the source (Zone 2) is based on a 50 day travel time (cf 3.8 above)

3.16 If a fixed radius circular zone around a source in an unconfined aquifer is required, then one may be estimated based on the rate of abstraction and the local aquifer recharge. Let q denote the daily quantity being abstracted, and R_e the daily rainfall recharge, then an area A_R given by :

$$A_R = \frac{q}{R_e} \qquad (3.1)$$

is required to support the abstraction, and the radius r_R of the circular "protection zone" of area A_R is defined as $r_R = \sqrt{(A_R/\pi)}$, where $\pi = 3.142$. Note that equation (3.1) is independent of the aquifer characteristics.

3.17 Figure 3.3a shows the relationship between r_R and q for values of recharge R_e representative of conditions[27] across England & Wales, while Figure 3.3b shows the relationship between r_R and R_e for $q = 250$ m^3/d. Thus, for example, an abstraction of 250 m^3/d in the dryer parts of the country requires the recharge over a circular region with a radius in excess of 500 m to support it. Similarly, recharge over the 50m zone proposed by MAFF[19], even in the wetter areas would only support an abstraction less than 10 m^3/d

3.18 While protection zones based on the "recharge area" radius are likely to be more defensible than those derived using an "arbitrary" radius, in that they provide a unique but universally reproducible circular area, the resulting zones exhibit little relationship in terms of shape to those defined on the basis of (darcian) groundwater theory, and therefore, are likely to be in error. In the following sections, the principles of capture zone delineation in "darcian" aquifers are summarized, followed by a description of the methods which are available.

Figure 3.3a

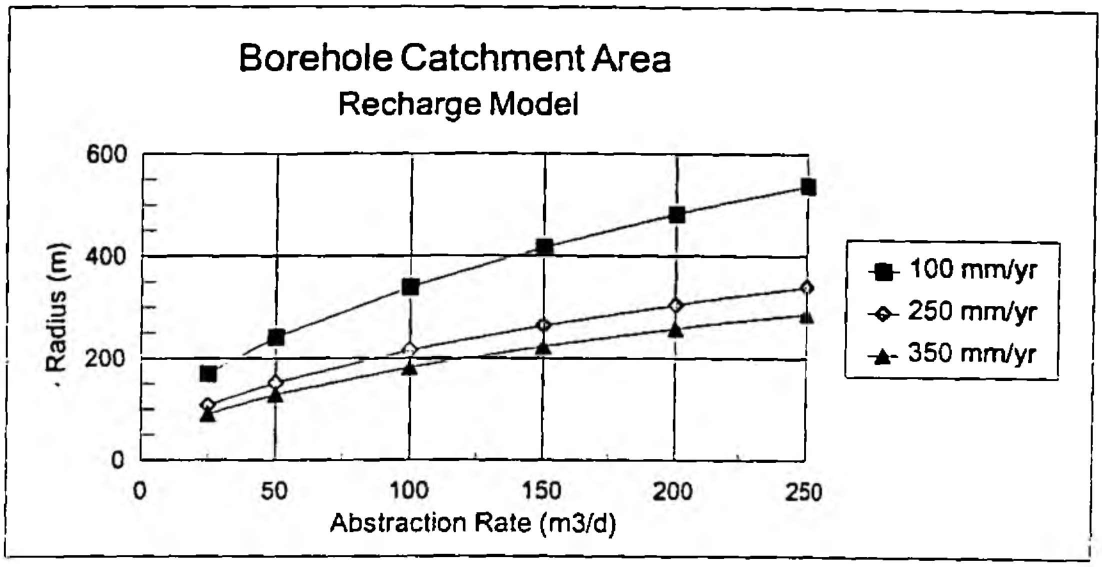
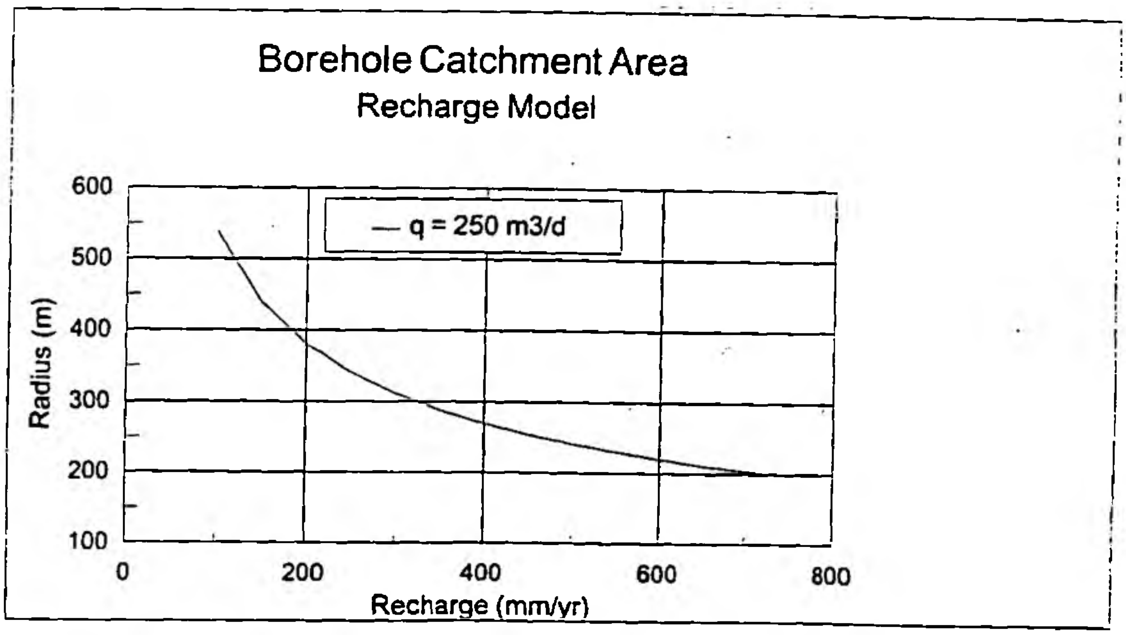


Figure 3.3b



Review of Capture Zone Hydraulics

3.19 Assuming a constant (steady state) abstraction q from a fully penetrating borehole in a homogeneous aquifer of constant thickness and infinite extent, the time t_d for water to flow radially (horizontally) from any point r_d in the flow field to the borehole in the absence of a hydraulic gradient (assuming that $r_d >> r_w$, the radius of the well) is given by[28,29]

$$t_d = \frac{\pi n b r_d^2}{q} \qquad (3.2)$$

where b represents the thickness of the aquifer and n is the effective porosity. (Note that the symbols and notation used in the text are defined on page 3).

3.20 Figure 3.4a illustrates the aquifer geometry while Figure 3.4b shows the relationship between t_d and r_d for an abstraction of 250 m^3/d from an aquifer 100 m thick with effective porosities of 1% and 10%. Taking the effective porosity as 1%, then the radius of the 400 day capture zone would be 178 m, Conversely, the travel time from a point 50 m distant from the borehole would be 31 days

3.21 More generally, assuming a constant (steady state) abstraction from a borehole in an aquifer of infinite areal extent, finite thickness and with a uniform hydraulic gradient, theory[28] shows the occurrence of a bounding streamline (flowline) in the flowfield within which flow is towards the borehole. The equation of the bounding flowline or "capture " zone is :

$$\frac{y}{x} + \tan\frac{2\pi K \Delta b y}{q} = 0 \qquad (3.3)$$

where the origin of the coordinate system is taken as the well, with x positive in the up-gradient direction, and the y- axis is orthogonal to the x-axis (see Figure 3.5). K is the aquifer permeability and Δ is the hydraulic gradient.

3.22 There is a null (zero velocity) point, distance x_L downgradient of the source where:

$$x_L = \frac{q}{2\pi K \Delta b} \qquad (3.4)$$

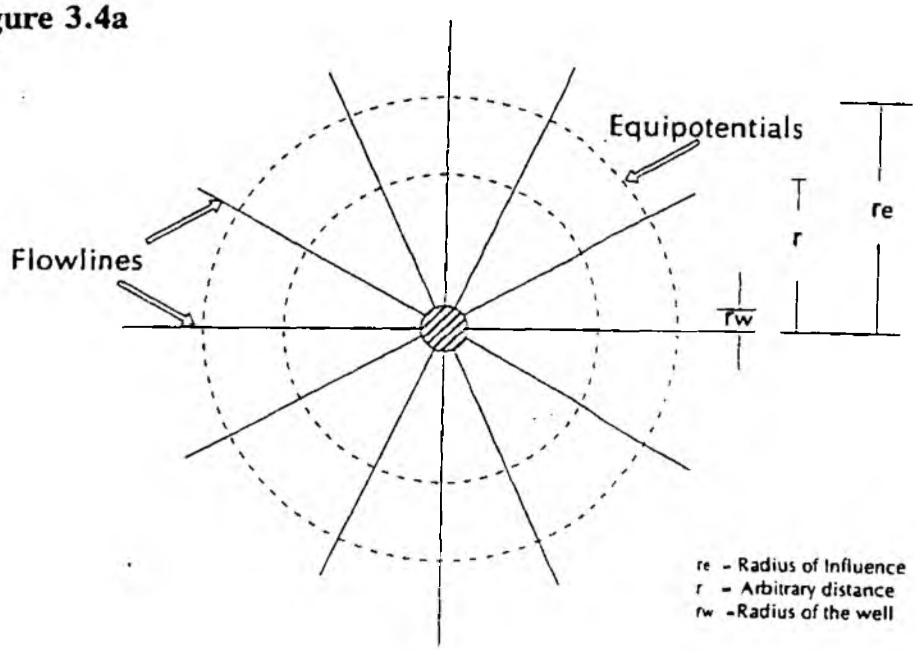
and the maximum distance y_{max} of the bounding flowline from the x- axis in the upgradient direction is :

$$y_{max} = \frac{q}{2K\Delta b} \qquad (3.5)$$

3.23 As an example, taking q = 250 m^3/d, b = 50 m, K = 10 m/d and Δ = 0.001, then the null point is some 80 m down gradient from the well, and the maximum width of the capture zone (= 2* y_{max}) is 500 m.

3.24 Equations may also be derived for all the flowlines and equipotential lines throughout the flow field[29] using the same theory although for brevity they are not described here. Such equations are used to derive expressions for the velocity at each point of the flow field from which particle tracks or paths[6] through the aquifer may be computed.

Figure 3.4a



Radial flow to a Well

Figure 3.4b

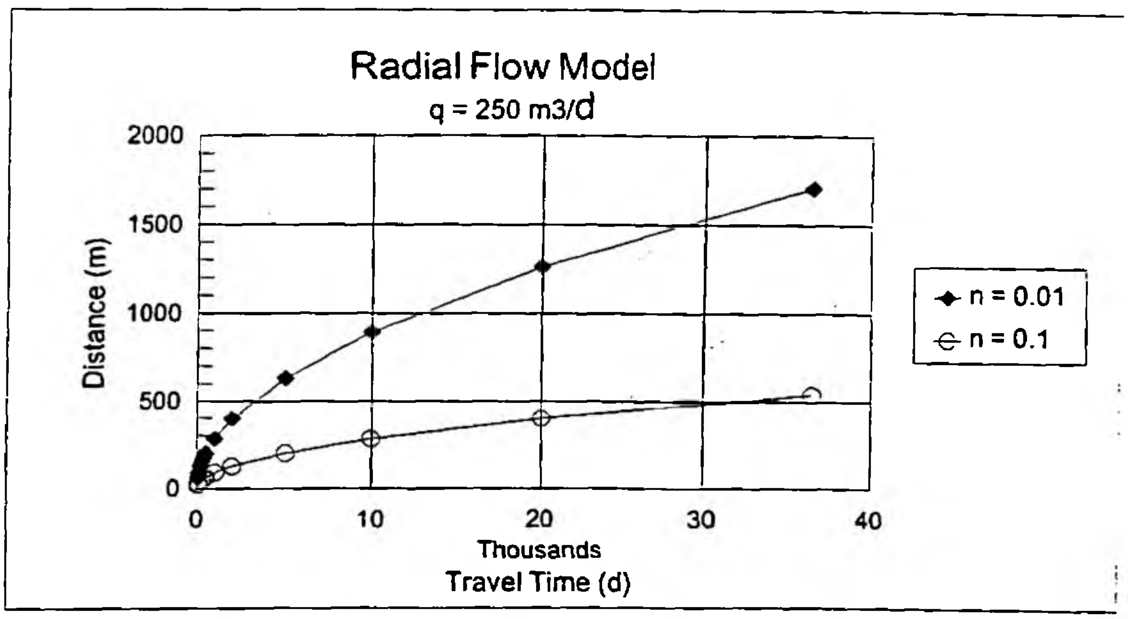
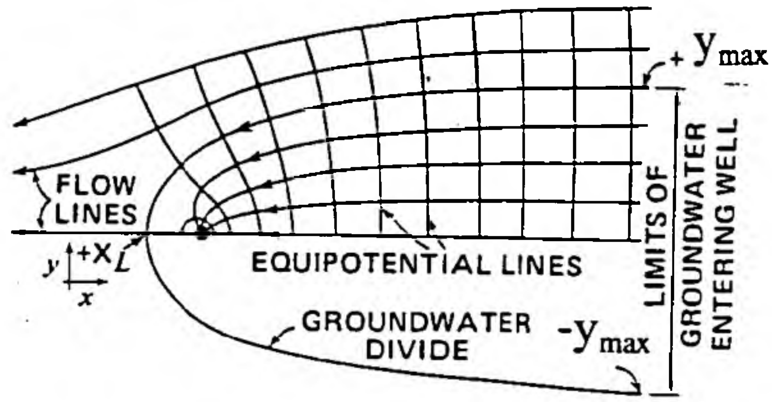


Figure 3.5 Capture Zone Geometry



Uniform Flow Equation:

$$\frac{y}{x} = \tan\left(\frac{2\pi kb\Delta y}{q}\right)$$

Distance to Null Point:

$$x_L = -\frac{q}{2\pi\Delta kb}$$

$$x_L = \frac{q}{2\pi Ti}$$

Boundary Limit:

$$y_{max} = \pm\frac{q}{2\Delta kb}$$

$$2y_{max} = \frac{q}{Ti} = 2\pi x_L$$

where :

k = permeability (m/d)
b = aquifer thickness (m)
Δ = hydraulic gradient
π = 3.142

3.25 The loci of all points in the aquifer from which particles of water take exactly t_d days to reach the borehole forms a curve which is termed an isochron, and the region bounded by this curve is called the t_d time of travel zone. In an aquifer of infinite extent, the equation for the t_d isochrons is[6] :

$$e^{-z}\left(\cos w+\frac{z\sin w}{w}\right)=e^{-t^*} \qquad (3.6)$$

where z, w and t^* are non-dimensional variables defined by:

$$z=\frac{2\pi K\Delta bx}{q}, \quad w=\frac{2\pi K\Delta by}{q}, \quad t^*=\frac{2b\pi(K\Delta)^2t}{nq}$$

and x and y are coordinates, parallel and orthogonal to the hydraulic gradient (see Figure 3.5)

3.26 Figure 3.6 shows 50 and 400 day isochrons deduced from equation (3.6) for an abstraction of 250 m^3/d, from a 100 m thick aquifer of permeability 1 m/d, an effective porosity of 1% and a hydraulic gradient of 0.001.

3.27 Isochrons intersect the x-axis up- gradient and down- gradient of the well, (see Figure 3.6) and the up- gradient point gives the maximum distance from the well on the curve. Along the x- axis, y = 0 and equation (3.6) above reduces to

$$t^*=z-\ln(1+z) \qquad (3.7)$$

which is plotted as Figure 3.7. For each value of t^* there are two values of z : z_{max} which is up- gradient of the well and z_{min} which is down- gradient.

3.28 Given any point x_d along the axis, t^*, and hence t_d can be easily calculated from equation (3.7), as in Figure 3.7 for example, but the inverse problem : to determine z_{max} and z_{min} ,the coordinates of the two intersection points, or more generally : to determine the coordinates of all the points along the isochron, for a given t_d as the solution to equation (3.6), requires the use of numerical methods, which in the past have not been readily available. For this reason, many authors have approximated the theoretical isochrons by "standard shaped" zones. A number of examples of such zones are described in the following sections.

Figure 3.6

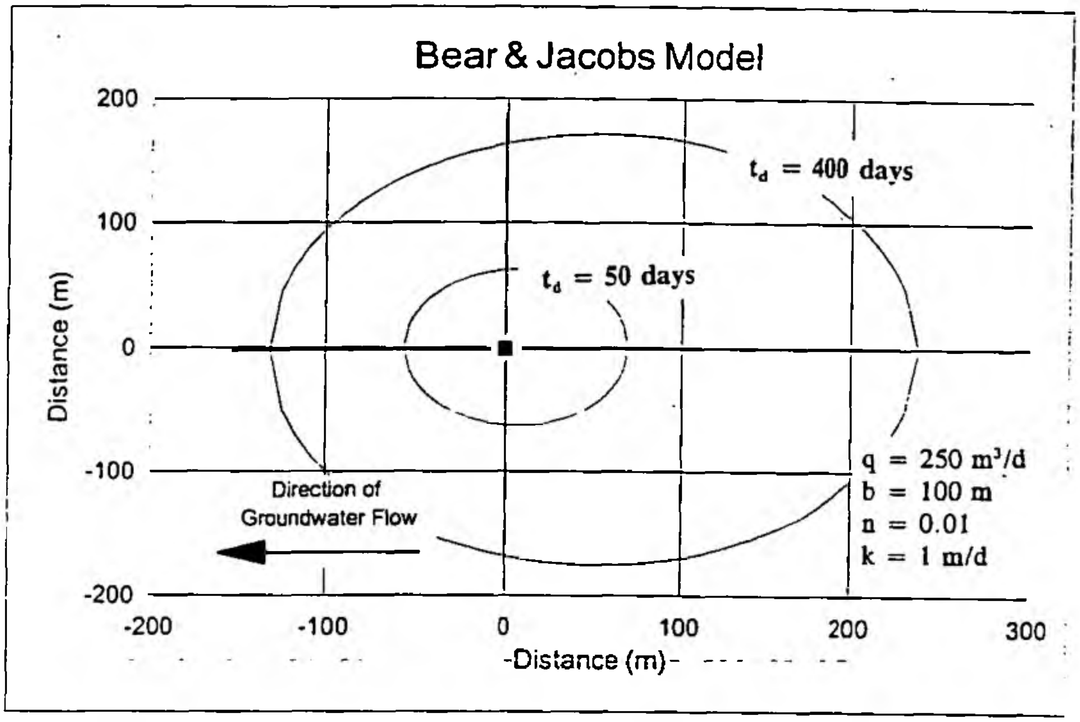
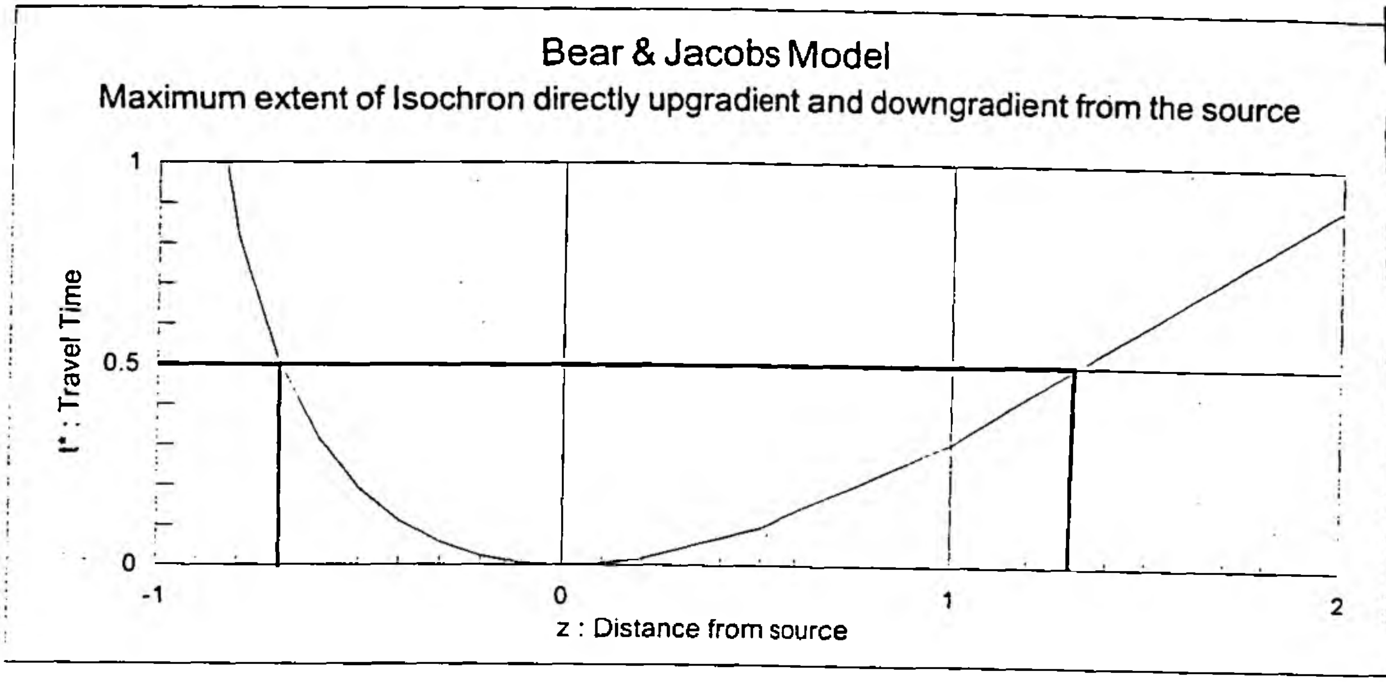

Bear & Jacobs Model
200
100
0
-100
-200
Distance (m)
-200
-100
0
100
200
300
Distance (m)
t_d = 400 days
t_d = 50 days
Direction of
Groundwater Flow
q = 250 m³/d
b = 100 m
n = 0.01
k = 1 m/d

Figure 3.7



Example

Let $q = 50\ m^3/d$, $b = 20\ m$, $k = 5\ m/d$, $n = 0.2$ and $\Delta = 0.001$

The graph above shows the relationship : $t^* = z - \ln(1+z)$,

When $t^* = 0.5$, $z = -0.7$ and 1.3.

