Investigation of rising nitrate concentrations in groundwater in the Eden Valley, Cumbria: Phase 1 Project Scoping Study

A joint project by the British Geological Survey and the Environment Agency

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Statement of use
This report describes the methodology and implementation plan for the project and outlines the content of the technical report of the project

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Cover Photograph:
Eden Valley pasture 2003 provided by Barbara Orme, Environment Agency, Penrith.

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1. INTRODUCTION

1.1 Background

The Eden Valley lies between two upland areas; the Pennines to the east and the Lake District to the west. Rainfall in the region is high and the average annual rainfall is approximately 1000 mm/y in the Eden Valley and is in excess of 1500 mm/y on higher ground. Runoff from the adjacent uplands drains to the River Eden, which flows northwards from Kirkby Stephen through Appleby and Penrith to the Carlisle Basin (Figure 1.1).

The Eden Valley, which is aligned approximately northwest-southeast, is some 56 km long and varies in width from 5 to 15 km. The valley floor is underlain by Permo-Triassic sandstones, which form the major aquifers in the region. Groundwater in these aquifers is used by industry, for minor farm supplies and for public water supply. Groundwater resources are considerable and there is potential for further development of the aquifers.

Groundwater was first used for public water supply in the late 1960s and early 1970s, although licensed groundwater abstractions from the sandstone aquifer have not increased much since this period. In recent years, a number of private farm supplies have been drilled, although the quantities pumped are quite small.

The Eden Valley is largely rural with a low population density of about 0.2/ha. Agriculture, tourism and some industry are the major sources of income. Livestock rearing is the main agricultural activity; in recent years more intensive farming and higher stocking densities have resulted in greater applications of fertilisers to grassland and to fodder crops. The spreading of slurry wastes on grassland has increased and both the timing and quantities applied are more dictated by the need to dispose of the slurry than to meet the crops nutrient needs. However, within the Eden catchment there are also significant areas of semi-natural habitat including unimproved grassland and woodland.

Monitoring of abstraction boreholes in the Permo-Triassic sandstone aquifers in the Eden Valley, Cumbria by the Environment Agency (EA), North West Region has shown that whilst most have low nitrate concentrations, there are a significant number of boreholes where nitrate concentrations are above 20 mg/l (as NO_3) and show a rising trend. Some groundwater nitrate concentrations even exceed the EC Drinking Water Directive (80/778/EEC) maximum admissible concentration (MAC) of nitrate in potable water supplies of 50 mg NO_3/l (11.3 mg NO_3-N/l). However there does not appear to be a systematic distribution of these higher nitrate groundwaters, the implication being that either the source of nitrate is localised (point source) or the travel times for water to move from the ground surface to the water supply boreholes are very variable. Long travel times may result in current pumped groundwaters originating as infiltration from the surface prior to the intensification of agriculture (which is the most likely source of high nitrate) and thus be of low nitrate concentration.