Using the relationships between z & x, and t^*& t :

$z = 2\pi kb\Delta x/q$, and $t^* = 2\pi b(k\Delta)^2 t/nq$

$t^* = 0.5 \Rightarrow t = 1592$ days

and

$z = -0.7 \Rightarrow x = -56$ m and $z = 1.3 \Rightarrow x = 103$ m

Approximations to Isochron delineation

Southern Water Authority

3.29 In 1985 Southern Water Authority[5] published its *Aquifer Protection Policy* which established approximate "time of travel" zones around each public water supply borehole in the region. Equation (3.6) above was utilized to compute 50 day travel time zones for a range of typical parameters and abstraction rates for each of the major aquifers in the region. Subsequently a series of zonal areas were constructed from the computed curves, reflecting the uncertainty in knowledge and understanding of the hydrogeology of each aquifer, and these were plotted on 1:50000 scale maps and used to define protection areas around each source. The SWA methodology, which is illustrated in Figure 3.8, is one of those recommended by the EPA[7]

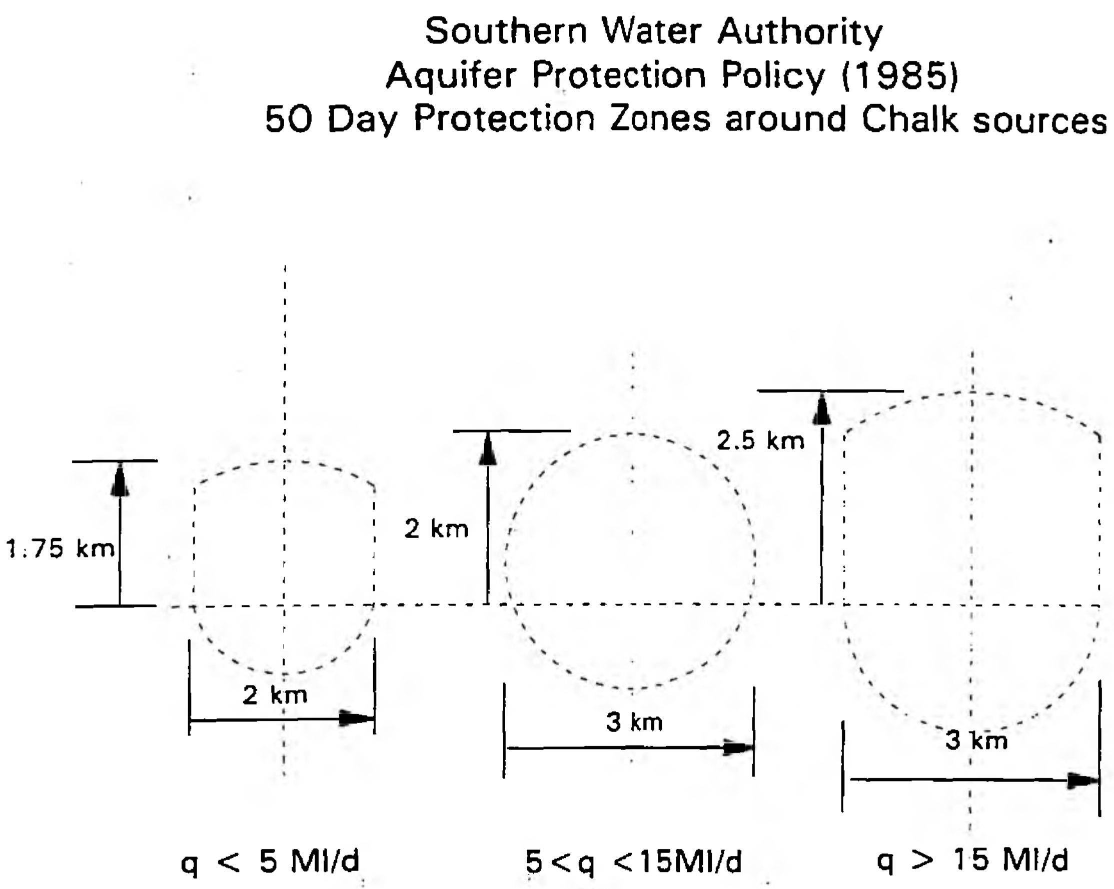
Thames Water Authority

3.30 In a variant of the SWA method, Thames Water Authority[30] (TWA) used equation (3.7) above, to calculate x_{400} the maximum up-gradient distance travelled in 400 days, together with those for the maximum width of the capture zone, and the position of the null point, (see Figure 3.5) to define "consultation zones" around sources. Latterly, these zones were modified to have regard to geology and topography.

Thames Region - NRA

3.31 In a further variant of the method, Thames Region have developed a series of standard shape zones, based on average aquifer parameters, to delineate "planning liaison zones" which are used internally to indicate to NRA Planning Liaison teams those areas for which Groundwater Quality staff should be consulted. The delineation of the zones follows the procedure adopted previously by TWA, but with the additional features that abstractions are banded into 5 Ml/d classes : (0 - 5 Ml/d, 5 - 10 Ml/d etc) and the travel time is 100 days.

Figure 3.8


Southern Water Authority
Aquifer Protection Policy (1985)
50 Day Protection Zones around Chalk sources
1.75 km
2 km
2 km
2.5 km
3 km
3 km
q < 5 Ml/d
5<q <15Ml/d
q > 15 Ml/d

Southwestern Region - NRA

3.32 More recently "standard shaped" capture zones have been used by Southwestern Region (NRA) (Appendix II) to delineate protection zones around sources in the vicinity of a proposed by-pass. For this application the distances travelled upgradient in 50 (x_{50}) and 100 (x_{100}) days were calculated using conservative aquifer parameters, (see Example 3 : Chipstable in Section 4), and a composite zone based on these distances constructed. The resulting zone, which is illustrated in Figure 3.9, consisted of a circle of radius x_{50} centred on the source, and a circle of radius x_{100} centred upgradient of the source so that the two curves were tangential directly downgradient from the source.

US EPA

3.33 A variant of the standard capture zones, based on the bounding flowline of the capture zone and calculated travel times has been proposed by the EPA. Typically, the upgradient distances are calculated from equation (3.7), while the downgradient distance is derived from equation (3.4). Figure 3.10 illustrates schematically, the resulting hybrid zone around a source abstracting 250 m^3/d from an aquifer 100 m thick, with a permeability of 1 m/d and a porosity of 1%.

Analytical & Semi- analytical Methods

3.34 While the use of fixed radius and standard shaped protection zones has been successful in the UK, particularly so given both the difficulties in computing the zones, and the need to establish such zones around the large numbers of public water supply sources relatively quickly, alternative methodologies are now available which enable borehole capture zones in the major (darcian flow) aquifers to be delineated with some ease.

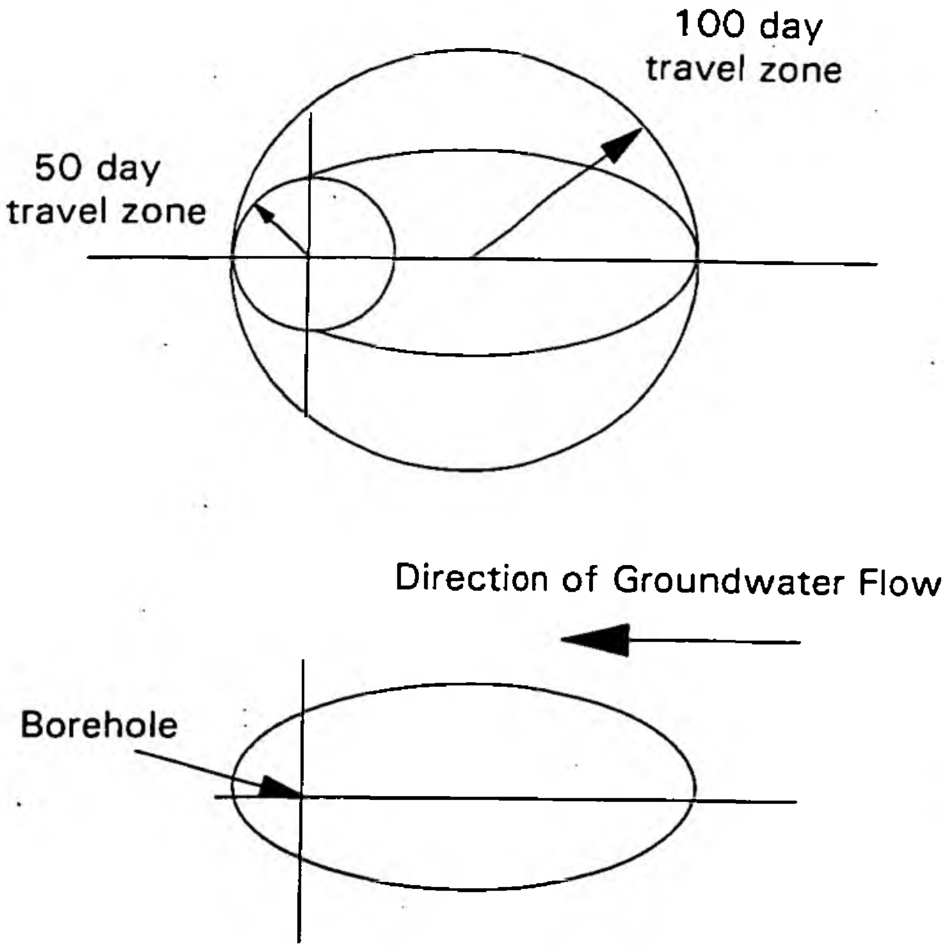
3.35 The use of particle tracking techniques to generate flow paths and time -of-travel data is now becoming relatively well established[31,32]. In general particles are tracked through a flow field explicitly by calculating the directional components of velocity at the particle's current position and then moving it to a new position that is computed by multiplying the velocity components by a time increment to obtain the incremental changes.

3.36 Particle tracking routines[36] are readily incorporated into numerical models, eg. MODFLOW and FLOWPATH[11], but are now becoming available with analytical and semi-analytical models. WHPA[12], for example, which may be termed a semi-analytical model, because it includes both analytical and numerical routines, has been developed specifically for the EPA Well Head Protection Program to enable borehole capture zones to be easily delineated.

Figure 3.9

South Western Region - NRA

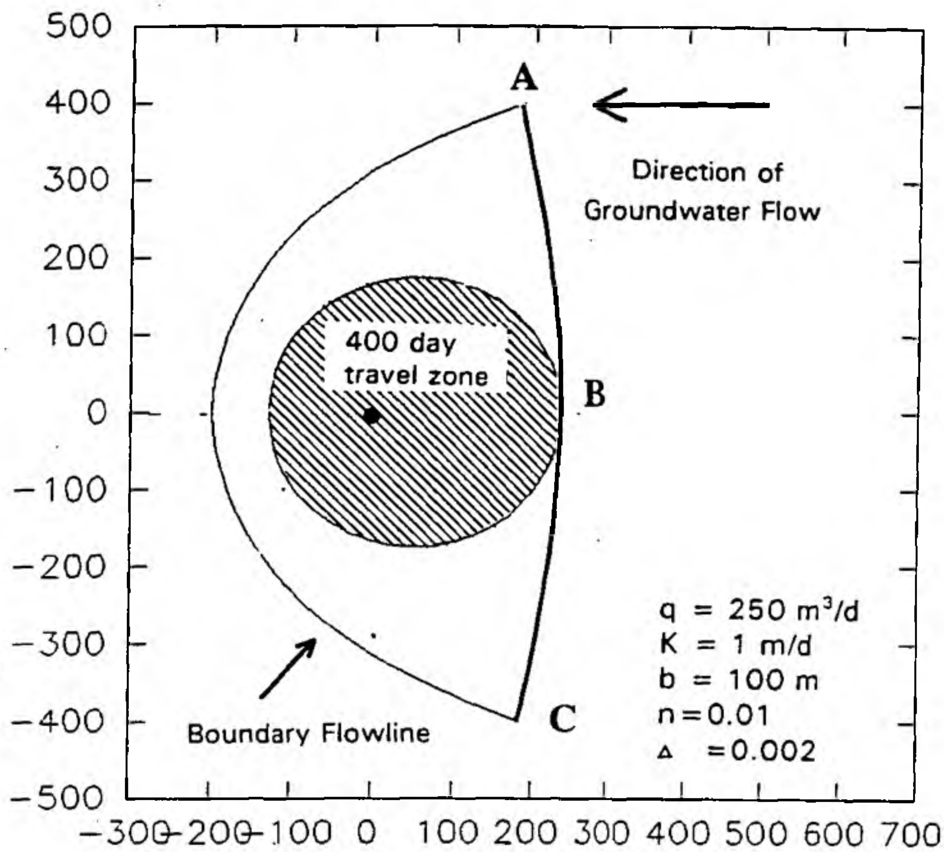
Method of Protection Zone Construction



3.37 QUICKFLOW[42] is an alternative semi-analytical model that simulates two-dimensional steady state and transient groundwater flow. The model simulates steady state flow using analytical functions as solutions to a series of standard problems developed by Strack[43], (Analytic Element Model) and transient conditions using the standard equations developed by Theis[44], Hantush and Jacob[45] for confined and leaky aquifers respectively. The model uses the principle of superposition to evaluate the effects of multiple sources in a uniform regional flow. Particle tracking is performed numerically, but capture zones are not specifically delineated. Figure 3.11 shows the model output for the case of the 250 m^3/d abstraction from a 100 m thick aquifer of permeability 1 m/d and effective porosity of 1%.

3.38 The analytical solutions allow for recharge, but there are limitations to general usage arising from the specific problems to which solutions have been included. Overall, the use of QUICKFLOW would appear to provide no significant advantages over the specifically designed WHPA model, which is discussed in some detail below. Recently published research[46], however, suggests that a generalized Analytic Element Modelling approach may be more appropriate than WHPA for simulating complex hydrogeological settings such as those involving aquifer interactions.

Figure 3.10 EPA Hybrid Protection Zone



The "400 day" HYBRID zone shown above comprises the steady state capture zone for the source (the region within the boundary flowline) but closed upgradient by a cap which is formed by the arc ABC with Point B on the principle axis of flow at a distance x_d from the source, with x_d = the distance travelled in 400 days, and A & C are at the points of intersection of the arc with the boundary flowline. In WHPA the upgradient cap is constructed as the arc of radius x_d centred at the source, but it is shown schematically above because the actual circle of radius x_d in the example does not intersect the outer curve. In these circumstances, WHPA cannot compute the required hybrid zone, which in general, represents a compromise between the total steady state zone (TCZ) and the specific time of travel zone (TOTZ).

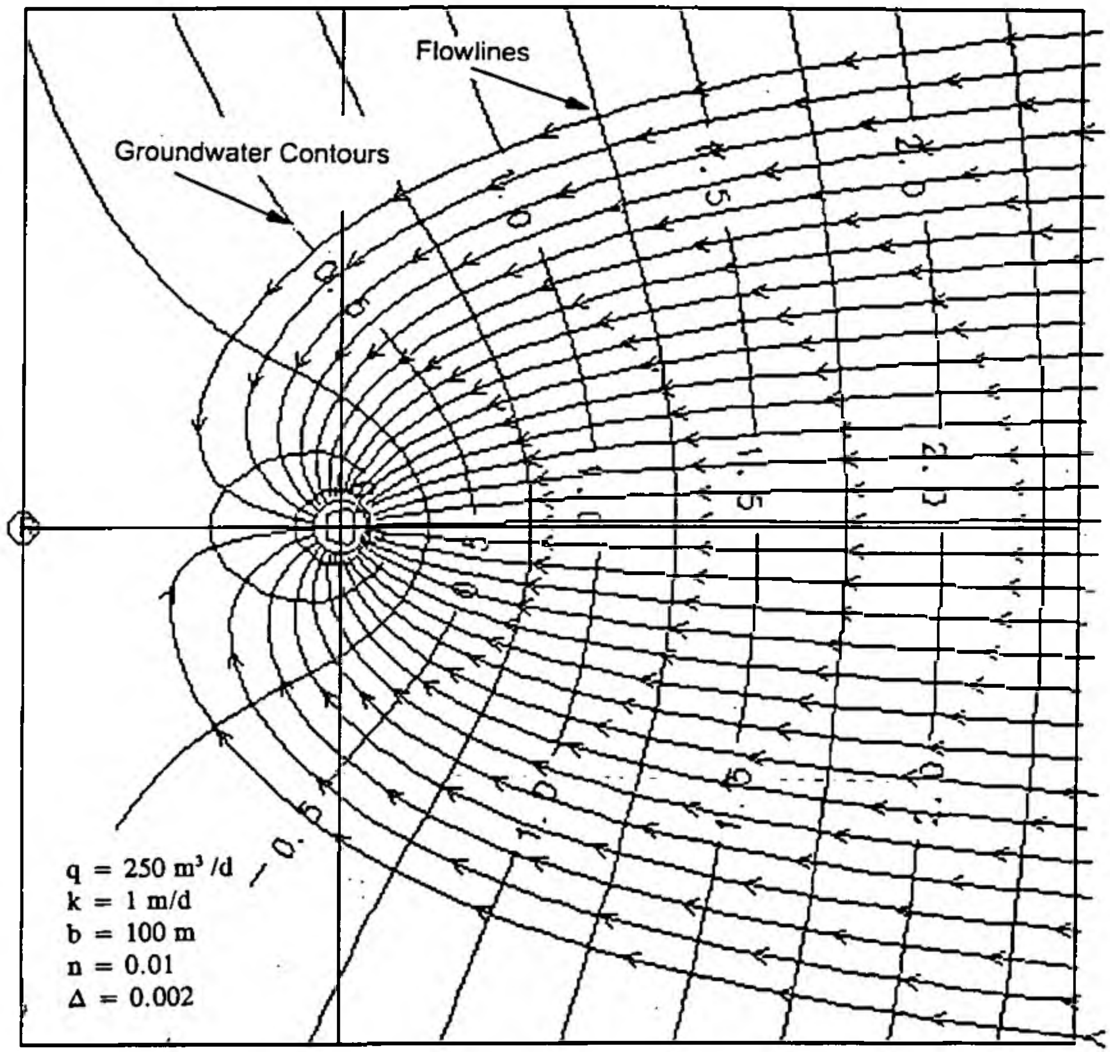
Example

Let $q = 250\ m^3/d$, $k = 1\ m/d$, $b = 100\ m$, $n = 0.01$ $\Delta = 0.002$

then $x_L = q/(2\pi K\Delta b) = 250/(2\pi x0.002x100) = 199\ m$

$x_d = 230$ m from equation (3.6) with $t_d = 400$ days

Figure 3.11 Quickflow Output



3.39 The equations on which the WHPA model is based are derived from steady state groundwater flow theory and the same assumptions of uniform thickness, of infinite areal extent, uniform hydraulic gradient etc as the Bear & Jacobs[6] model. However, the computer program is relatively straightforward to use, and has graphical output facilities, thereby enabling the delineated zones to be easily generated.

3.40 The WHPA model has 4 independent computational modules which may be used to compute capture zones :

- RESSQC Delineates time-related capture zones around sources in homogeneous aquifers of infinite areal extent and uniform groundwater flow

- MWCAP Delineates steady state, time related or hybrid capture zones for sources in homogeneous aquifers with steady and uniform ambient groundwater flow. The aquifer may be infinite in areal extent or the effects of nearby stream or barrier boundaries may be included.

- GPTRAC *Semi-analytical Option* - Delineates time related capture zones for sources in homogeneous aquifers with steady and ambient groundwater flow. The aquifer may be of infinite areal extent or it may be bounded by parallel stream and/or barrier boundaries. The aquifer may also be confined, leaky confined or unconfined with areal recharge.

  Numerical Option - Delineates time-related capture zones for sources under steady state groundwater conditions. This option performs particle tracking using groundwater head data derived from numerical models, and acts in effect as a particle tracking post-processor to non-WHPA numerical models lacking this facility

- MONTEC This module performs uncertainty analysis for time related capture zones for single sources in homogeneous aquifers (confined or leaky confined) of infinite areal extent.

3.41 Figures 3.12-3.15 show the capture zones predicted by each of the WHPA modules, for a well abstracting 250 m^3/d from the 100 m thick aquifer, with K = 1 m/d, n = 1% and Δ, the hydraulic gradient, = 0.002. 400 day zones are illustrated in Figure 3.12 (RESSQC), Figure 3.14 (GPTRAC) and Figure 3.15 (MONTEC). while Figure 3.13 (MWCAP) shows the hybrid 1000 day zone. The upgradient boundary of the t_d hybrid zone is constructed geometrically as the arc of a circle, centred at the well, passing through the boundary flowline and through x_d on the x-axis. For the particular data set used in this example, the method does not work for t_d = 400 days because x_d (230 m) is too small relative to the dimensions of the boundary flowline to generate the required arc. This is clearly a limitation of the geometrical method of capping used in the MWCAP module but the model user is advised of the problem.

Figure 3.12

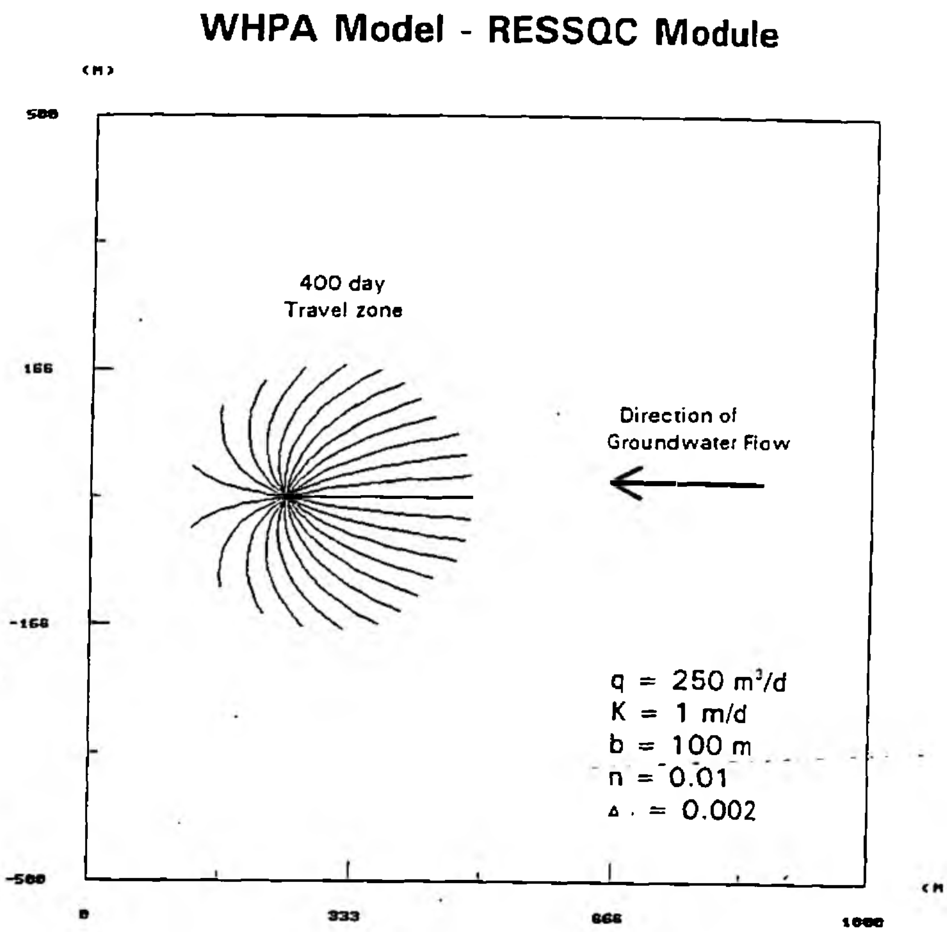

WHPA Model - RESSQC Module
(M)
500
166
-166
-500
400 day
Travel zone
Direction of
Groundwater Flow
q = 250 m³/d
K = 1 m/d
b = 100 m
n = 0.01
= 0.002
0
333
666
1000
(M)

Figure 3.13

WHPA Model - MWCAP Module

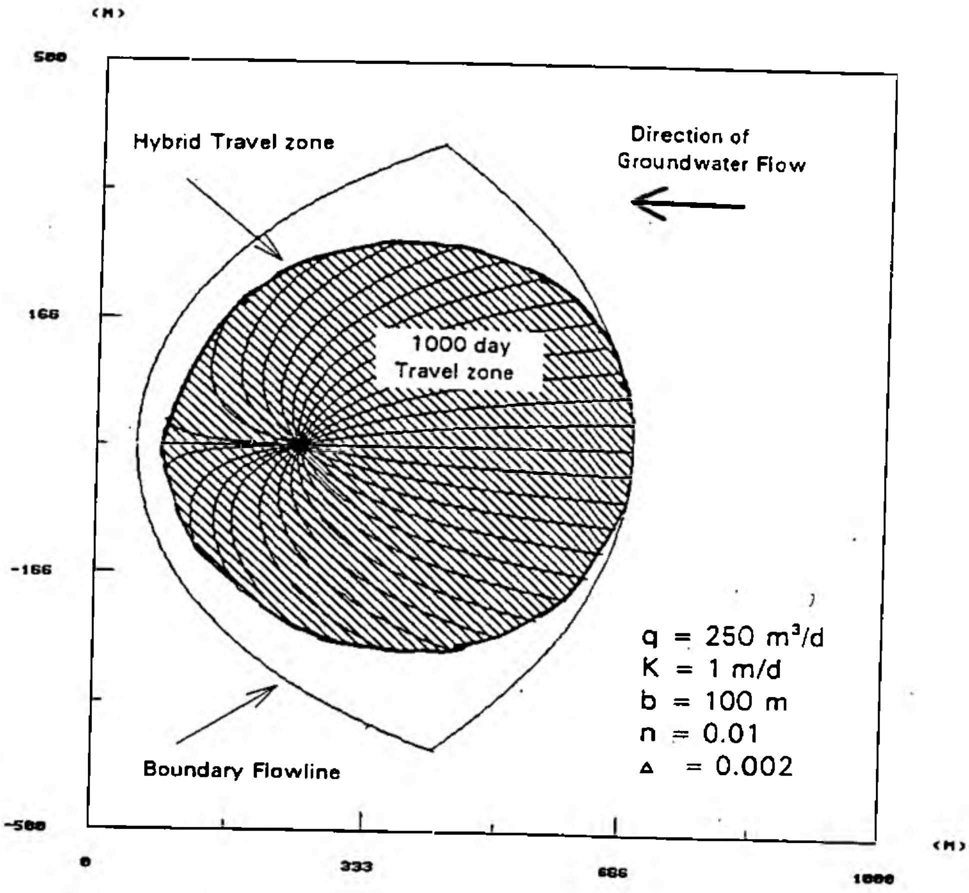


Figure 3.14

WHPA Model - GPTRAC Module

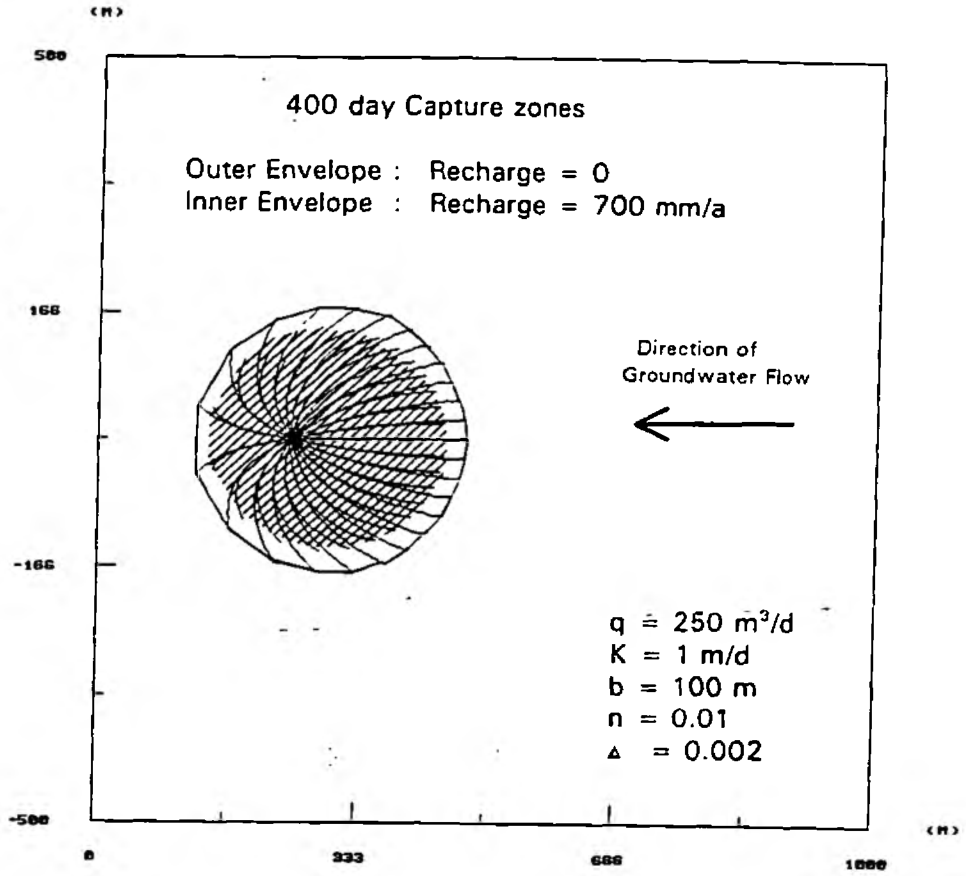
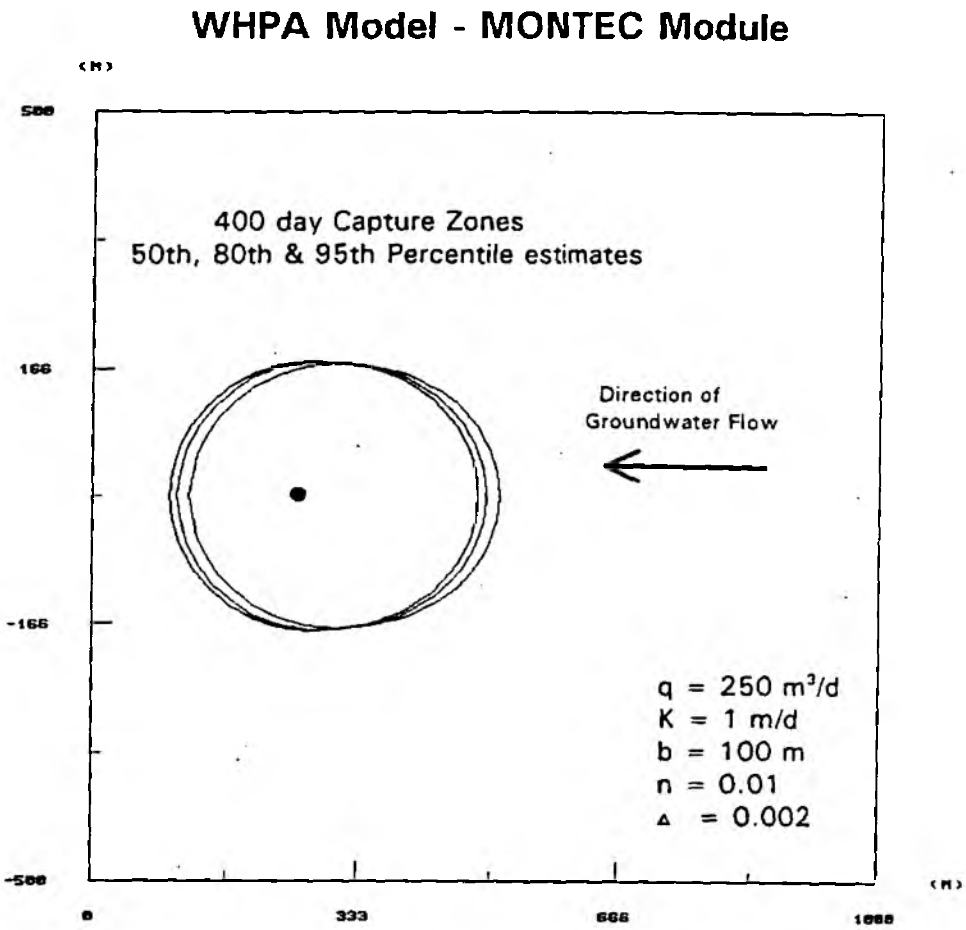


Figure 3.15



Parameter	Distribution	Mean	Standard Deviation	Lower Bound	Upper Bound
Discharge q (m^3/d)	Constant	250	-	-	-
Permeability K(m/d)	Lognormal	1	0.2	0.5	5
Gradient Δh	Normal	0.002	0.0005	0.001	0.003
Porosity n	Normal	0.01	0.005	0.009	0.011
Thickness b (m)	Constant	100	-	-	-

3.42 Recent developments with the WHPA model, which is now used extensively throughout Europe and the USA include:

- the introduction of the Monte Carlo simulations[33], which are now incorporated into WHPA as the "MONTEC" module,
- the direct incorporation of the package into Geographic Information Systems[34] containing local area maps to aid the development of groundwater management systems in urban areas, and
- the formulation of capture zone delineation as an optimization problem[37], to predict the optimal pumping regime from a municipal wellfield surrounded by potential contamination sites.

3.43 The WHPA model is based on steady state uniform groundwater flow in an aquifer of infinite areal extent which enables the t_d day capture zone to be determined. The assumption of uniform flow in an infinite aquifer without recharge results in a capture zone which is unbounded upgradient of the source with the quantity of water flowing across any transect of the zone perpendicular to the hydraulic gradient (the principal axis of flow) equal to the volume abstracted from the well. Integrating the area within the t_d isochron, using the equations developed by Bear & Jacobs[6] (equation (3.6)), which are equivalent to those in WHPA, will give a relationship between A_d (the areal extent of the t_d capture zone) and t_d, but the "ultimate " area as t_d becomes infinitely large has no meaning. Relating A_d to A_R (the TCZ based on recharge and abstraction and defined by equation (3.1)) for finite t_d, however, remains a possibility.

3.44 An approximate method of capping the capture zone upgradient of the source has been proposed by NRA Groundwater Centre (see Volume III) based on the recharge area required to satisfy the abstraction, and the assumption of radial flow. The upgradient limit to the capture zone is defined as that distance x_d from the source for which a travel time t_d derived from the following analysis would result.

3.45 In t_d days, the volume V_d of water abstracted from the aquifer is given as :-

$$V_d = qt_d$$

Assuming that the water is withdrawn from an aquifer of thickness b and effective porosity n, the volume of the cylinder V_d from which the abstraction takes place may also be expressed as

$$V_d = bnA_d$$

where A_d is the surface area of the cylinder.

Thus t_d may be determined as:

$$t_d=\frac{bnA_d}{q} \qquad (3.8)$$

Now assuming that A_d the area of the t_d time of travel zone (TOTZ) is equal to the recharge area A_R of the source, (TCZ) then

$$A_d=\frac{q}{R_e}$$

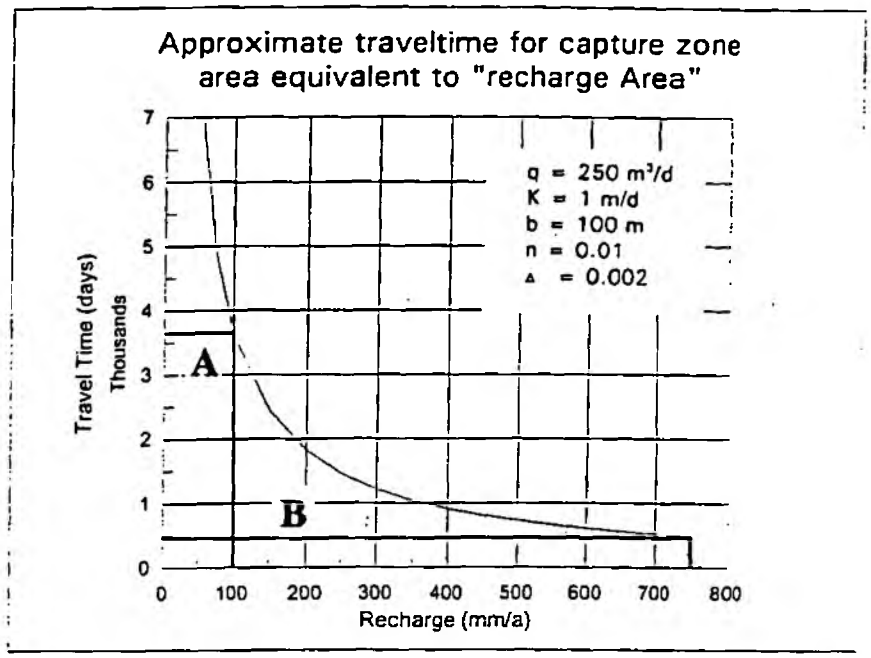
from equation (3.1) and the travel time to be used to compute the upgradient limit is given as

$$t_d=\frac{bn}{R_e} \qquad (3.9)$$

3.46 Using the standard example of a 250 m^3/d abstraction, with n = 0.01, b = 100 m and K = 1 m/d, from an aquifer subject to annual recharge of 100 mm, the approximate travel time which produces a circular area equivalent to the "Recharge area" is 3650 days, while if the annual recharge is 750 mm, then the corresponding travel time would be 486 days. (Figure 3.16). Arguably, the required capture zone could be defined by capping the zone formed by the bounding flowline at an upgradient distance from which the travel time is t_d days. The validity of the approximation, however, must be questioned because of the assumption of area equivalence which is required to introduce recharge into the equation. Furthermore, the method can give rise to protection zones which are too small. For example, with annual recharge equal to 100 mm, the predicted 10 year travel time zone may be considered to provide adequate long term protection, but the 1 year zone, for an annual recharge of 700 mm does not provide the same degree of security and is probably unacceptable.

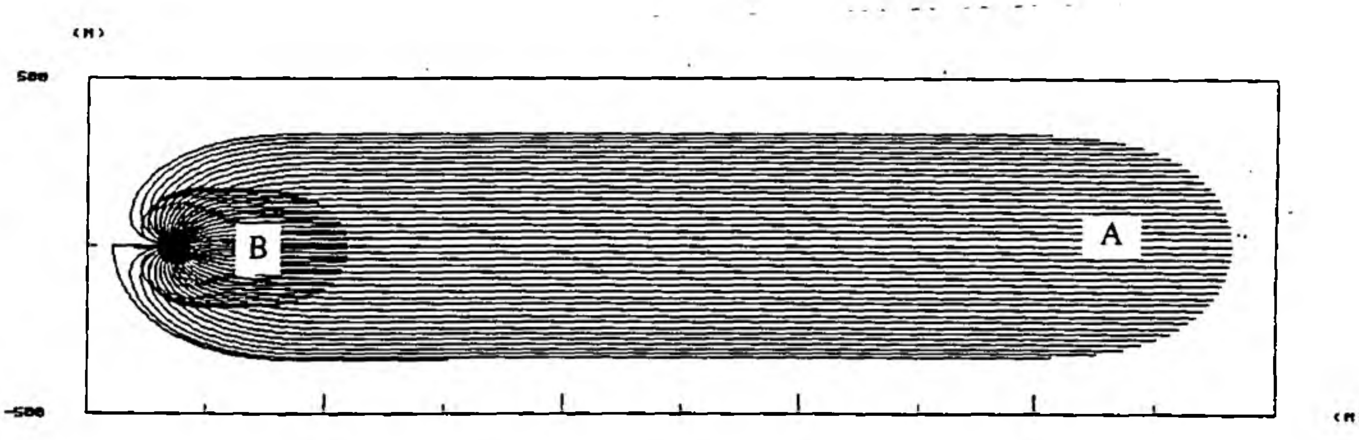
3.47 A further problem associated with the use of WHPA is the assumption of uniform flow in an infinite aquifer. In practice, aquifers are bounded, catchment divides may exist within the aquifer and recharge may be spatially varying. In general, numerical models, e.g FLOWPATH[11] and MODFLOW [36] are used in such circumstances, but an alternative semi-analytical model, (called ABARM in this report) is becoming available for use on simplified aquifer geometries.