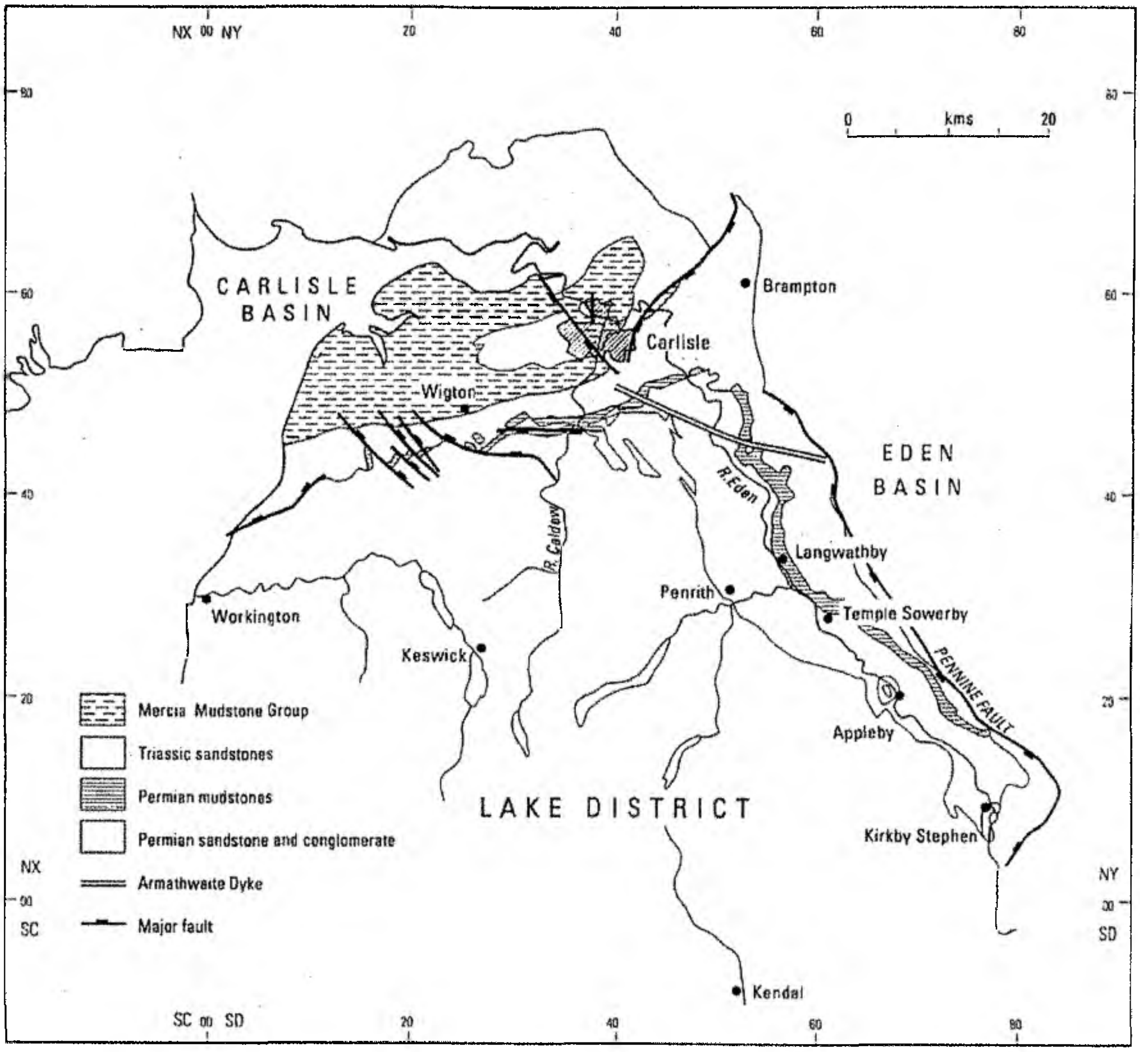

Figure 1.1. Location map

1.2 Potential sources of groundwater nitrate

Nitrate pollution of groundwater arising from agricultural activities has increased largely as a result of intensification and the increasing use of fertilisers. The consumption of nitrogen fertilisers in the UK has increased more than six fold since 1950, whilst the total number of livestock in the UK increased from 108 million in 1940 to 188 million in 1987 (Hooda et al, 2000).

In a review of post-war changes in farming systems, Hooda et al (2000) described how, because of intensified farming practices where large numbers of animals are reared on relatively small areas, the disposal of wastes (e.g. farm manure, slurry, etc.) is becoming an increasing concern. Such wastes are considered as a disposal problem rather than a useful source of plant nutrients. As a consequence, quantities of farm manure and slurry, far in excess of crop requirements, are frequently applied to soils, with storage and weather considerations often determining the timing and rate of application, rather than crop requirements (Hooda et al, 2000).

An assessment of groundwater quality beneath dairy cattle farms in California demonstrated that the most important source of groundwater nitrate originated from the applications of manure and slurry to forage fields (rather than point sources such as slurry ponds or stores) (Harter et al, 2002). An earlier study in the UK to evaluate the risk to groundwater from unlined livestock slurry pits concluded that the contribution of nitrate from such sources was relatively small (compared with that derived from intensively cropped arable or grassland) (Gooddy et al, 2001).

In the late 1980s DOE commissioned research to estimate rates of nitrate leaching from grassland soils overlying both the Chalk and Permo-Triassic sandstone aquifers. This research showed that for lightly fertilised grass pasture, rates of nitrate leaching to groundwater were low. However, when applications of nitrogen fertilisers exceeded 100 kg N/ha/y, then losses of nitrate from the soil to deep percolation became appreciable (Chilton and Foster, 1991). Nitrate concentrations in the porewater of the unsaturated zone beneath grass pasture receiving fertiliser applications approaching 250 kg N/ha/y were similar to, or even higher, than intensively cropped arable soils (Parker et al, 1989).

In the Eden Valley, slurry is widely disposed of to grass pasture and in places at rates in excess of crop nutrient requirements. Rates of nitrogen application in excess of 200 kg N/ha/y are not uncommon. Leaching from these intensively cropped (mainly grass) fields is therefore considered to be the most likely source of the nitrate found in groundwater in the sandstone aquifer.

For large abstraction boreholes, slurry pits represent a relatively small point source of nitrogen within a large groundwater catchment and thus there is considerable potential for dilution (Gooddy et al, 2001). The potential for contamination of a low yielding farm borehole is however much greater because of its smaller groundwater catchment permitting only limited dilution.

1.3 Rationale and research issues

Nitrate is probably the most common and widespread contaminant found in groundwater of the UK. During the late 1990s concern was expressed about the rise in groundwater nitrate concentrations observed in many abstraction boreholes across England and Wales. However, the lack of a good understanding of the hydrogeological and hydrochemical processes controlling nitrate movement, both in the unsaturated and saturated zone, hampers prediction of long-term water quality trends. Concerns about nitrate in groundwater relate to human, livestock and aquatic health and impacts of changes on surface water quality.

Human health

Consumption of nitrate can cause a medical condition called methemoglobenemia or "blue-baby syndrome" in infants under six months of age. Nitrate in drinking water used for instance to make baby formula milk can be converted by chemical reduction to nitrite in the stomach. Nitrite modifies haemoglobin in blood (that part of the blood that carries oxygen to the body) to methemogloben and can result in the infant being deprived of oxygen. Other studies have implicated nitrate exposure as a possible risk factor associated with other disorders including gastric cancer (Fraser et al 1980, Fraser and Chivers 1981).