Figure 3.16



Capture zones for t_d = A) 3650 days, Recharge = 100 mm/a
= B) 487 days, Recharge = 750 mm/a

derived using WHPA Model - GPTRAC Module



Examples

Let q = 250 m³/d, b = 100 m, k = 1 m/d, n = 0.01 & Δ = 0.002

A) Annual recharge = 100 mm and $t_d = b*n/R_e$ = 365x100x0.01/0.1 = 3650 days

B) Annual recharge = 750 mm and t_d = 487 days

Aquifer Boundary and Recharge Model (ABARM)

3.48 Figure 3.17 illustrates the location of a source in a rectangular aquifer, of uniform permeability and porosity, which is, bounded to the north and south by impermeable strata and has fixed water levels on the west and eastern boundaries. Assume also, that flow is steady state and that recharge occurs uniformly over the aquifer.

3.49 Analytical equations for the components of groundwater velocity at each point of the aquifer for the flow problem illustrated in Figure 3.17, and other relatively simple geometries, have been derived by Lerner[39,40], which allow particle tracks and hence capture zones to be delineated The derivation of these equations is not presented here because of their complexity and the interested reader is referred to the original publications. However, comparisons between the results from this model, and those from the same simulation using FLOWPATH, are presented in Figures 3.18 and 3.19 for the parameters defined on Figure 3.17.

3.50 Figure 3.20 gives a comparison between the ABARM results of Figure 3.17 with the bounding flowline from WHPA together with the circular "Recharge Area" zone. In general terms, the WHPA capture zone, truncated at the groundwater divide appears to provide a reasonable approximation to the ABARM result.

Figure 3.17 Illustration of the flow problem simulated in the ABARM Model

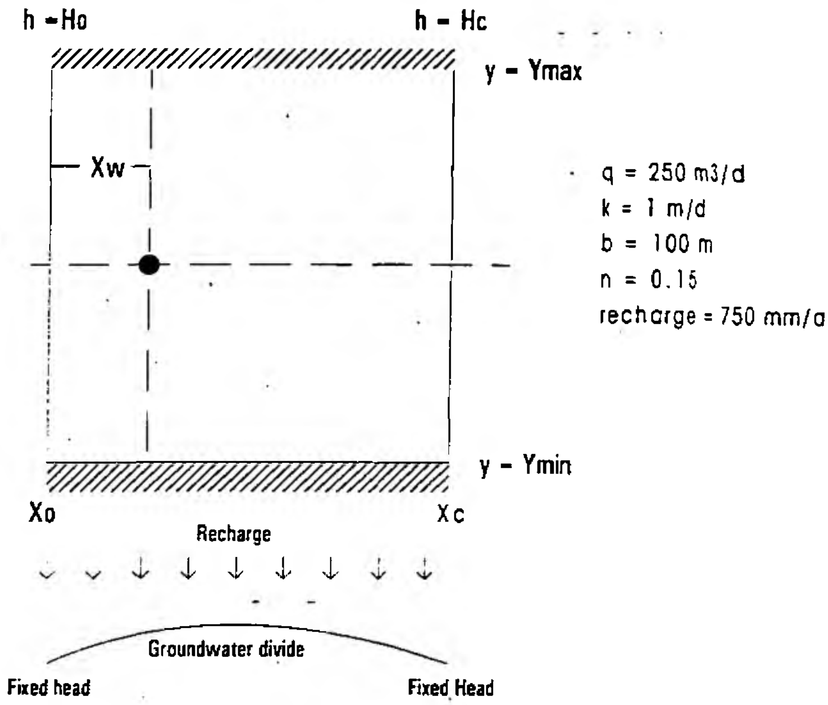


Figure 3.18 ABARM Output
(From scenario in Figure 3.17)

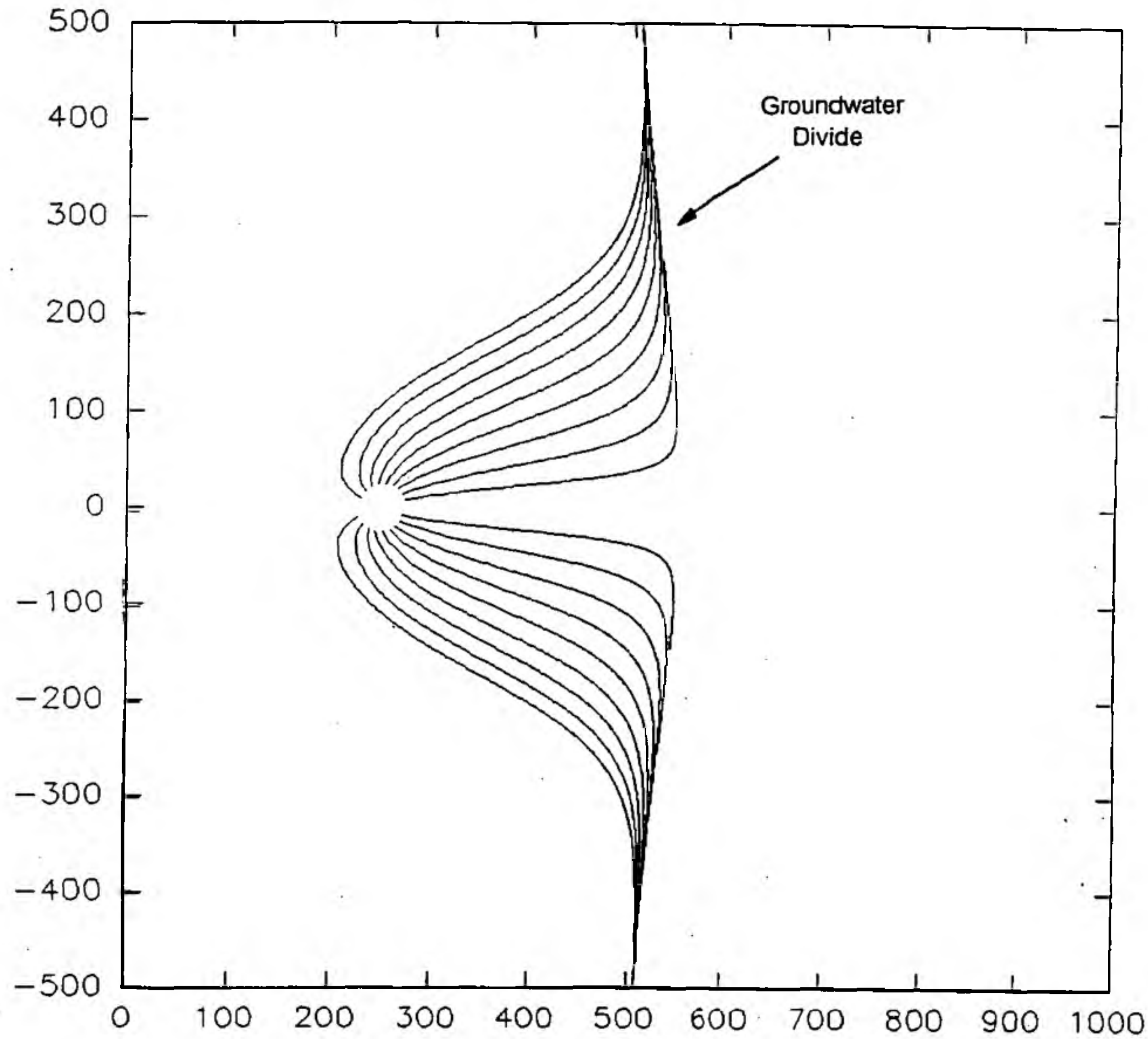


Figure 3.19 FLOWPATH Output
(From scenario in Figure 3.17)

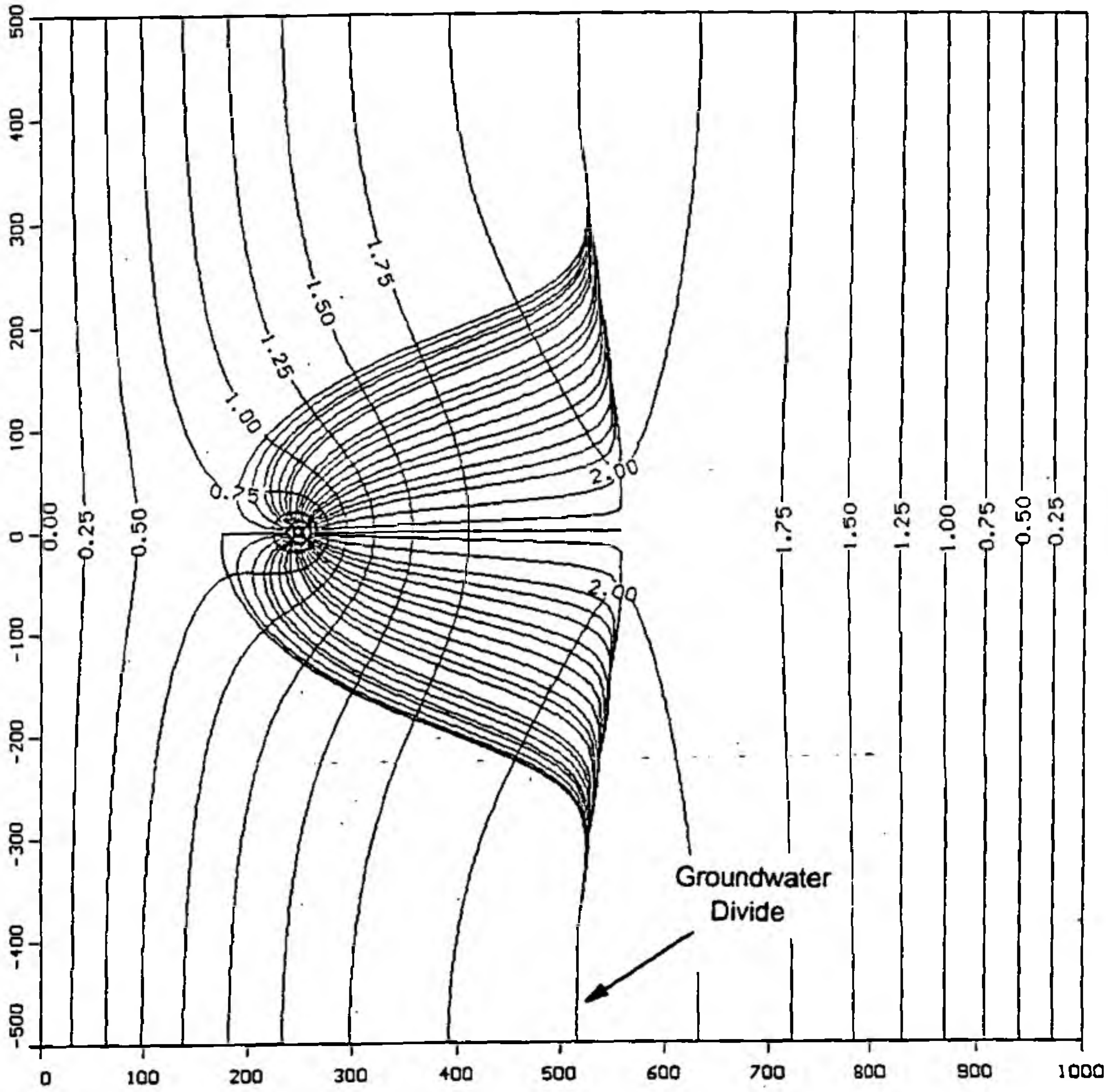
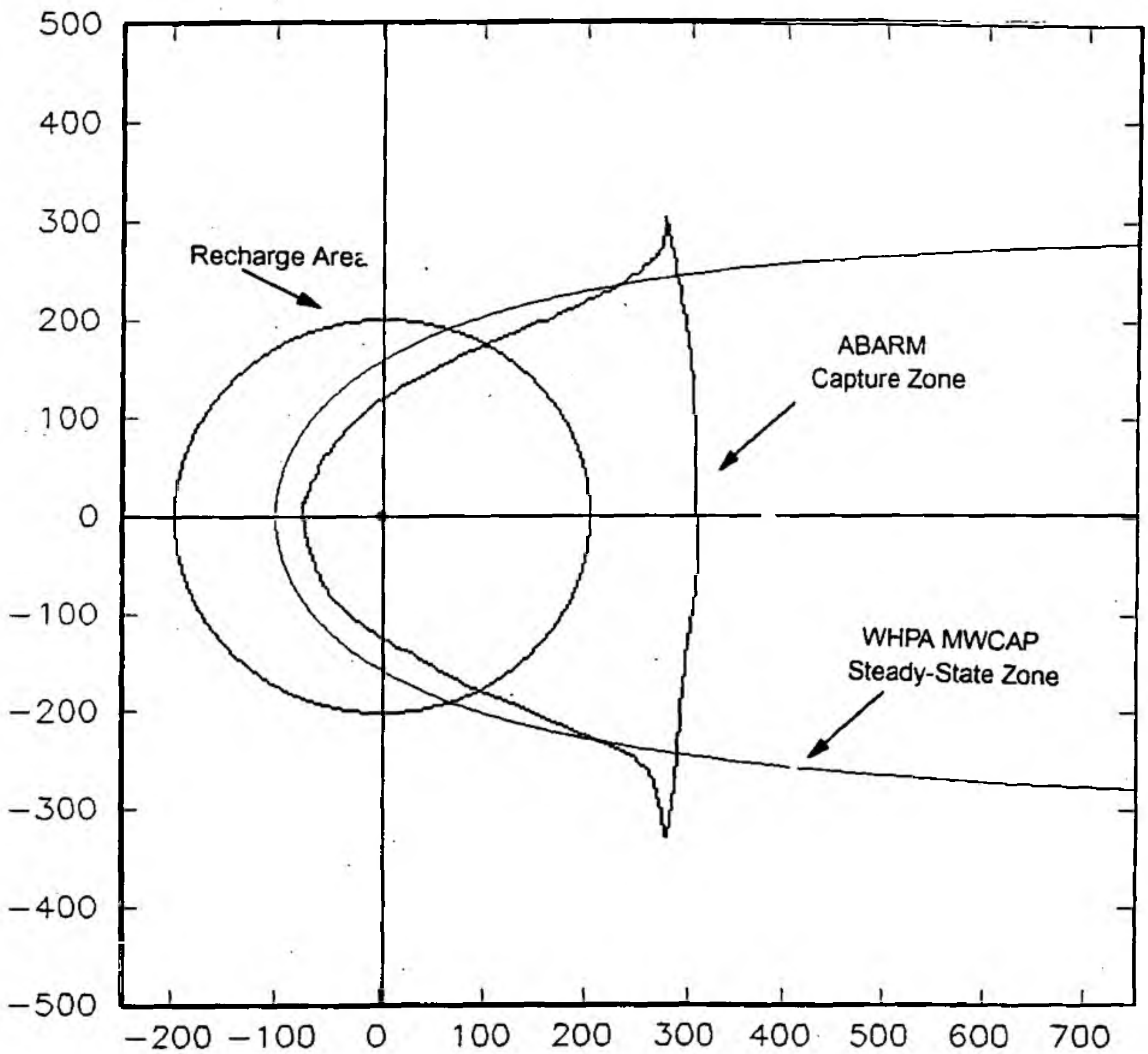


Figure 3.20 Comparison between ABARM & Recharge Area Model (From scenario of Figure 3.17)



Capture Zones in Fractured Aquifers

3.51 The application of Wellhead Protection Methods to non-darcian aquifers is an area of ongoing research by the US EPA[17,18], but the database search carried out for this project did not find any other studies reported in the literature.

3.52 The EPA studies reported to date involve the delineation of capture zones in fractured pre- Cambrian crystalline rock and fractured sedimentary carbonate rock aquifers in the USA. At the sites studied, however, abundant fractures ensured that the aquifers responded as porous media at the scale of the field tests which were carried out.

3.53 Four main approaches were utilized to delineate capture zones in these studies:

- classical groundwater flow theory
- geological & hydrogeological mapping
- geochemistry
- 3-D numerical flow/transport modelling of the study area.

3.54 The conclusions from the studies were :

- Capture zones based on fixed or calculated radii are unrealistic because of the (often) complex geological & hydrogeological features which could affect local groundwater flow patterns,
- Capture zones delineated using classical groundwater theory were appropriate provided that, at the scale of the problem, the aquifer behaved as a porous medium.
- Geochemistry or tracer studies, combined with field mapping of the flow features could be a useful technique for delineating capture zones, particularly where the assumptions of porous media were inappropriate ,
- 3-D numerical modelling was found to give the "best" results, but models which represent flow in discrete fissures in non-porous media are essentially research tools at present. It should also be noted that modelling such aquifers would require extensive field investigations to characterise the distribution, orientation and size of the fissures

- The overall conclusion from this work was that while conventional theory and field mapping could provide reasonable estimates of the capture zones, overall the resulting zones were smaller than those derived from the actual modelling of the system - reflecting the hydrogeological controls exerted by the sparse, discrete nature of the fissures.

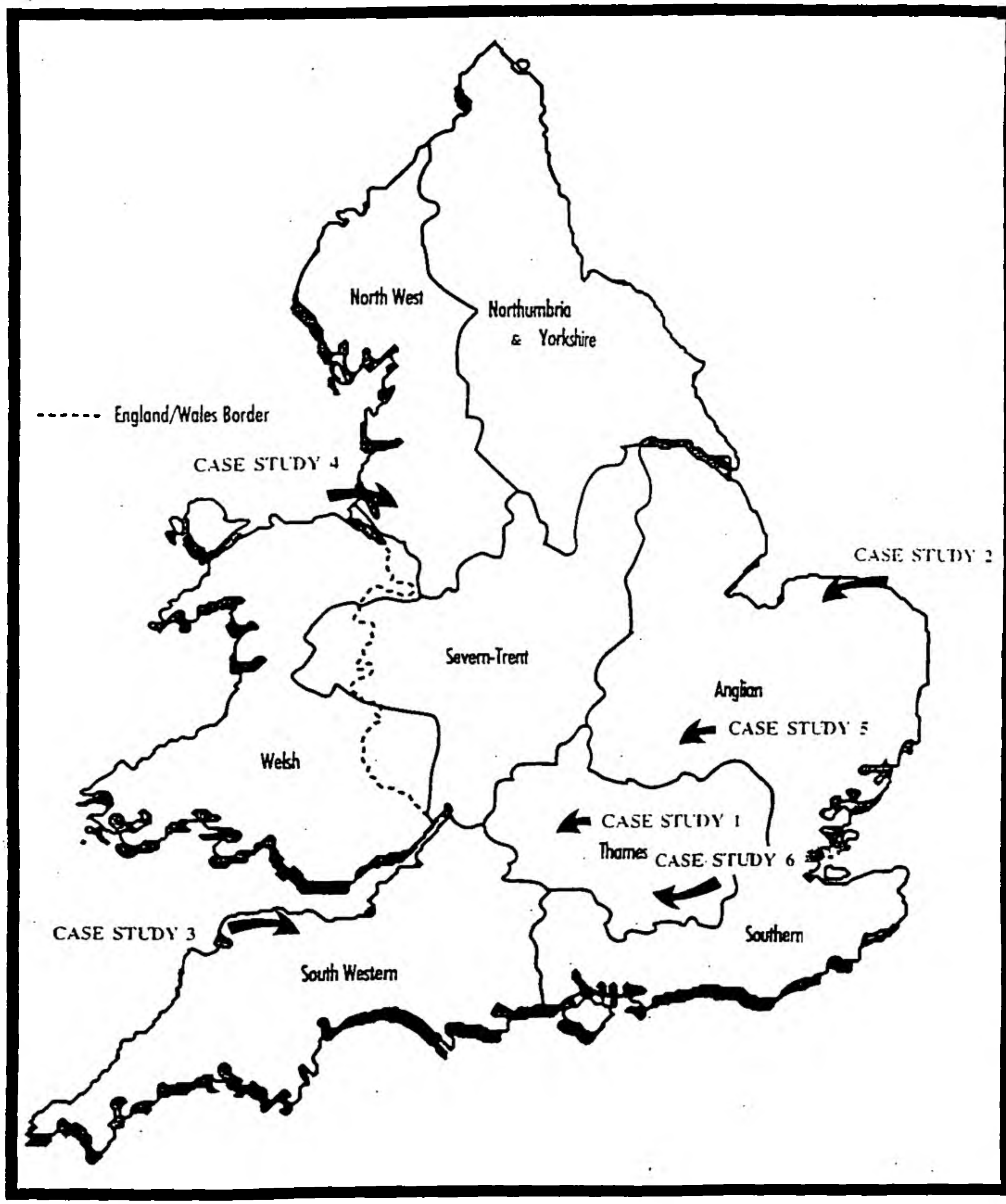
3.55 It is clear that if the geology of an aquifer is such that the assumption of flow in a porous medium is not valid, (the aquifer is non-darcian), then capture zones delineated by conventional methods will be in error; and the magnitude of the error will be dependent upon the extent to which groundwater flow departs from the darcian assumption. As an example, groundwater flow in karstic systems, which are clearly non-darcian in character, cannot usually be represented by darcian flow theory and so zone delineation using the methods described in this report would be inappropriate.