Livestock health

Nitrate intake by dairy cattle is related to the levels found in forage and drinking water. According to research conducted on dairy cattle (Crowley, 1974), nitrate in drinking water at levels under 10 mg/l is considered to be safe for animal and humans. Between 10 and 20 mg/l nitrate, water is considered as safe for livestock unless their feed has high nitrate levels. Problems for livestock can occur between 20 and 40 mg/l nitrate if feed contains more than 1,000 mg/l. If water is between 40 and 100 mg/l nitrate, feed should be low in nitrate, well balanced and fortified with vitamin A. At levels between 100 and 200 mg/l nitrate in water, poor appetite occurs. If nitrate is over 200 mg/l in water, acute nitrogen poisoning and death is likely in swine.

Aquatic life

Nitrate does not appear to be acutely toxic to adult fish except at extremely high concentrations where mortality is due to salinity effects. However, available research indicates that nitrate concentrations lower than drinking water standards cause substantial egg and fry mortality in some salmonid fish species (Kincheloe et al., 1979).

Surface water

Groundwater can carry nitrogen (in the form of nitrate) into surface water bodies. Plant-available nitrogen and phosphorus in surface water promotes excessive growth of weeds and algae, a process called “eutrophication.” Nitrate supplied by groundwater discharge may cause increases in rooted aquatic plants.

The EA, which is responsible for protecting the environment and, under current European Union legislations (especially the Water Framework Directive and Nitrate Directive), for reversing deteriorating trends in water quality, is concerned about the apparent rising trend in groundwater nitrate concentration in some boreholes in the Eden Valley and the potential impact this may have on both public and private drinking water supplies and on surface water quality. Accordingly, the EA initiated, and co-funded, this scoping study. The purpose of this scoping study was to make a preliminary assessment of the problem, based on existing data, and to recommend what subsequent investigation may be required to provide a sufficient understanding of the causes of the rise in nitrate concentrations and the likely impact on groundwater and surface water quality so that the problem can be effectively managed.

The British Geological Survey (BGS), a national research organisation within the Natural Environment Research Council (NERC), agreed to co-fund and undertake the initial scoping study because it considered that the rising trend in groundwater nitrate was a national issue (as mentioned earlier, similar rising trends in groundwater nitrate concentration have been observed in aquifers within England and Wales). A generalised timetable of project activities and meetings of the Steering Group is in Appendix 3.

1.4 Project objectives

The main objectives of the project are to investigate the causes of rising nitrate concentrations in groundwater in the Permo-Triassic sandstone aquifers of the Eden Valley area and provide sufficient understanding of the groundwater and surface water flow system, including the sources of the nitrate contamination and the processes controlling nitrate movement, so that possible management options for reversing this trend can be considered. However it is accepted that, in this first phase of the investigation, which is a desk-based study, there is probably insufficient data to provide an adequate understanding. Therefore a further purpose of the first phase is to develop technical specifications for field-based investigations to provide the data and understanding needed by the EA to implement management options as necessary.

The broader objectives of any subsequent phases of the project could be, depending on the interest of the Steering Group and the funding available, to provide practical guidance to those abstracting groundwater. Issues that could be considered include:

- how best to protect existing groundwater sources from potential nitrate problems.
- Where to locate and how to construct new groundwater sources to reduce the likelihood of a nitrate problem developing in the future
- How to modify existing sources where a nitrate problem exists
- What tests could be undertaken to assess whether a nitrate problem is likely to develop, or not.

An additional objective of a future phase of work could be to assess the longer term impact on surface water quality of a rising trend in groundwater nitrate concentrations.

It is important to recognise that nitrate is a widespread contaminant of both surface and groundwater and that an EC MAC of 50 mg/l has been set in response to environmental and health concerns.

1.5 Approach

During the 'Project Inception' meeting, the Steering Group considered the availability and location of existing data and reports appropriate for the study. Data from The EA North West Region groundwater monitoring network and several reports were collected and other data from the Steering Group were requested.

A review of the geological and hydrogeological setting in the Eden Valley was undertaken using previous key studies, borehole hydrogeology reports and reviews from the area. As some of the previous reviews (Ingram, 1978, Allen et al, 1998, Younger and Milne, 1997) had aggregated data from the Eden Valley and Carlisle Basin, some reference to the latter has been made, particularly in terms of Permo-Triassic aquifer properties.

Existing literature relating to nitrate concentration in groundwater was reviewed. This review was used to investigate which (and if) specific factors control groundwater nitrate concentrations in boreholes in the Eden Valley. A spreadsheet matrix was developed and several factors considered significant in influencing the groundwater nitrate concentration at the borehole sites were recorded. These factors included bedrock (solid) and superficial (drift) geology nature and thickness, unsaturated zone thickness and borehole construction. These are discussed in more detail in Section 4.1.