4 APPLICATION OF AVAILABLE METHODOLOGIES TO SMALL SOURCES

4.1 In this section, the results of applying the methods of capture zone delineation described in Section 3, to a range of typical "small source" problems will be discussed. Six case studies are presented. In each case, the only data used are those provided by the NRA Regional offices. Local hydrogeological or topographical maps have not been consulted, and therefore the capture zones presented have not been modified to take account of possible local influences.

4.2 Figure 4.1 shows the approximate location of the six sites for which aquifer parameters were supplied. The assumption is that the flow within the aquifer is darcian - even at the local scale. Capture zones have been derived using standard groundwater theory where sufficient data exist to do so. Elsewhere, comparisons are drawn between the alternative approximations.

Figure 4.1 Approximate Location of Case Studies



CASE STUDIES

Case 1: Cholsey

Setting

The source consists of a borehole abstracting from the Upper Greensand aquifer in the Thames Region.

The Upper Greensand is a minor aquifer although it may be locally important. The formation has a relatively narrow outcrop around the source and therefore receives little direct recharge. The formation generally relies on its hydraulic continuity with the overlying Chalk for recharge.

In the area surrounding the source the unsaturated zone is very thin and is estimated to extend to about 6m below ground level. The groundwater flows towards the River Thames and the hydraulic gradient is estimated at 0.003. It is believed that the water table is in hydraulic connection with the River Thames. The Upper Greensand is in hydraulic continuity with the overlying Lower Chalk. The flow regime in the Upper Greensand is darcian intergranular flow. Estimates of direct recharge are not available.

Parameter	
q (m^3/d)	455
k (m/d)	7
b (m)	35
n	0.01
∆	0.003
Recharge (mm/a)	*

Analysis :

Figure 4.2 shows the computed 400 day hybrid capture zone, delineated using the WHPA MWCAP module, superimposed on the zone originally drawn by Thames Water on the basis of the maximum predicted width of the capture zone and uniform flow but modified to have regard to the local hydrogeological setting. The zone calculated by MWCAP extends further upgradient because the original analysis was based on travel times in the absence of abstraction. In the absence of recharge both MWCAP & GPTRAC effectively produces the same results. However, there is a limit on the number of rows and columns which may be used in the GPTRAC computational grid. This could lead to inaccurate solutions because of a poor resolution of the flow field.

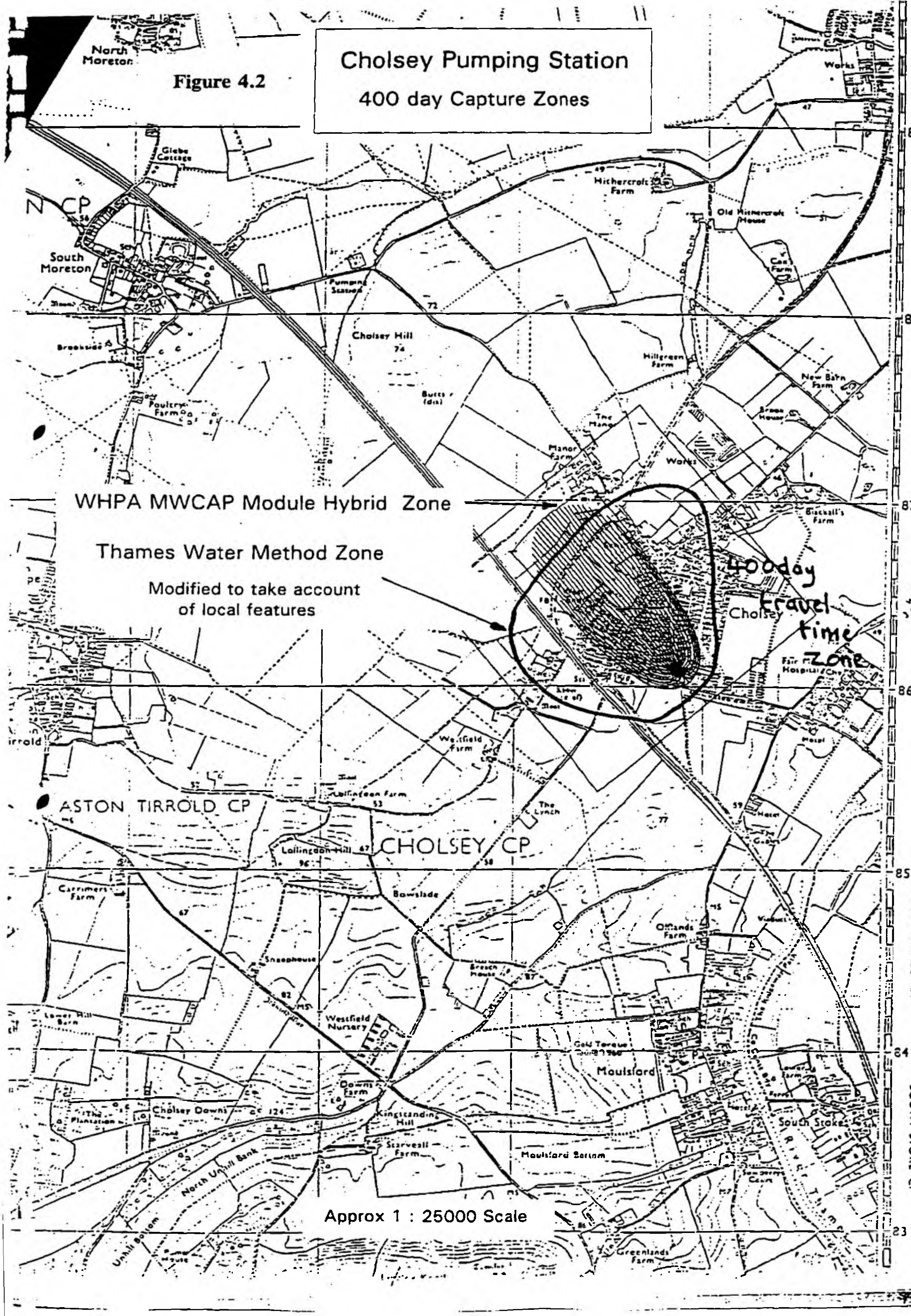


Figure 4.2
Cholsey Pumping Station
400 day Capture Zones
WHPA MWCAP Module Hybrid Zone
Thames Water Method Zone
Modified to take account
of local features
400day travel time zone
Approx 1 : 25000 Scale
North Moreton
South Moreton
Glebe Cottage
Hithercroft Farm
Old Hithercroft House
Pumping Station
Cholsey Hill
Hillgreen Farm
New Barn Farm
Poultry Farm
The Manor
Manor Farm
Works
Blackall's Farm
Cholsey
Fair Mile Hospital
Westfield Farm
Lollingdon Farm
The Lynch
ASTON TIRROLD CP
CHOLSEY CP
Lollingdon Hill
Bowsilade
Carrimers Farm
Offlands Farm
Sheephouse
Westfield Nursery
Lower Hill Barn
Moulsford
Downs Farm
Cholsey Downs
Kingstanding Hill
Starveall Farm
Moulsford Bottom
South Stoke
North Unhill Bank
Unhill Bottom
Greenlands Farm
HENLEY CO CONST
SOUTH STOKE CP
89
88
87
86
85
84
23

Case 2: Sculthorpe

Setting

There are three small borehole sources at the site providing a domestic water supply. The boreholes penetrate the Chalk aquifer in the Anglian Eastern Area.

As elsewhere in England, the Chalk is characterized by high porosity but low primary permeability which is greatly enhanced by fissuring. Yields are dependent on the number of fissures intercepted by the boreholes.

The transmissivity at the site is estimated to be between 200-1000m^2/d with an effective porosity of 1%. The saturated thickness is taken as 50m and recharge is approximately 133mm/annum. There is no information available on the local hydraulic gradient.

Parameter	
q (m^3/d)	37
k (m/d)	10
b (m)	50
n	0.01
Δ	*
Recharge (mm/a)	133

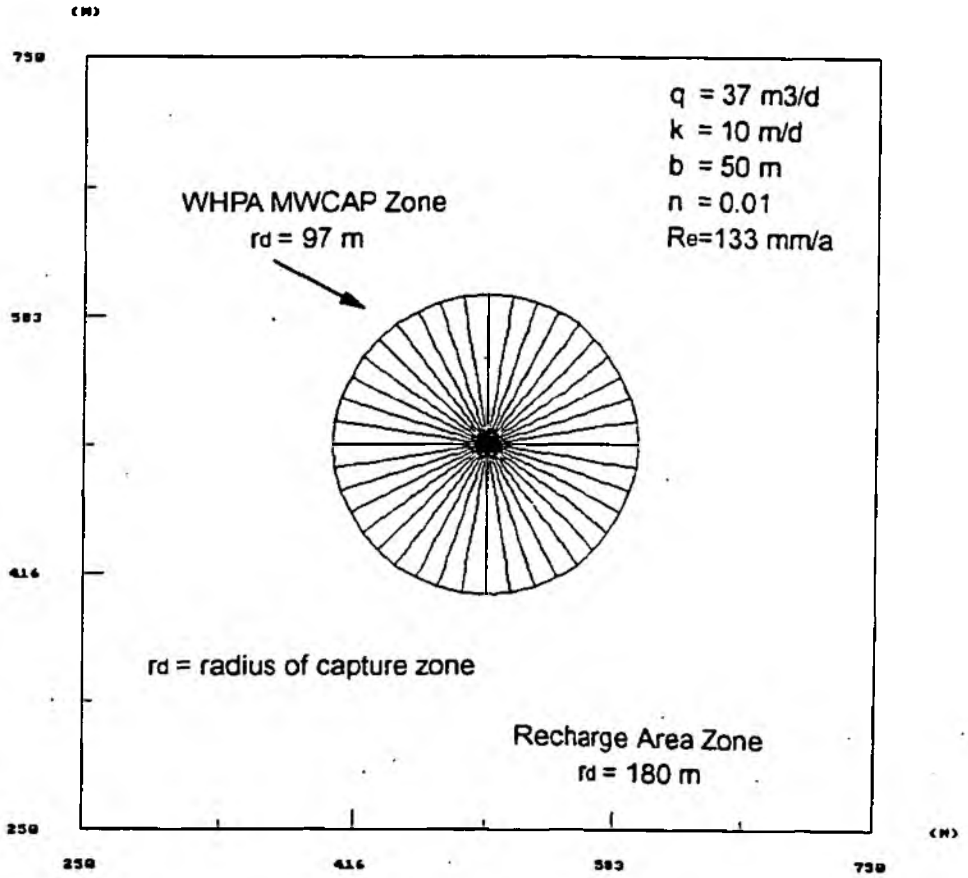
Analysis :
In the absence of hydraulic gradient data, the water table is assumed to be horizontal, and capture zones, derived on this basis are circular.

Figure 4.3 shows the computed 400 day circular capture zone, delineated using the WHPA MWCAP module. This module predicts a radius of some 97 m, which agrees with the values derived from equation (3.8)

The radius of the circular "recharge area" (from equation 3.1) = 180 m, from which the minimum 400 day radius can be determined from the 25% rule as 90 m. The 180 m radius represents a travel time of 1373 days or approximately 3.75 years, (from equation (3.9))

The consequence of omitting data on hydraulic gradient is a circular protection zone which underestimates the upgradient extent of the actual t_d zone. Although the MWCAP radius is greater than that deduced from the "25% rule", nevertheless ignoring hydraulic gradient from the calculations leads to reduced protection.

Figure 4.3 Sculthorpe



Case 3: Chipstable

Setting

The source consists of a single borehole penetrating Devonian slates and sandstones (Pickwell Down Beds) in the Southwestern Region.

The aquifer consists of mainly weathered slates forming a relatively shallow fissured aquifer. The porosity and primary permeability are generally low and unknown and the yield is largely dependent on the presence of fissures.

The borehole is drilled to a depth of 70m although the active aquifer horizon is estimated to be about 30m thick. The specific yield is taken as 0.5%. Recharge is estimated to be some 700mm/annum (rainfall minus evaporation, no runoff), but the capacity of the aquifer to accept this volume is considered unlikely. There is no information on hydraulic gradient or permeability

Parameter	
q (m^3/d) q(Ml/a)	20 4.6
k (m/d)	*
b (m)	30
n	0.005
Δ	*
Recharge (mm/a)	700

Analysis :

NRA Southwestern derived a circular zone 2 based on annual abstraction and recharge, but increased (x2) to allow for fissure flow, (x2) for late summer conditions and (x2) for surface runoff in winter when the ground is fully saturated.
Thus the area of the zone was estimated as : 4.6*2*2*2*1000/0.7 = 5.3 ha. which, assuming a circular shape, has a radius of 129 m.

The area of the zone 1 was determined in a similar manner as follows : 50 days @ 20 m^3/d =1000 m^3. Assume specific yield = 0.5%, then 200,000 m^3 of aquifer is required to support the abstraction. Increase (x2) for fissure flow and (x2) for late summer (lower water levels with thinner aquifer) = 800,000 m^3 of aquifer storage required. With b=30 m, surface area = 800,000/30 = 26700 m^2, say 180 x 150 m^2, or radius of circular zone = 92 m.

WHPA RESSQC & MWCAP modules require porosity $n \geq 0.01$, and transmissivity T ($=kb$) > 0 . Since neither of these conditions hold true, WHPA cannot be used for the problem.

Assuming recharge =700 mm/a, then from equation (3.1) the radius of the "recharge area" would be $\sqrt{(4.6*1000/(0.7\pi))}$ =46 m. However, given the uncertainty in the assimilative capacity of the aquifer to absorb 700 mm of potential recharge, the 46 m circle must be considered to represent a lower estimate for the TCZ of the source.

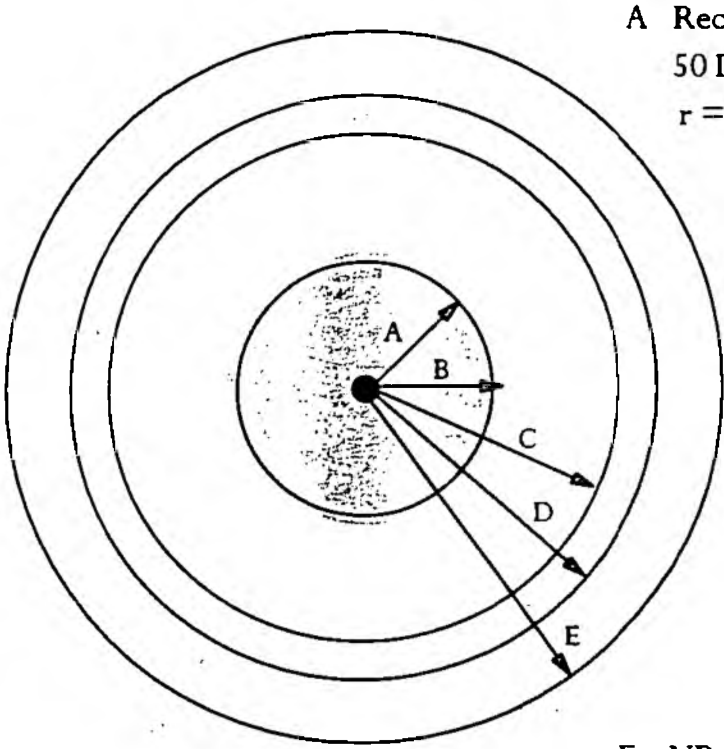
Alternatively, from equation (3.8), the area of the 400 day zone would be :
5300/(30*0.005) =35333 m^2, giving a radius of 106 m, and the area of the corresponding 50 day zone = 6667 m^2 with a circular radius of 46 m.

Note that with an annual maximum of 4.6 Ml and a daily maximum of 20 m^3, the maximum abstraction in 400 days is: (4600 +35*20) = 5300 m^3

Arguably, a 50 m zone 1, (50 day zone) conforming to the MAFF Code of Good Practice, and a 100 m zone 2 (400 day) could be specified, but these values have no regard to the complex local conditions. The effects of hydraulic gradient have also been ignored. In practice, if the water table configuration is considered to follow the surface topography, albeit at a reduced gradient, then carrying out sensitivity studies using values for Δ ranging from zero to the surface gradient is likely to improve the estimate of the capture zone.

Figure 4.4 Chipstable

Comparison of calculated 50 day and 400 day Circular Time of Travel Zones



A Recharge Area (Eqn 3.1)
50 Day zone (Eqn 3.8)
r = 46 m

B MAFF COGAP Zone
r = 50 m

C NRA - SW
50 Day + Safety Margin
r = 92 m

D 400 Day zone (Eqn 3.8)
r = 106 m

E NRA - SW 400 Day + Safety Margin
r = 129 m

Case 4: Sherwood Sandstone

Setting

The scenario represents a typical well/borehole source in the Sherwood Sandstone aquifer in the North West Region. The flow regime is intergranular and darcian, and the formation has a high porosity and relatively high permeability which is enhanced by fracturing.

The transmissivity varies between 250-300m^2/d and the specific yield varies between 0.1-0.15. The permeability is approximately 1.2m/d. The borehole is assumed to fully penetrate the aquifer but no information is available on the local hydraulic gradient or recharge.

Parameter	
q (m^3/d)	100
k (m/d)	1.2
b (m)	225
n	0.13
Δ	*
Recharge (mm/a)	*

Analysis :

In the absence of estimates of recharge and hydraulic gradient, circular capture zones may be delineated using equation (3.8), thus:

The area required to support the 400 day abstraction = 100*400/(225* 0.13) = 1367 m^2
$\therefore$ radius of 400 day zone $= \sqrt{(1367/\pi)}$ = 21 m.

The MWCAP module produces the same result.

The radius of the Zone 1 could be set at 50 m, using the MAFF code, and the travel time corresponding to this = 2300 days. Extending the zone radius in this manner is a plausible way in which to compensate for the lack of recharge and hydraulic gradient data.

If recharge is assumed to equal 365 mm/a, then the corresponding area associated with the abstraction would be : 100*365/0.365 = 100000 m^2, and the radius of the circular area would be 178 m. From equation (3.8), the associated travel time = 80 years. On this basis, the extent of the zone 2, assuming 25% of the total catchment area would be a 90m radius circle.

Case 5: Bedford

Setting

The scenario represents a typical well/borehole in the Bedfordshire Great Oolite Limestone in the Anglian Central Area.

The Great Oolite Limestone comprises thin limestone beds intercalated with clay or marl beds. The Cornbrash and Blisworth Clay sediments act as confining layers, but due to the lack of information on the aquifer it is not certain whether confined or unconfined conditions occur across much of the area. The limestones are fissured and fractured although the main fissure horizons are confined to the upper few metres of the formation.

The transmissivity values for the limestones are within the range of 120-1830m^2/d with an average of 570m^2/d. Storage coefficient values are within the range 0.0001 - 0.002, with an average value of 0.0008, reflecting the confined aquifer. The hydraulic gradient varies between 0.001-0.002 and recharge is some 135mm/annum. The effective porosity is unknown.

Parameter	
q (m^3/d)	150
k (m/d)	11
b (m)	50
n	*
Δ	0.0015
Recharge (mm/a)	135

Analysis :-

The WHPA modules requires porosity n > 0.01 therefore cannot be used for this problem.

Similarly, equation (3.8) also requires a value of porosity and therefore cannot be used either.

Now from basic capture zone hydraulics, equations (3.4) & (3.5), the down gradient distance to the null point in the flow field $x_L = 150/(2*\pi*11*50*0.0015) = 29$ m, while the lateral extent of the capture zone : $2*y_{max} = 2\pi x_L = 2*91$ m = 182 m
The recharge area is given as 150*365/0.135 m^2 = 405556 m^2, yielding a radius of 359 m.