A selective data processing exercise was conducted initially focussing on the network of approximately 150 Environment Agency groundwater quality monitoring boreholes in the area around the Eden Valley. Some boreholes examined are located in the Carlisle Basin or at the edges of the Eden Valley. These were retained in the study for comparison with those in the centre of the study area. Where boreholes had not been sampled and tested for groundwater nitrate concentration they were excluded. Borehole construction details held in the National Groundwater Archive were examined to determine whether these were comprehensive enough to use for further study. A subset of approximately 115 boreholes were finally reviewed in greater detail.

The groundwater nitrate concentration data available ranged from single measurements usually undertaken on completion of drilling, to datasets spanning longer periods. The data available from the EA cover the period from 1962 to 2002. However, the frequency of the groundwater nitrate data are generally very intermittent. Data were plotted and a brief assessment of whether any reliable trends in the nitrate concentration could be made.

The spreadsheet was conditionally formatted to classify 'high' (greater than 40 mg/l NO_3), 'intermediate' (20-40 mg/l NO_3) or 'low' (less than 20 mg/l NO_3) groundwater nitrate concentrations in the boreholes. Locations of the boreholes were then plotted onto a series of A0 sized sample maps and colour coded according to their classifications. The maps included several different backdrops including solid and drift geology mapped at 1:50 000 scale, shaded digital elevation models, land use, modelled piezometric contours and surface water features. The maps were useful resources for investigating general spacial relationships, particularly between the locations of boreholes with high groundwater nitrate concentrations and the other mapped features.

In the early stages of the study it was difficult to identify any significant trends in the locations of the high nitrate boreholes. However, subsequently the proximity of several of the higher nitrate boreholes to 'windows' in the superficial (glacial drift) deposits became apparent.

Conceptual models were developed (based on typical hydrogeological settings found in the Eden Valley) to identify possible scenarios that could then be investigated further using numerical modelling. A basic conceptual model was generated and adapted in stages to take account of, and to investigate the influences of the different factors/processes controlling groundwater nitrate concentrations by using numerical modelling. Trends in the surface water quality at selected major flow and water quality gauging locations in the Eden Valley were also examined.

A simple nitrate mass balance exercise was undertaken using surface water nitrate concentration data (provided by the EA) and daily gauged flows of the River Eden and tributaries (provided by the Centre for Ecology and Hydrology) at several gauging points. The data were used to consider the flow regimes present in the catchment and the surface water nitrate flux. This helped in considering the implications of changes in the groundwater nitrate component in the baseflow and hence in the surface water.

Summary

- Groundwater nitrate concentrations in the Eden Valley are variable and patchy: most boreholes have nitrate concentrations less than 20 mg/l but a significant number have higher concentrations, some exceeding the EC maximum admissible concentration for drinking water of 50 mg/l.
- Grass pasture is the most common land use in the Eden catchment and is used for cattle and sheep rearing. Agriculture is quite intensive; especially in the lower part of the Eden valley and nitrogen applications to grassland, both as slurry and as inorganic fertilisers, can exceed 200 kg N/ha/a. In particular slurry is applied to fields in excess of the crops needs.
- Previous research has shown that nitrogen leaching from grassland can be considerable, especially when nitrogen applications exceed 100 kg N/ha/a. Nitrogen leaching from grassland is considered to be the likely principal cause of the rising trend in groundwater nitrate.
- An approach using available data was undertaken to investigate which are the significant factors leading to high nitrate concentrations.

2. REVIEW OF GEOLOGY AND HYDROGEOLOGY

The Permo-Triassic sediments of the Eden Valley are dicussed by Arthurton, et al (1978) within Moseley's volume describing the Geology of the Lake District. Within the same volume, the hydrogeology of the area is described by Patrick (1978). More detailed descriptions of the geology of specific parts of the area are given for example by Arthurton and Wadge (1981), for the Penrith District and Millward and McCormac (2003 in press) for the Appleby District. The Hydrogeology of the Permo-Triassic Aquifers of North Cumbria is described by Ingram (1978) whilst Monkhouse and Reeves (1977) provide a preliminary appraisal of the groundwater resources of the Vale of Eden. More recently the geology, hydrogeology and aquifer properties of the Permo-Triassic aquifers was reviewed (Allen et al, 1997). Younger and Milne (1997) review the hydrostratigraphy and hydrogeochemistry of the Vale of Eden. Relevant information from these studies is summarised below.

2.1 General Setting and Geology of the Vale of Eden

The Vale of Eden lies to the northeast of the Lake District massif (Figure 1.1). The Vale of Eden Basin is a mainly fault-bounded trough about 50 km long and 5-15 km wide and contains Permian and Triassic strata which dip gently to the northeast. The Pennine Fault and associated escarpment form its north-eastern boundary, and the Permo-Triassic succession wedges out south-westwards against Carboniferous strata (Figures 2.1 and 2.2).

There are two aquifer systems and an aquitard unit within the Permo-Triassic sediments of the Vale of Eden. The Penrith Sandstone Formation and St Bees Sandstone Formation form the aquifers and are separated by the Eden Shale Formation, which acts as an effective aquitard (Table 2.1).