An alternative method using equations (3.4) & (3.5) together with the recharge area may be used to construct an approximation to the capture zone as follows :

From equation (3.3), the intersection of the boundary flowline with the line perpendicular to the hydraulic gradient and passing through the source occurs at a distance y_o equal to that of the null point x_L down gradient from the source. Figure 4.5 shows the approximation to the capture zone which may be constructed as follows :

Down gradient : semi-circle of radius x_L
Up gradient : trapezium of minimum width $2x_L$ at the y-axis and maximum width at distance x_d from the y-axis of say $2y^*$ where y^* is the average of x_L and y_{max} .

The up- gradient extent may be determined by equating the areas of the geometrical figure to the recharge area :

Recharge area : $A_R = 405556 \text{ m}^2$

Area of semi-circle : $A_c = 0.5\ \pi\ x_L^2 = 1321 \text{ m}^2$

Area of trapezium $A_T = 0.5\ (3x_L + y_{max}) * x_d$ = where x_d is the upgradient distance

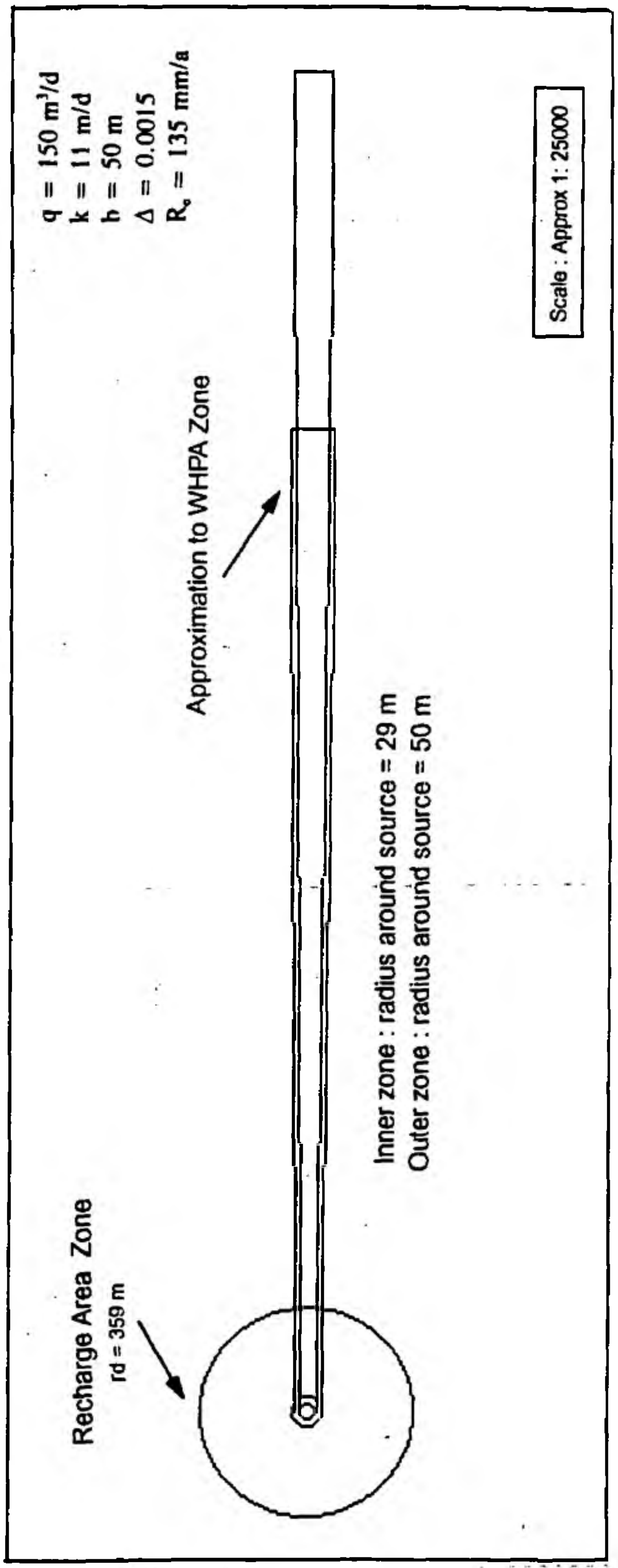
Now $A_R = A_c + A_T$ from which x_d may be determined as : 4542 m

Alternatively, assuming a zone of minimum radius = 50 m around the source, then A_c = 3927 m,

and $A_T = 0.5(3*50+91)x_d = 121x_d$, from which x_d = 3319 m

To summarise, the circular protection zone with an area equal to the recharge area of the source has a radius of some 360 m. In contrast, the simple geometric representation of the capture zone extends over 4.5 km up gradient, although with a minimum zone of 50 m radius around the source, the distance reduces to some 3.3 km. A "400 day" zone based on the 25% rule, would extend a distance 1725 m or 975 m up gradient assuming that the width of the zone remains equal to y_o . The practicalities of delineating protection zones over 1 km long and < 100 m wide cannot be ignored.

Figure 4.5 Bedford



Case 6: Staines

Setting:

The borehole abstracts from Thames Valley river gravels at Staines in the Thames NRA Region. The area is relatively flat and low-lying and is covered by river deposits of the Thames and its tributaries. The river gravels are underlain by London Clay. The flow regime in the gravels is darcian intergranular flow.

The borehole has a total depth of 8.5m with a diameter of 0.61m. The transmissivity of the gravels is taken as $50m^2/d$ with a specific yield of 0.2. The saturated thickness of the aquifer is estimated to be some 7m, with a relatively flat water table across the area. The river is only 100 m distant from the borehole and is considered to provide a significant but unknown proportion of the total yield. The hydraulic gradient is unknown. Recharge is also unknown, but an estimate, based on regional values has been assumed

Parameter	
q (m^3/d)	100
k (m/d)	7
b (m)	7
n	0.2
Δ	*
Recharge (mm/a)	250 est

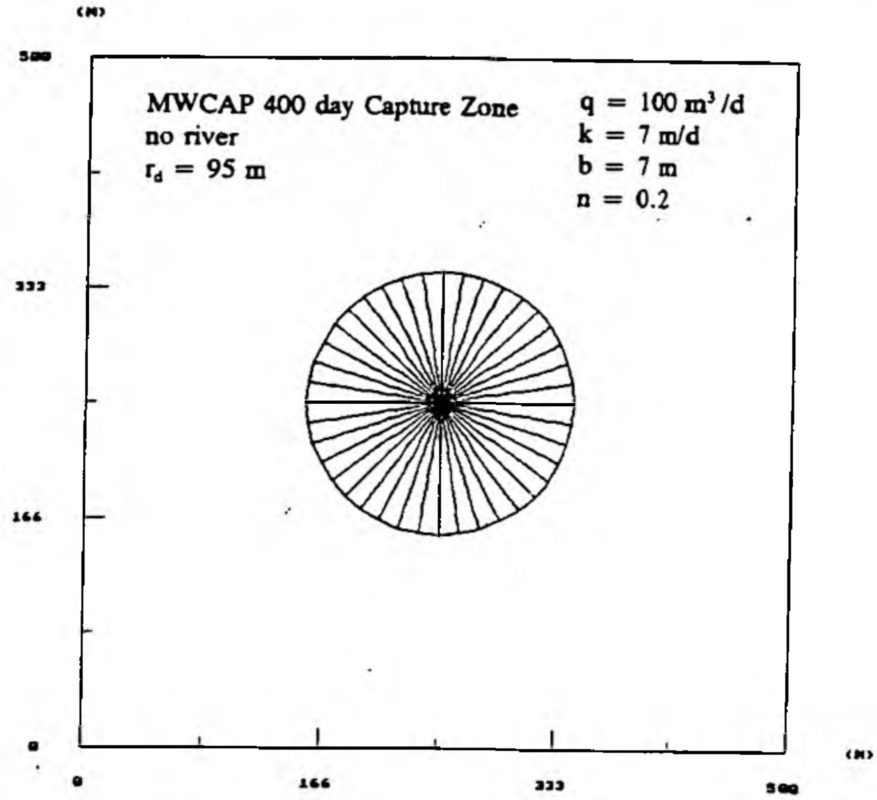
Analysis:-

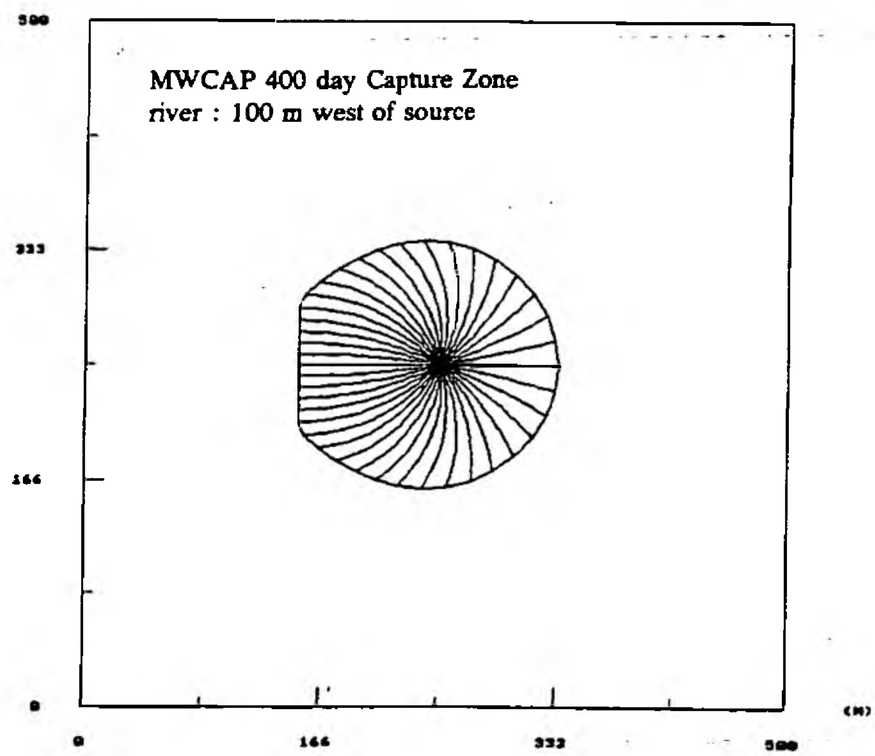
Approximate radius of recharge area, assuming no contribution from the river, $=\sqrt{(146000/\pi)}$ = 216m.

The WHPA MWCAP module cannot produce either steady state or hybrid capture zones because the hydraulic gradient in unspecified, but they can produce circular travel time zones. For t_d = 50 & 400 days, the corresponding radii = 34 m & 95 m. respectively. The 400 day zone is shown in Figure 4.6a

The MWCAP module allows river boundaries to be considered. Figure 4.6b shows the resulting 400 day zone assuming the river is 100 m west of the source, running in a north-south direction.

Figure 4.6 Staines





Practical application of zone delineation methods to small sources

4.3 There are a number of practical issues, arising from the case studies which affect the delineation of capture zones around small sources :

- available methodologies
- effects of data shortfalls
- practicalites of delineating zones
- hydrogeological setting
- delineation of zones in non-darcian aquifers

and these issues are discussed below

4.4 Table 4.1 lists the methodologies which have been used so far in England & Wales to delineate capture zones around sources and records the advantages and disadvantages of each method. An evaluation of these methods has been carried out by the NRA Project Review Panel and Groundwater Centre in order to define those which are most suitable for small source use and to assess their ease or rapidity of application. These are described in Table 4.2 and comprise the current definitive NRA list of recommended techniques. The following ten sections 4.5 - 4.14 provide more detailed guidance on the applicability of the seven NRA techniques which are available and should be read in conjunction with Table 4.2.

4.5 Numerical modelling is clearly the preferred method, but there may be difficulties in specifying a computational grid with sufficient resolution to fully describe the flow regime in any given situation. The Bedford case study, for example, illustrates the point, with the null point in the flow field only 29 m from the borehole when it is abstracting 150 m^3/d. The dimensions of the finite difference mesh used to resolve such small distances accurately clearly have to be locally very small, (say $x_L/10$, where x_L is the distance between source and null point) which tends to be impractical, in terms of computational efficiency and accuracy. Conversely, Figure 3.19 shows the capture zone for a source abstracting 250 m^3/d determined using FLOWPATH, which agrees reasonably well with the results from the ABARM analytical model illustrated in Figure 3.18. With the set of aquifer parameters used for those examples, numerical modelling produces acceptable results, albeit with poor rates of convergence and extended run times. For the Bedford study, however, analytical methods are better suited to defining the capture zones.

4.6 Other significant disadvantages to using numerical models are the need for a sound conceptual model of the groundwater flow in the catchment, and the substantial data requirements. In many instances, the detailed understanding of the catchment hydrogeology is not available nor are there sufficient data to develop and calibrate the model. In such circumstances, it is more appropriate to use analytical models, with their minimal data requirements.

4.7 The ABARM model is a compromise between the simplistic analytical models, (WHPA and QUICKFLOW) and the more complex (in terms of aquifer representation) numerical models. At present, however this model is not available as a commercial package, neither is it in the public domain, and therefore it cannot be recommended for general use.

4.8 The WHPA model is recommended for general use when delineating capture zones in darcian aquifers, but the implications of using the model with less than the minimum data requirements must be noted. Specifically, if hydraulic gradient data are absent for example, the model assumes that the water table is flat and the resulting zone is a circle. This clearly underestimates the extent of the capture zone in the up-gradient direction. In the absence of field measurements of hydraulic gradient, it is suggested that estimates based on the surface topography be used, albeit with caution, and sensitivity runs be carried out. The MONTEC module would, for instance, provide a useful sensitivity indication for a range of gradients

4.9 Geological controls and hydrogeological boundaries influence the shape of capture zones, and unless such factors are taken into account, the resulting zones are likely to be in error. It is recommended, therefore, that local knowledge be used as necessary to modify the capture zones delineated by WHPA on a case by case basis.

4.10 If estimates of permeability or porosity are unavailable, then WHPA cannot be used, and recourse to the empirical methods of Section 3 is recommended.

4.11 The results from the studies carried out by NRA-GC on the effects of parameter combinations on the shape of capture zones, and which are appended to this report as Volume III, suggest that there are likely to be practical problems associated with designating zones around the very small sources with parameter uncertainty adding significantly to the problem. This difficulty may be overcome, to an extent, by adopting a fixed lower abstraction rate to define minimum levels of protection under given hydrogeological conditions. Since domestic abstractions less than 20 m^3/d are excluded from Water Resource licensing control, it is an NRA Review Panel recommendation that the capture zones for all sources of $\leq$ 20 m^3/d should be represented by the zones delineated for this value.

4.12 If a minimum abstraction rate is adopted, then pre-defined zonal shapes, based on a representative selection of regional parameters, may be used to produce credible but rapidly applied source protection zones for the many private supplies which have a low GPZ programme priority, but a high public health significance. Such an approach has been proposed by NRA-GC. A compendium of such standard simple shapes has been compiled, together with instructions on use and is included as Volume III. These represent the NRA recommended technique for pre-defined zonal shapes succeeding and replacing the variety of methods applied by Water Authorities or Regions in the past(Table 4.2#5)

4.13 It is suggested that regardless of the method of zone delineation, the minimum radius of an inner protection zone should be 50 m, in accordance with GPP[48] (page 19) and also with the MAFF Code of Good Agricultural Practice. The degree of protection, in terms of travel time, afforded by such a zone clearly varies across the country and examination of the NRA-GC results illustrates this point. But nevertheless, the pedigree is sound and it is likely to be the more defensible for being consistent with an existing practice in the rural environment. This is, however, the only arbitrary fixed radius which is recommended (excepting possibly planning liaison zones which have an indirect link with source protection)

4.14 Comments on the use of basic hydrogeological mapping techniques have been left until the last but this in no way reflects on its utility, because it should be normal practice to use this method as a complement to all other zone definition techniques in order to ensure that the resultant zones make hydrogeological/geological sense. There will also, invariably be instances where aquifer behaviour is poorly understood but where the source is either too large or it is known with some confidence that rapid non-darcian flow through fissures occurs. In these cases, hydrogeological mapping using the standard techniques (outcrop pattern, dip, thickness, structure and flow behaviour estimation, topographic divide, stream baseflow behaviour, hydrochemical anomalies etc) may be the only applicable zone delineation method.

Table 4.1 Available methodologies for capture zone delineation

Capture zone Methodology	Parameters which can be represented	Advantages	Disadvantages
Hydrogeological Mapping	• system boundaries & approximated divides	• Should be combined with all other methods • Good for karst & fractured aquifers with strong geological control	• Poor in areas with distinct boundaries • Not quantitative
Fixed radii circular zones	• None	• Low cost • Easy and quick to implement • Highlights lack of data	• No technical basis • Does not have regard to local hydrogeological conditions
Calculated circular zone based on recharge & abstraction	• Recharge • Time of Travel • Abstraction Rate	• Low cost • Easy and quick to implement with minimal data requirements • Some technical basis	• Does not have regard to local hydrogeological conditions • Does not represent catchment or time of travel zones
Standard shaped zones based on idealized representation of local conditions	• Hydraulic Gradient • Hydraulic Conductivity • Aquifer Thickness • Effective Porosity • Recharge But all as single value parameters	• Can represent a very simple system • Easy and quick to implement • Semi-quantitative	• Local conditions may differ significantly from those used in the initial delineation • Data may not be available
Analytical modelling - WHPA, Quickflow, ABARM	• Hydraulic Gradient • Hydraulic Conductivity • Aquifer Thickness • Effective Porosity • Recharge • Simple Recharge/Barrier Boundaries • Some limited parameter variability possible	• Capture zones based on idealized representation of local aquifer conditions • Can represent a simple system • Quantitative • simple & uniform boundaries & recharge allowed for	• darcian flow assumed • Modest data requirements • Assumes infinite aquifer. • Does not allow complex boundary and recharge effects to be considered
Numerical Modelling - FLOWPATH ,MODFLOW	• All hydrogeological parameters • Much flexibility in varying parameters	• can represent most Geological & hydrogeological boundaries	• Conceptual model of local hydrogeology required • Significant data requirements, • darcian flow assumed, • Practical difficulties of obtaining adequate resolution of the flow field

Capture zone delineation in non-darcian or poorly documented aquifers

4.15 Many small sources are located in aquifers where the flow regime is non-darcian. In these aquifers classical groundwater flow theory does not apply and the analytical and numerical methods described in Section 3 should not, in principal, be employed. The extent to which they may be used, however, depends upon the distribution of fissures and fractures at the catchment scale and the degree of homogeneity in their distribution. Such research that has been carried out on non-darcian flow has suggested that capture zones delineated by classical methods are likely to underestimate the extent of the zones calculated by more appropriate numerical methods, which do have regard to the longer flow paths within the fractures. Unfortunately, the degree to which classical methods understate actual zones is likely to be aquifer dependent, and thus they should be used with caution, with local knowledge being used to modify the predicted zones. In karstic aquifers the discrete nature and distribution of the fissures ensures that even dual porosity models are inappropriate and the delineation of capture zones around specific sources should be carried out on a case by case basis. For the present this means that source protection in karst will be guided by pragmatic considerations in the absence of more rigorous numerical methods.

Consultation Zones

4.16 In those aquifers where classical methods are deemed inappropriate, or in the absence of reliable data on a regional scale, it has been suggested that " Source Consultation Zones" be designated. One definition (proposed by NRA Southwestern) of a "Source Consultation Zone" is : "the zone within which the source catchment is highly likely to be situated, defined using currently available hydrogeological knowledge, but taking a precautionary and inclusive approach where there is a limitation in that knowledge". In practice, such a zone is likely to represent the best estimate, based on local knowledge, of the catchment zone of an individual or group of sources.

4.17 In contrast, NRA Anglian have suggested that consultation zones could correspond to the whole aquifer outcrop to allow for unknown and possibly very long flow paths. In the East Anglian chalk, for example where very fast travel times are encountered, particularly during the winter recharge periods, the flow regime tends to be non-darcian and there are clear difficulties in using classical methods. Similarly NRA Thames have suggested that consultation zones could be designated in highly fissured and karstic aquifers, because only local knowledge of the area will allow credible capture zones to be drawn. One consequence of designating consultation zones on this basis is that zone delineation could be carried out reactively on a case by case basis possibly using appropriate field techniques.

4.18 There are therefore a number of "Consultation Zone" options which are emerging from NRA Regions and further dialogue and consultation is needed at a national level to bring about a convergence of views on their nature and role in groundwater protection. Whichever option may be adopted, a set of techniques for zonal delineation will be required and pending the convergence of a consensus view on such zones the present small source programme will concentrate on the development and modification of the other zonation aids described in this report. Table 4.2 summarises the available methods. while Table 4.3 provides practical guidance on the application of the methods and Table 4.4 gives the likely applicability of the techniques recommended in Table 4.2 to different aquifer flow conditions.