Penrith Sandstone Formation

The early Permian Penrith Sandstone Formation was deposited in a structurally-controlled, intermontane basin that was broadly coincident with the present Vale of Eden. The eastern and southern margins of this basin cannot have lain far beyond the limits of the present Permo-Triassic outcrop. To the west, however, the Penrith Sandstone Formation probably extended well beyond its present outcrop. The formation tends to thicken into depressions on the underlying, late Carboniferous to earliest Permian land surface. A ‘saddle’, characterised by attenuated deposition, separated this basin from the Carlisle Basin to the north and northwest. Gravity estimates indicate that the formation is locally about 900 m thick in the centre of the basin (Bott, 1974). The sandstone is largely aeolian in origin, the cross-bedding foresets indicating the accumulation and migration of barchan-type sand dunes each likely to be of the order of 30 m thick. Towards the margins of the basin the aeolian sandstones pass laterally into water-lain, alluvial fan sandstones with lenses of breccia (Macchi, 1991 and Holliday, 1993). Breccia (known locally as Brockram) becomes progressively more dominant southwards so that, in the south of the basin, the sandstones are absent and the early Permian is represented entirely by Brockram.

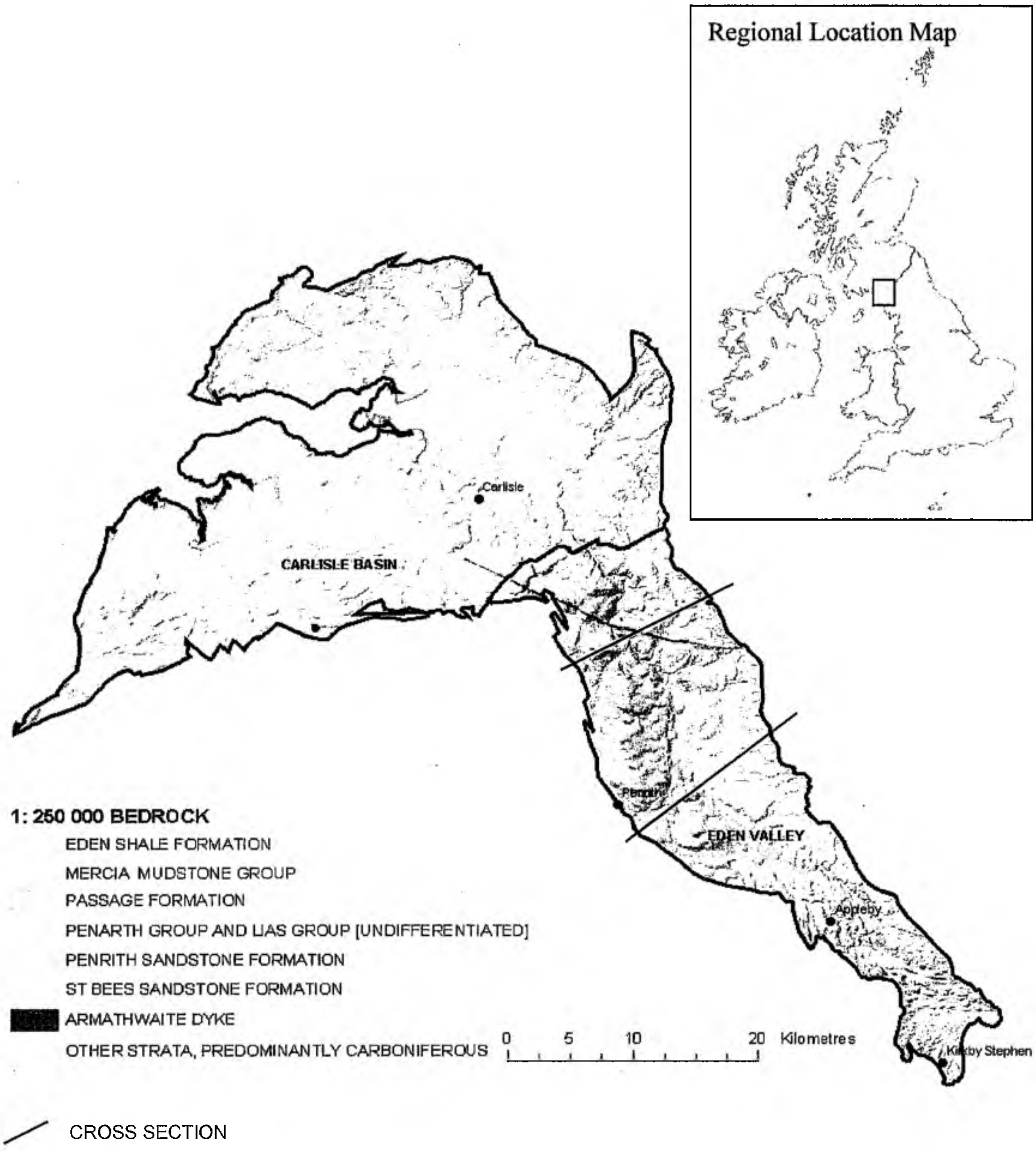

Figure 2.1. Geological map: bedrock (solid), 1:250,000 scale

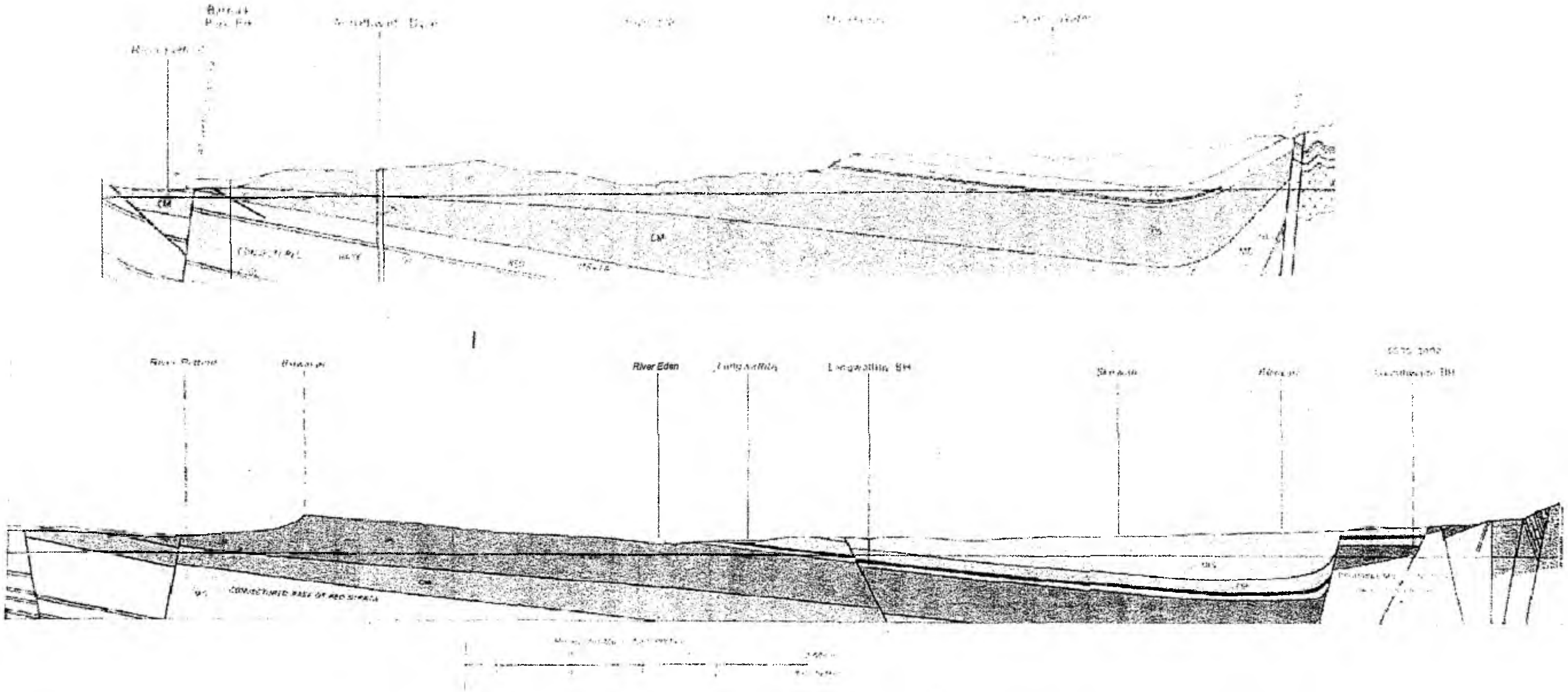

Figure 2.2. Geological Cross Sections (superficial deposits not shown)

The Penrith Sandstone is red-brown to brick red in colour, consisting of well-rounded and well-sorted, medium to coarse grains. Less well-sorted, fine to coarse-grained sandstone beds with thin mudstone intercalations are common at some levels and indicate episodes of fluvial deposition; these occur mainly near the top of the sequence and at the margins of the basins. Brockram lenses, present within the sandstone towards the basin margin, consist largely of angular fragments of dolomitised limestone in a strongly cemented calcareous sandstone matrix.

In the northern part of the basin, parts of the top 100 m or so of the Penrith Sandstone Formation have been secondarily cemented by silica, producing quartz overgrowths with well-developed crystal faces. In places these overgrowths fill up to 70% of pore space. The extent of silicification is reflected in the local geomorphology on the formation outcrop: where the silica cement is sparse the outcrop has low relief and is commonly drift covered, but where the cement is abundant the relief is strong with prominent scarps and dip slopes. Silicification probably occurred at the same time as deposition (Waugh, 1970), resulting from the production of silica dust by abrasion of sand grains in the desert environment, its solution in alkaline groundwaters and subsequent precipitation by capillary evaporation. These siliceous sandstones are very indurated and poorly permeable, and have been used locally as a building stone. They typically occur in layers up to 10 m thick, separated by less well-cemented sandstone. Beneath this silicified zone, the Penrith Sandstone Formation is only moderately cemented and in parts completely uncemented (Ingram, 1978), forming some of the most permeable strata of the Permo-Triassic sandstones of the Vale of Eden. Other cements include calcite, gypsum and anhydrite. These are present locally at depth but have been dissolved at outcrop.