Table 4.2 Recommended techniques for adoption to delineate small source protection zones

No	Description	Report Section	Report Page	Ease or Speed of application	Comments
1	HYDROGEOLOGICAL MAPPING	-	-	2	Groups wells into hydrogeological domains/aquifer types enabling classification of behaviour; must apply in all case at paper map level and be used in conjunction with other methods to ensure results make geological sense
2	ARBITRARY FIXED RADIUS CIRCLES (AFRCs)	3.5-3.6	18	1	A default 50m radius zone (AFRC$_{50}$) is possibly the only option for either very small sources or those for which further effort is not justified. Other AFRCs not defensible.
3	CALCULATED CIRCULAR ZONES BASED ON RECHARGE & ABSTRACTION (+EFFECTIVE POROSITY & THICKNESS FOR TOTZs)	3.16-3.20	23-27	2	Easy to apply; is clearer when applied to groups of similar q & R_e. Arithmetically valid approach. Where no aquifer parameters available could be used with 50m default AFRC. Problematic if actual daily rates >> annual q/365. Only suitable for TOTZs if no hydraulic gradient available. Underlying concept easy to grasp by non-specialists
4	CATCHMENT ZONES BASED ON CAPTURE ZONE HYDRAULICS	3.21-3.24	25-28	2	Useful starting point where some aquifer parameters, including hydraulic gradient, are known. No TOTZs or upgradient catchment curtailment available.
5	STANDARD SIMPLE SHAPES BASED ON IDEALISED REPRESENTATION OF LOCAL CONDITIONS	3.25-3.33	29-35	1	Previous UK variants may be difficult/inappropriate to apply to small abstraction rates because of extreme variation in shape factor. WHPA-MWCAP code produces EPA hybrid version and has been used by NRA-GC to compile compendium of standard shapes based on parameter values typical of aquifers in England & Wales. These succeed & replace previous SWA,TWA, NRA Southwestern & NRA Thames approaches.
6	SEMI-ANALYTICAL MODELLING WITH WHPA	3.40-3.46	39-45	2	MWCAP module can be used as interactive code where data are adequate to provide non-idealised parameter values. Otherwise use pre-drawn capture zones (see technique 5 above)
7	NUMERICAL MODELLING WITH FLOWPATH, MODFLOW	3.47	45-50	3	Generally only justified where numerous small sources occur across a small area or in vicinity of large sources already being modelled.

Table 4.3 Guidance on practical problems which may be encountered when zoning small sources

No	Description of limitation encountered in application of recommended techniques	Ease or rapidity of application.	Comments/policy advice to aid compliance with recommended techniques
1	SOURCE SO SMALL, NO CALCULATED ZONES CAN ECONOMICALLY BE APPLIED	-	Public health aspects of small sources too important to neglect protection as many used for potable supply. $AFRC_{50}$ can always be applied as minimum measure eg for sources <20 m^3/d.
2	NO PRACTICAL INNER ZONE CAN BE DRAWN .	1	Inner (50day) Zone for low abstraction rates eg less than 20m^3/d may be impracticably small in some groundwater settings. In such cases apply $AFRC_{50}$ as minimum 50 day zone
3	NO PRACTICAL OUTER ZONE CAN BE DRAWN EITHER	1	Where Outer (400 day) Zone is also impracticably small and less than 50m radius in any direction apply $AFRC_{50}$ as minimum 400 day zone following precautionary principle.
4	400 DAY ZONE IS < 25% OF TCZ	2	Where area of Outer Zone ($A_{400} = q*t_d/bn$) at 400 days is less than 25% of TCZ area ($A_t = q/R_e$), choose value of t_d required to produce 25% area by substituting back into equation ($t_d = bn*0.25/R_e$)
5	PREVIOUS ATTEMPT AT ZONING SOURCE EXISTS	1/2	Check method & verify (i) that it is one of the recommended techniques described in Table 5.1 (ii) that it is appropriate to the hydrogeological setting, water use, size of abstraction/flow, methods being applied to other sources in same aquifer unit. If not, apply one of recommended techniques in Table 4.2

Table 4.4 Applicability of zone delineation techniques to aquifer flow conditions

Aquifer flow conditions	Ample data available	Poor data availability
Intergranular flow dominant	e.g q, k, b, n, Re (q > 20 m^3/d) WHPA MWCAP techniques 5 or 6 supplemented by local knowledge & mapping Technique 4 if data array incomplete	e.g. q, Re (q > 20 m^3/d) Techniques 1,2 & 3
Fissure flow dominant but aquifer approximates to darcian conditions	No satisfactory methods yet available but use of methods for intergranular flow supplemented by local knowledge	
Non-darcian conditions or Poorly documented aquifers	q & location plus field data, tracer studies or mapping available : Technique 1 Professional judgement supplemented by local knowledge or fixed 50 m radius zone for zone 1 Combined zone II & TCZ across all or part or the outcrop	Only q and location available Fixed 50 m radius for zone 1 Combined zone II & TCZ across all or part of outcrop*

Notes :- * Possibly subject to revision after NRA evaluation of utility of consultation zones

5 APPLICATION OF AVAILABLE METHODOLOGIES TO SPRING SOURCES

Occurrence of Springs

5.1 Springs occur in a variety of forms and under differing physical circumstances, although they may be broadly classified[50] as those produced by gravity acting on groundwater and those arising from non-gravitational forces deep within the earth. Springs in the latter category tend to be geothermal in origin with their temperature greater than local groundwater and they will not be discussed further in this section.

5.2 A number of "gravity springs" are illustrated[49] in examples A - H in Figures 5.1. Depression springs (A) arise where the watertable intersects the land surface, and such springs may also be *artesian* if the local groundwater table, or piezometric surface is above ground level. Contact springs occur where the plane between a permeable and an impermeable rock intersects the ground surface. Typical locations include the foot of Chalk escarpments at the contact with the underlying Gault Clay for example (B), and in interbedded shales and sandstones. such as the Coal Measures (Westphalian) or Millstone Grit (Namurian) where the restricted recharge area of each sandstone unit can often make such overflow springs transient or flashy in nature. Other contact springs occur at the foot of scree slopes and weathered mantle (C); along fault lines which juxtaposes permeable and impermeable strata together (D, H); or where impermeable barriers (E) extend to the ground surface. Discharges issuing through many of these springs tend to be relatively small, although the flows through fracture springs (F) and in limestones (G) may be somewhat larger. It has also to be recognized that in many cases the local geology of springs is poorly understood.

5.3 Groundwater-fed springs may be seasonal or *ephemeral* in nature, drying up as the water table falls during the summer months, or they may flow continuously as *perennial* springs with only variations in discharge rate throughout the year. If the aquifer storativity is relatively high, as in the Triassic Sandstones, for example, where effective porosity is around 10%, then the seasonal variations in groundwater level, and hence spring discharge, will be relatively low. Conversely, the variations in flows of springs in Chalk aquifers may be relatively high because of the low storativities (0.5 - 2 %) and consequent large groundwater level fluctuations therein. A similar effect can occur as the water-table falls below zones of enhanced permeability; for instance as fissure systems dewater in Jurassic or Carboniferous Limestones or as the potentiometric surface drops below the base of the Middle Chalk into the more argillaceous Lower Chalk. The behaviour of springs in fissure flow systems can also be unpredictable in the sense that the effects of interference between say spring and nearby borehole will depend on the geometry and connectivity of fissures. The presence of a strong spring in such aquifers indicates a well connected, transmissive system, possibly enhanced over time by solution or planar erosion, and such a system could be unconnected or poorly connected to a fracture plane intersection penetrated fortuitously by a borehole.

5.4 In the context of the present small sources contract, the maximum discharge under consideration amounts to some 250 m^3/d and the size of the natural groundwater catchments supporting a spring discharge of such a magnitude may be determined from Equation (3.1) or by interpolation from Figure 3.3. For example, the catchment area to a spring discharging 130 m^3/d (1.5 l/s) continuously in an area with an annual recharge of 180 mm is only 26 ha, equivalent to a radius of 290 m around a borehole of the same discharge. The remainder of this section is concerned with the practicality of delineating "capture" zones or time of travel zones around such relatively small naturally occurring aquifer discharges or springs.

Representation of Springs

5.5 Springs of the type shown in Figure 5.1A (depression springs) are perhaps the commonest type modelled. Denoting the ground level at the spring by h_g and the local water table elevation as h, then as a first approximation the discharge q_s may be considered to be proportional to the difference between these two levels as :

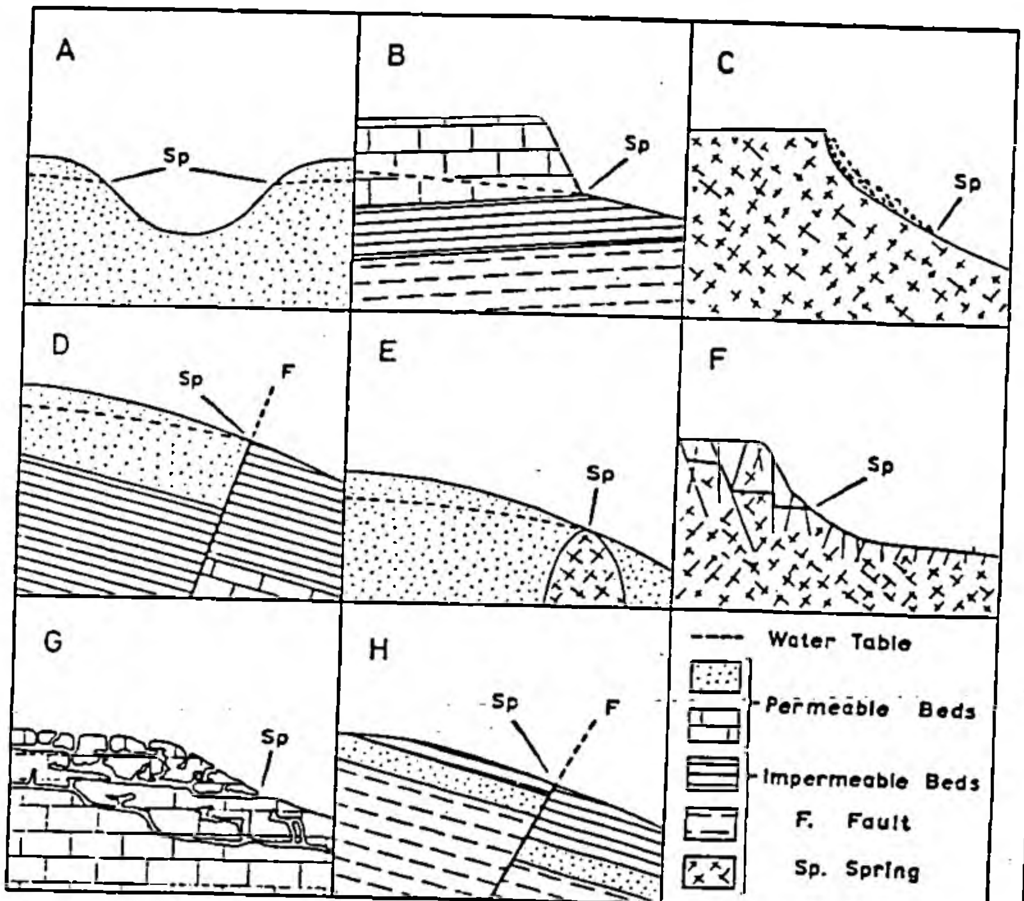
$$q_s = L_s(h - h_g) \text{ whenever } h \geq h_g \qquad (5.1)$$
$$q_s = 0 \text{ for } h \leq h_g$$

with L_s = spring leakage factor. In steady state groundwater models, springs are either flowing ($q_s > 0$) or not present, for ephemeral flows cannot be accommodated.

5.6 Perennial springs of the types illustrated in Figures 5.1B- 5.1E, particularly where they occur as the discharge point for the catchment as a whole, may be represented in groundwater models as "Fixed Heads" with the watertable h equal to the local ground elevation h_g, and the discharge q_s equal to the balance of catchment recharge minus any abstraction.

5.7 Where springs are used as a source of water supply, and many of the small unlicensed upland sources listed in Table 2.1 occur as springs, only a proportion of the flow may be used for water supply and excess water may continue to flow downstream of the discharge point. When considering source protection, it is clear that protection must be afforded to the total spring discharge, as the travel paths in the aquifer of waters issuing through the spring at any instant of time are clearly unknown. Therefore, protection zones around springs which are used as sources of supply must be derived on the basis of the total flows issuing through the spring.

Figure 5.1 Typical Occurrence of "Gravity Springs"



Source :
Principles of Hydrology
R C Ward, (1967)

Delineation of Spring Protection Zones

5.8 Springs arise as natural aquifer discharges rather than as forced discharges through borehole abstractions. Capture zones or protection zones however, are usually referred to in the context of well protection, and the methods described in Section 3 are normally used in that particular context. However, it is instructive to examine the groundwater configuration around various types of spring in order to assess the suitability of the available capture zone methodologies for delineating such zones around them. In particular, the problems associated with the delineation of total capture zones and time of travel zones around depression springs and contact springs in homogeneous aquifers are discussed below using two simple numerical modelling examples. In the first example, the simulation of a *depression spring* by the equivalent abstraction from a borehole at a rate equal to the spring discharge is described. While in the second example, the discharge from a wedge shaped aquifer is used to simulate a *contact spring*.

Depression Springs

5.9 A series of tests were carried out using FLOWPATH to determine the resulting groundwater configuration in a homogeneous aquifer arising from a small spring discharge. The catchment was assumed to be square of size 6 km x 6 km with a uniform base set at -25 m OD. Annual recharge was set at 183 mm, while the permeability and effective porosity were taken as 10 m/d and 1% respectively. Groundwater levels along the western boundary were assumed to be at 0 m OD while the remaining three boundaries were defined as no-flow boundaries.

5.10 In the first series of model runs, an initial grid spacing of 250 m was refined around a point, 2 km distant from the western boundary and 3 km from the northern and southern boundaries, to accurately predict groundwater levels around this area, (see Figure 5.2). A spring as described by equation 5.1 was established at this point using the "Surface Water Cell" formulation in FLOWPATH. The value of the "Spring leakage factor" was set and the model rerun to yield a spring discharge of some 150 m^3/d. Particle tracking was then carried out from a series of points established around a circle of 5 m radius centred on the spring node, and the total capture zone of the spring determined. At this stage, the grid spacing around the spring was 2.5 m, while overall, the model comprised 53 rows and 47 columns, with a maximum spacing of 250 m adjacent to the boundaries.

5.11 In a second series of tests, the spring was deleted and replaced with an abstraction equal to the spring discharge, and the model rerun with all other features remaining constant. The source capture zone was subsequently delineated and then compared with that of the spring. Not surprisingly, the two zones were found to be identical, within the constraints of the modelling, thereby suggesting that "depression springs" may be modelled as abstractions with an equivalent discharge. Figure 5.3A shows the 400 day capture zones delineated around the spring using FLOWPATH. For comparison, the equivalent zone delineated using WHPA -MWCAP is given as Figure 5.3B. It should be noted, however, that in order to use this module, estimates of the local hydraulic gradient and transmissivity are required. However both parameters vary across the model aquifer as the water table varies, and so average values, based on the FLOWPATH outputs were used (see Figure 5.2)

Contact Springs

5.12 Many natural groundwater discharges arise as *Contact Springs* at the point where the junction between a permeable and an underlying impermeable stratum intersects the ground surface, (see Figure 5.1B for example). Such discharges cannot be modelled using the analytical techniques of WHPA because of the local thinning of the aquifer at the point of discharge, and the relatively large changes in transmissivity which can occur. But numerical methods do allow this feature to be considered and therefore, the local groundwater flow regime and the time of travel zones may be determined.

5.13 Figure 5.4 illustrates a small wedge shaped aquifer in both plan and cross-section, which is assumed to be bounded below and laterally by impermeable strata, and which discharges naturally at a single point, representing a contact spring. The permeability of the aquifer is taken as 10 m/d, the effective porosity 10% and the annual recharge equal to 180 mm. The base of the aquifer is taken to be at -5 mAOD at the spring, but dipping to -25 mAOD at the eastern boundary of the catchment which has a total area of some 6.25 ha. With no abstractions in the catchment, the spring discharge is estimated as 31 m^3/d.

5.14 The catchment has been modelled, in plan, using FLOWPATH with the spring represented by a fixed head boundary condition, (FLOWPATH requires at least one fixed head node in the aquifer domain to supply or remove surplus water, in order to satisfy the mass balance constraint). The grid spacing in the model was varied from 5 m around the discharge point to 25 m at the extremities of the catchment. Figure 5.4 shows the resultant steady state water levels in the aquifer, together with the computed 50 day and 400 day travel time zones.

5.15 In the example, the spring is located at the apex of a triangle with a maximum side of length 500 m, and the 400 day travel time zone extends some 175 m up- gradient from the spring. The circular recharge area supplying the spring using the approximation of equation 3.1 only has a radius of some 140 m, and the adoption of this latter method of zone delineation would have led to a serious underestimation of the extent of the total capture zone in this particular situation. Conversely, a semicircular recharge area (because the spring is at the aquifer edge) would have a radius of 200 m, a slight overestimation.