Table 2.1. Permo-Triassic stratigraphy of the Vale of Eden and Carlisle Basin northwest England (after Warrington et al. 1980)

Age	Group	Formation				Aquifer Unit
		Carlisle Basin	Max. Thickness (m)	Vale of Eden	Max Thickness (m)	
Triassic	Mercia Mudstone		400	absent	-	Aquitard
	Sherwood Sandstone	Kirklinton Sandstone	10-100			Aquifer
		St Bees Sandstone	500	St Bees Sandstone	350	
Permian	-	St Bees Shale	90	Eden Shale	180	Aquitard
		Penrith Sandstone (present at depth)	0-?	Penrith Sandstone	900	Aquifer

Eden Shale Formation

The Penrith Sandstone Formation is overlain by the Eden Shale Formation which is up to 180 m thick. The formation is broadly equivalent to the St Bees Shale Formation of West Cumbria and the Carlisle Basin. It consists mainly of mudstone and siltstone; sandstone, breccia and conglomerate intercalations are subordinate, though they increase in abundance towards the south of the basin. The strata are mainly red in colour with brown, green and grey beds in places. Gypsum and anhydrite are present as beds, scattered nodules, cements and gypsum veins. These evaporites have been dissolved in places and are likely to be responsible for high groundwater salinities in the sandstone aquifers above and below. The gypsum and anhydrite has been mined, at Kirkby Thore, Glassonby and Cocklakes. Dolomite beds are also present locally. The Eden Shale Formation sediments were deposited in the late Permian on a continental alluvial plain or sabkha, on which saline lakes periodically developed (Holliday 1993).

St Bees Sandstone Formation

This formation conformably overlies the Eden Shale Formation and is very similar in depositional environment and lithology to its equivalent in the Carlisle Basin. It has a maximum thickness of around 350 m in the Vale of Eden and 500 m in the Carlisle Basin. The outcrop of the St Bees Sandstone is five kilometres wide and occupies the axial part of the Vale of Eden syncline. It consists mainly of very fine to fine-grained, indurated sandstone. Mudstone beds are generally subordinate, though increase in abundance towards the boundary with the underlying Eden Shale Formation. The formation was deposited on an alluvial plain, crossed by a number of braided rivers. The sandstones accumulated in stream courses, while the layers of mudstones were laid down during widespread flooding of the plain.

Drift Deposits

Drift deposits in the Eden Valley resemble those in the Carlisle Basin to the north, but are less extensive and thinner, typically being around 10 to 20 m thick with a maximum of 30 m. The stratigraphy of these deposits is complex. Interdigitations of sand, gravel, silt and clay each develop their own piezometric level, resulting in complex perched water tables above the Penrith Sandstone Formation. Drift cover, dominated by till, covers more than 50 percent of the outcrop of the sandstone aquifers. Abstractions are recorded from drift deposits and in some places these may be considered as minor aquifers of local importance.

Structure and Faulting

The eastern edge of the Vale of Eden is bounded by the Pennine Fault system, which throws the Permo-Triassic rocks against Carboniferous or Lower Palaeozoic rocks. The Pennine Fault follows the foot of the Pennine escarpment from near Brampton [NY 530 610] in the north to Stainmore [NY 830 130] in the south, where it is joined by another major structure, the Dent Fault, which trends northeast to south-west through Kirkby Stephen [NY 780 085]. The extent of hydrogeological control exerted by structure and faulting has not been investigated in detail.

2.2 Hydrogeology

The main aquifers in the region are the Penrith Sandstone Formation (early Permian age) and the St Bees Sandstone of the Sherwood Sandstone Group (early to mid-Triassic age). The aquitards within the sequence are formed by the Eden Shale Formation and the Brockram Formation. The Eden Shale Formation separates the Penrith Sandstone Formation and St Bees Sandstone aquifers in the Vale of Eden. The Bockram interdigitates with the Penrith Sandstone Formation in the southern part of the Vale of Eden.

The groundwater in the Permo-Triassic sandstones is widely used for industry, public supply and small (often unlicensed) private water supplies for farms.

The Penrith Sandstone Formation is a major aquifer from which large quantities of groundwater for public supply are obtained from a number of boreholes located in the northern part of the outcrop. The formation is confined by the Eden Shale Formation to the east of the River Eden and by drift cover over much of the area to the west. Boreholes that intersect silicified parts of the formation tend to have very low yields. Where present, the silicified zones will have a significant effect on the local hydrogeological regime. Perched water tables may be present resting on the low permeability layers which are separated by less well-cemented sandstone. Ingram (1978) produced a map of the extent of the silicified layers in the Eden Valley north of Penrith. The friable nature of other layers of the formation may cause borehole construction problems.

The St Bees Sandstone Formation is an important aquifer in the lower part of the Sherwood Sandstone Group, however with depth its matrix permeability decreases and fracture apertures reduce so these are less transmissive. In consequence the effective aquifer thickness is restricted to the upper half of the formation.

The Eden Valley is surrounded, and to a large extent, underlain by formations of Carboniferous Limestone and Millstone Grit. These are not detailed in Section 2.1 but both contain productive aquifer horizons. They are hydrogeologically significant as they provide a baseflow to streams in sub-catchments of the River Eden and tributaries and issue as springs along the western margin of the Eden Valley. The quantity of groundwater contributed by the Carboniferous aquifers yielded to the overlying Permo-Triassic aquifers has not been investigated.