Figure 5.2 FLOWPATH model aquifer used to simulate spring discharges

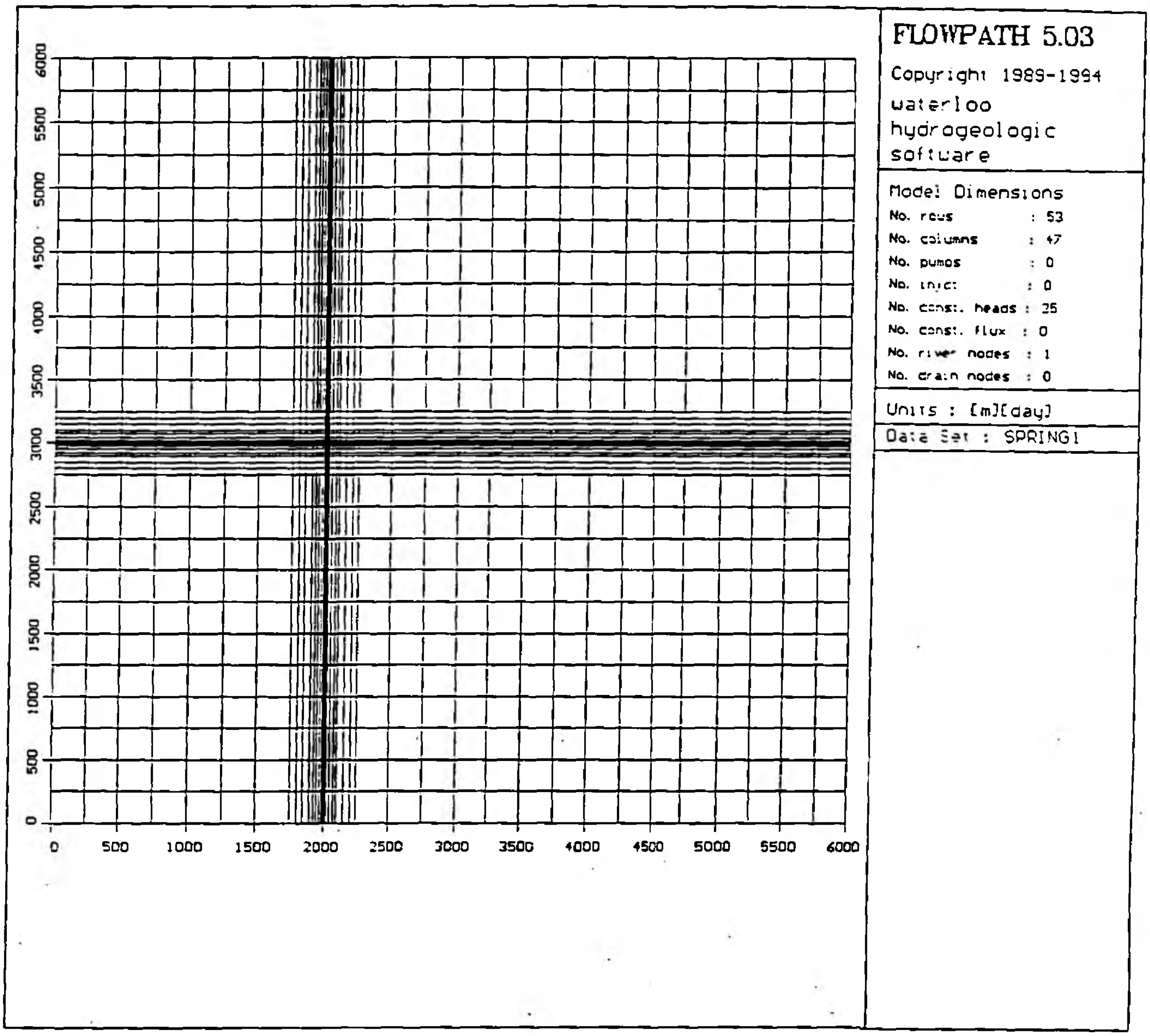
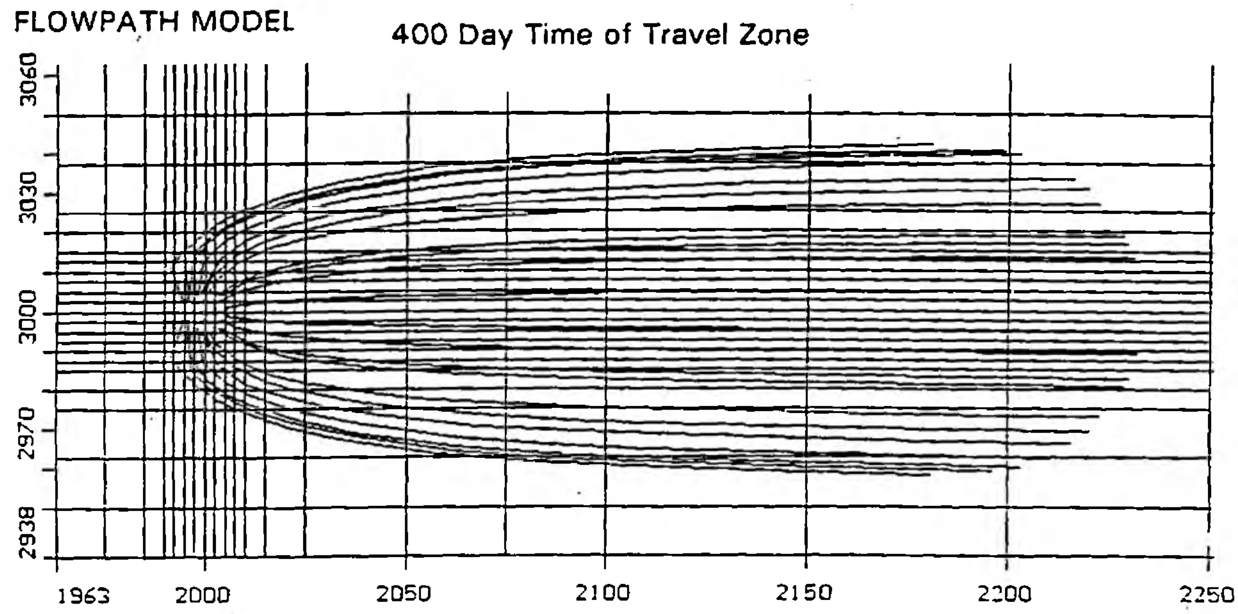
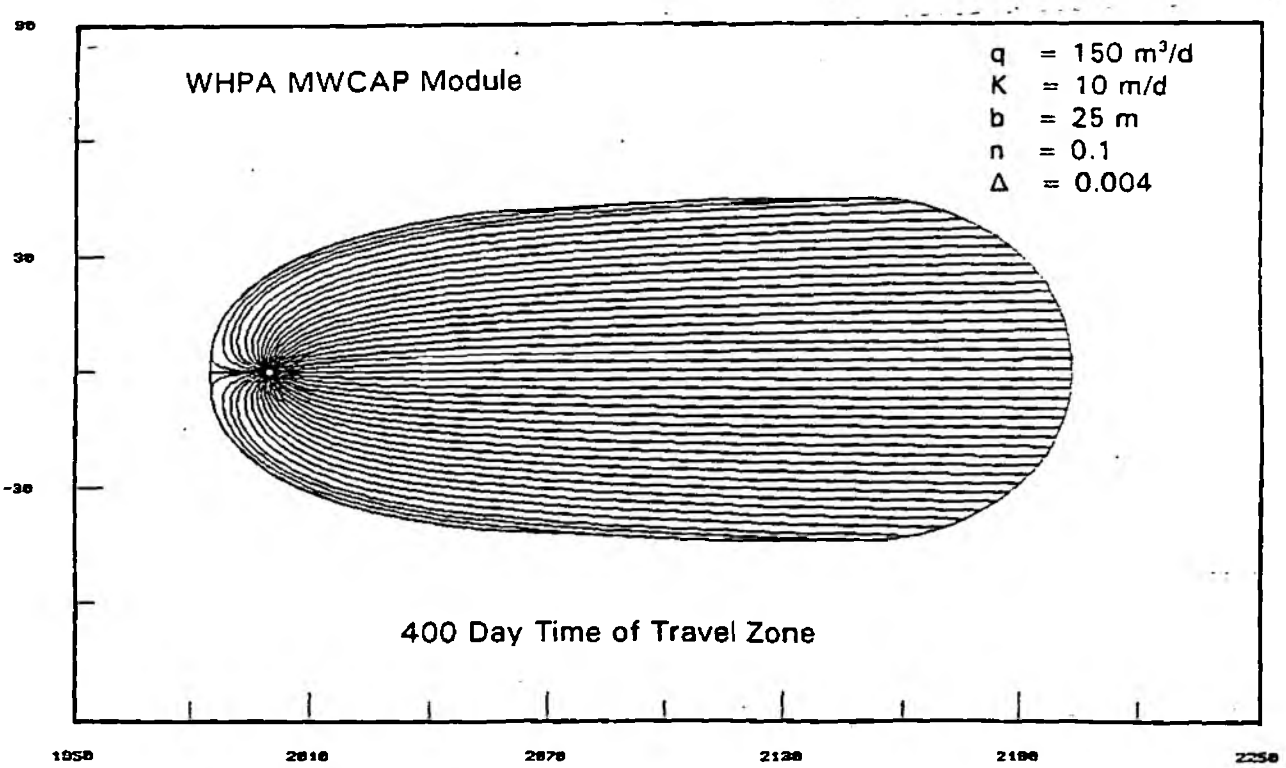


Figure 5.3 Capture zones around a spring discharge





Summary of available methodologies

5.16 The two simple examples described above have demonstrated that it is possible to delineate the capture zones and time of travel zones in two of the more common types of spring setting using the methods described earlier. It is clear however, that the assumptions necessary to formulate the numerical models may not necessarily apply in field situations, and this will inevitably limit their application in some hydrogeological settings. Rapid fissure flow[50], for example, may give rise to local problems, and it is clear that as fissure flow becomes the predominant mode of water transmission, models based on darcian conditions will be unsuitable. No modelling techniques are yet available to cope with karstic flow. The complexity of the local geology which gives rise to a spring may be poorly documented or understood. But such difficulties are not restricted to spring catchment definition and poor data availability is a common problem encountered when attempting capture zone definition around many small sources. The information outlined in Table 4.4 proposes a methodology to overcome such difficulties by suggesting how a lack of data and/or the complexity of the geological setting may be overcome in a given hydrogeological situation.

Recommendations

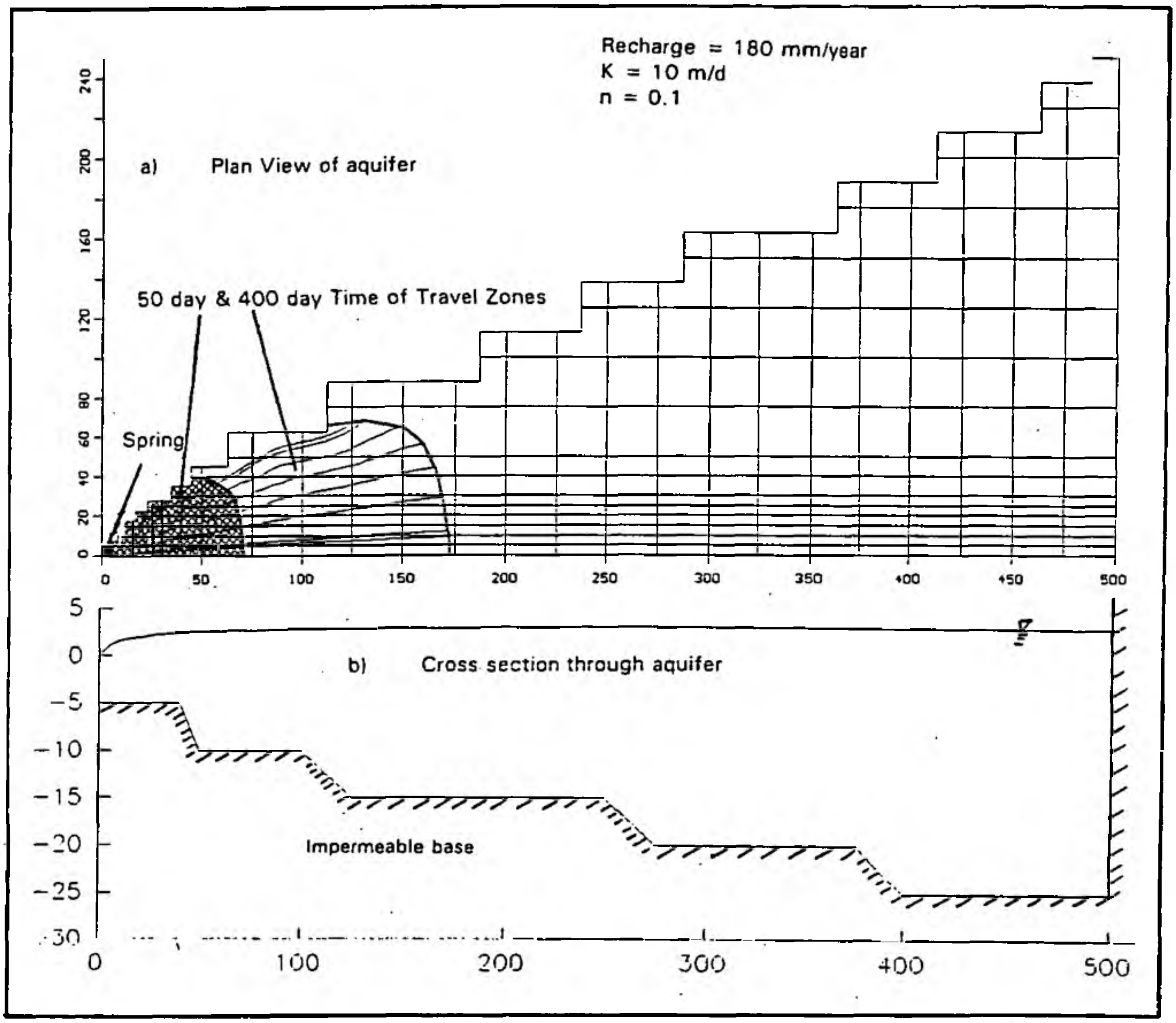
5.17 Wherever springs are used as a small source of supply, protection must be given based on the total flow of the spring.

5.18 *Depression springs* may be treated as boreholes abstracting at the equivalent rate, and the appropriate methodologies, based on the nature of the aquifer and the availability of data may be used to delineate capture zones and time of travel zones around them, (see Table 4.2)

5.19 Captures zones and time of travel zones above *Contact springs* may be delineated numerically, and FLOWPATH is an appropriate tool for this task, but again, the nature of the aquifer and the availability of data and time could make this a non-viable option for the majority of small source circumstances.

5.20 The principles of Table 4.2 should be used when delineating small source protection zones for springs, with emphasis being placed on the use of hydrogeological mapping skills.

Figure 5.4 FLOWPATH Model of Contact Spring



6 CONCLUSIONS AND RECOMMENDATIONS

6.1 The number of small sources in England & Wales ($q < 250\ m^3/d$) is upwards of 76000, with a relatively large proportion in minor aquifers with non-darcian characteristics.

6.2 Methods for delineating capture zones around boreholes in darcian aquifers, (i.e those to which the assumptions of intergranular flow in a porous medium apply), are well established and they are used extensively. Published accounts of the development of protection zone programmes refer to those established around public water supply sources, which, in general, tend to be relatively large abstractions.

6.3 Research into the nature of capture zones in fractured porous media is limited. But studies carried out for the US EPA suggest that wherever the darcian approximation is valid, then the standard theory and therefore the standard methods apply. Clearly, however, these methods may only be utilized if the darcian approximation is valid at the scale of the borehole catchment area. The US EPA studies show, for example, that predicted zones, using numerical models based on darcian flow theory, may severely underestimate actual capture zones if the local fracture or fissure density is relatively low compared with fracture flow models.

6.4 The designation of a minimum 50 m arbitrary fixed radius circle ($AFRC_{50}$) protection zone around a small source, following advice in the NRA GPP and the MAFF Code of Good Agricultural Practice, has a sound pedigree but in practice it provides little protection in low storativity aquifers (Chalk for example) where velocities can be high and travel times correspondingly short, or in low recharge areas. In contrast, in sandstones where the porosity may be an order of magnitude higher, the travel times are significantly longer, thereby providing greater security.

6.5 Arguably the 400 days travel time zone used for GPP Outer Zone designation, is a more appropriate general standard for it allows time for alternative sources to be developed should problems with a given source arise. Such an approach is practised in the US, where small communities are recommended by the EPA to instigate source protection zones, ahead of the State WHPA programmes, based on travel times which provide acceptable risks (in terms of time) and costs to the community of replacing the sources being protected.

6.6 The WHPA model, developed for the US EPA, is a suitable model with which to delineate capture zones of finite extent in aquifers in which the assumptions of darcian flow are valid at the borehole catchment scale. The model, however, cannot directly delineate total catchment zones, (TCZ). Approximations based on the circular recharge area required to support the abstraction, may lead to relatively foreshortened zones, with corresponding short travel times, which could provide inadequate long term protection.

6.7 In practice, actual capture zones are modified by the presence of nearby sources and flow boundaries within the aquifer, e.g rivers, canals, impermeable barriers and groundwater divides etc., and computed zones should similarly have regard to such hydrogeological features where known.

6.8 Comparisons between solutions to the flow equations derived using FLOWPATH and an analytical model which also includes the effects of recharge and local boundaries have shown that it is possible to compute capture zones, including TCZ's, which reflect local hydrogeological features. As an approximation, however, the hybrid zones, produced by the WHPA-MWCAP module give a reasonably conservative representation of the capture zones when truncated at the groundwater boundaries.

6.9 In aquifers in which the porous media assumption is not valid, (for example: in karstic systems where flow paths are usually unknown, and travel times may be very short), or in formations where the complex geology prohibits the identification of recharge areas and/or flow paths it is not practicable to compute capture zones and there appears to be no alternative to the designation of an arbitrary area of land surface. Although circular zones are recognized to be technically inadequate, the adoption of the $AFRC_{50}$ zone would provide a valuable sanitary area around the source which would be the more important in view of the lack of hydrogeological information available. Such circular zones also appear to be intrinsically more acceptable to planning authorities and public alike, their arbitrary nature being offset by the objectivity of a fixed radius circle.

6.10 In sparsely populated upland areas with good geological exposures, or in non-darcian aquifers, delineation of capture zones may be achieved through detailed field mapping, the use of geochemistry or conservative tracers and occasionally with unconventional approaches such as assistance by caving societies.

6.11 One proposal from the regional meetings was for the establishment of "consultation zones" around sources. Given the difficulties of estimating capture zones in the strictly non-darcian aquifers, (those in which the intergranular flow assumption is not valid on the catchment scale) it is suggested that the outcrops of these aquifers be so designated. However, the relative density of sources across the aquifer is important in this respect, for unless they are many and widely distributed, designating the whole outcrop may prove to be over cautious. If consultation zones are to be adopted in future as source protection tools, Regions should identify both the non-darcian aquifers and the extent of such zones to users and potential developers. One way could be to indicate their extent as overlays on the 1:100,000 aquifer vulnerability maps currently in preparation and production.

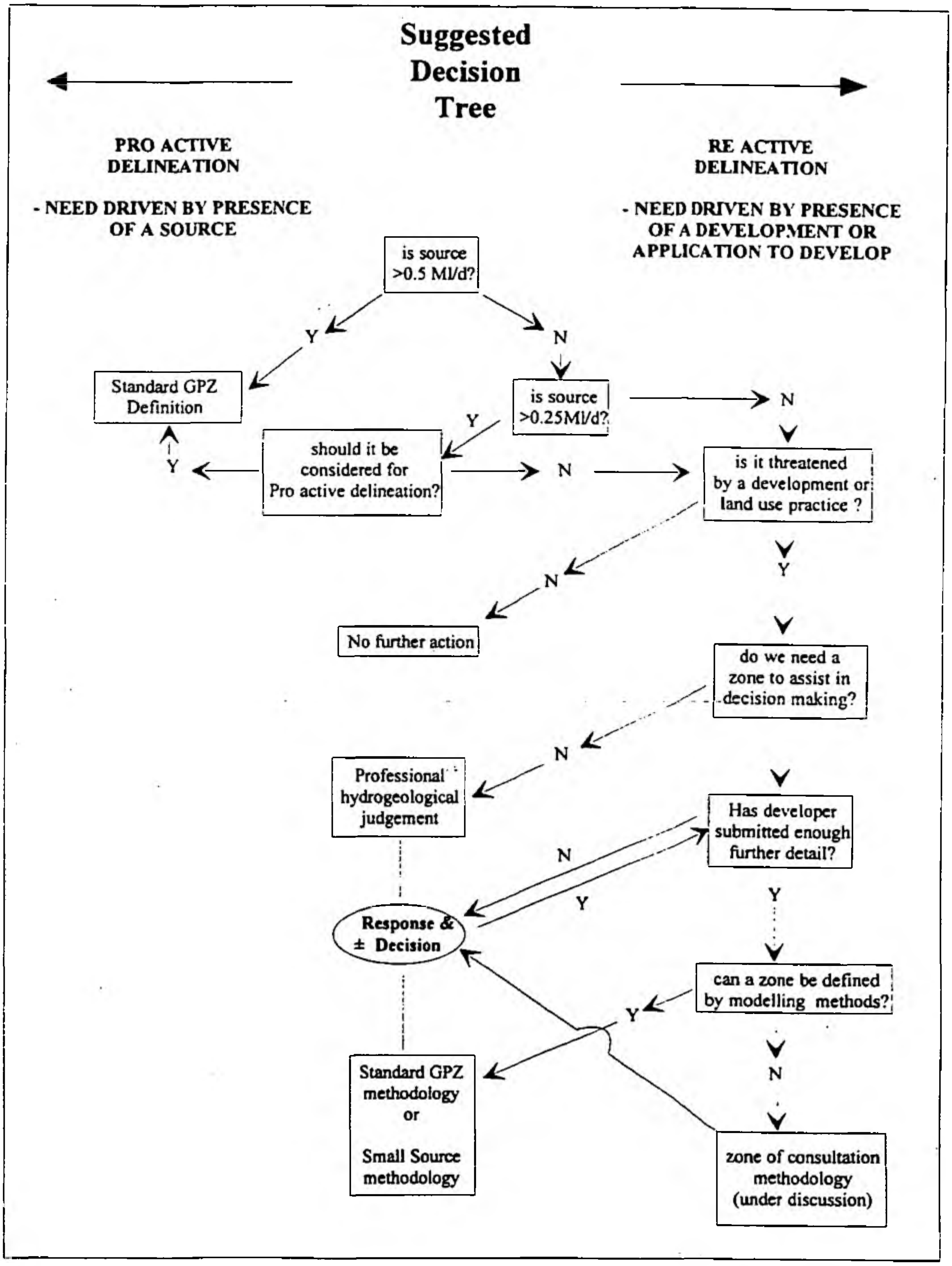
6.12 The nature and methods of defining consultation zones are still under internal discussion within the NRA but one scenario could comprise a 50 m radius circular inner zone around each individual source and a composite outer and total catchment zone covering part or all of the outcrop around an aggregation of sources. Standard protection policies would apply in each zone in accordance with the acceptability matrices shown in the national GPP.

6.13 The designation of an aquifer as a "consultation area", however, while obviating the need to delineate capture zones until "local" developments become a possibility, does not preclude the requirement to have a methodology for responding to the problem if it arises and this project is dedicated to its development. Figure 6.1 shows one suggested approach to the problem.

6.14 In summary, no one method of capture zone delineation would appear to be appropriate in all situations, rather, there exists a range of models and field techniques which may be applied in given circumstances. Table 4.2 summarises the NRA recommended techniques for adoption to define protection zones for small sources.

6.15 A final recommendation restates the truism that every source is located in a unique hydrogeological setting. Regardless of the techniques applied to define its protection zone(s), these will by their very nature be approximations to reality, and so the methods selected should be applied on a case by case basis. An obvious example of this in practice is the application to standard techniques of insights arising from the hydrogeological mapping of features around particular sources. This can only serve to make the zoning more realistic and, therefore, more useful with the added bonus of better defensibility.

Figure 6.1 Example of Small Source Methodology (Proposed by NRA Northwest)



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AUDIT TRAIL

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