Faults are present in the Eden Valley. The two main sets trend west-northwest and north-northeast and are extensional normal faults (Knott, 1994). These faults are likely to be of low permeability across their shear zones, though they may rapidly transmit water parallel to any associated fracturing. Fault zones are generally thicker, (i.e. a thicker sheared zone), where there has been significant fault displacement and therefore may be less permeable to flow perpendicular to the fault than those faults which have only a small displacement. However boreholes in the St Bees Sandstone Formation that intersect fault zones have higher yields, suggesting that generally the fracturing increases the permeability of the sandstones. This permeability enhancement may be directional and aligned parallel with the faulting. Fault zones may be detected in the Vale of Eden where there is no drift cover, but the more general drift cover in the Carlisle Basin obscures faults within the sandstone. Very detailed mapping of West Cumbria has revealed many faults within the Sherwood Sandstone Group and suggests that faulting is prevalent throughout the formation but is frequently obscured by drift and weathering of the sandstones at outcrop.

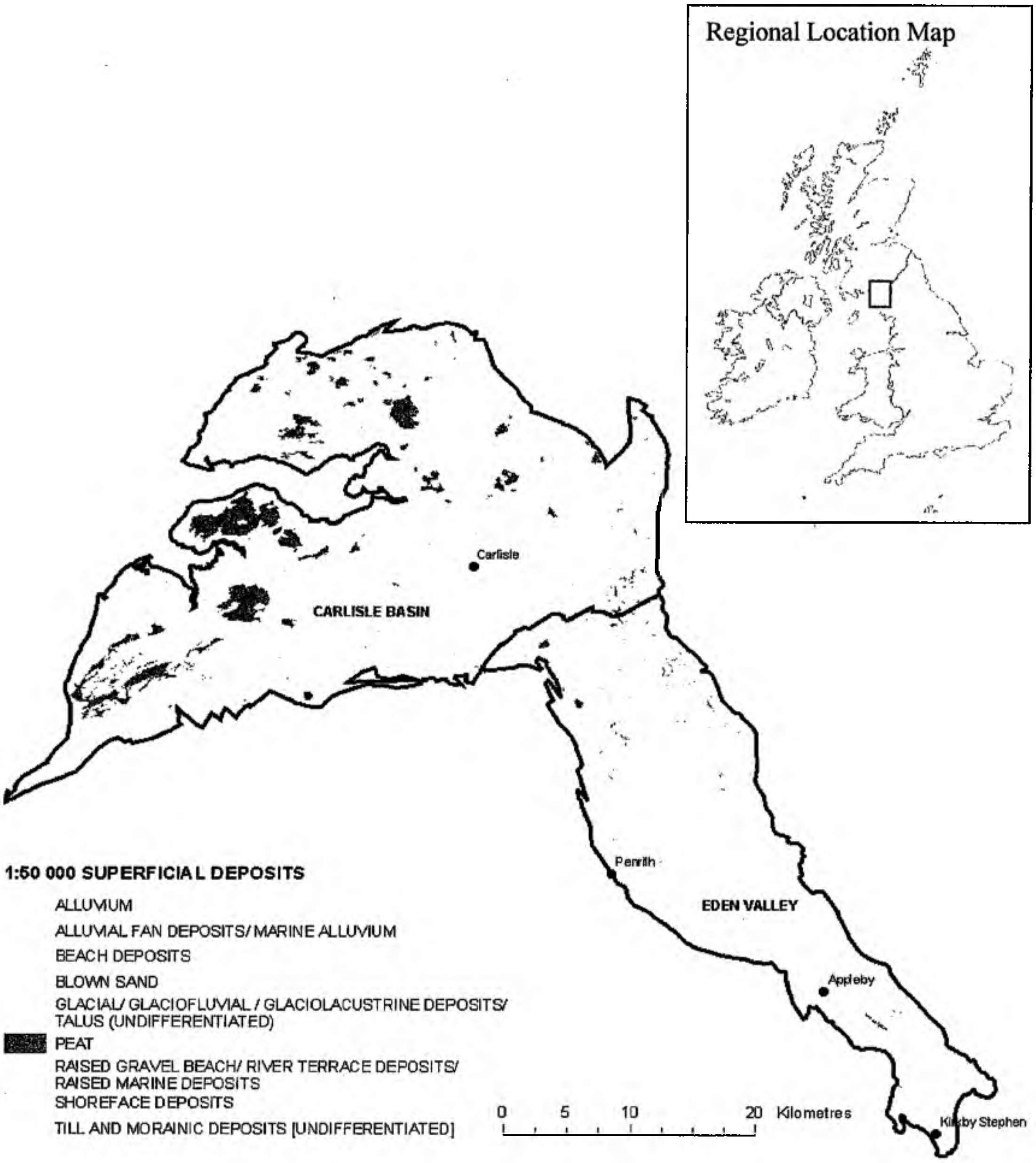

Figure 2.3. Geological map: superficial deposits (drift), mapped at 1:50,000 scale

Piezometry and groundwater flow

Groundwater flow in the Vale of Eden is dominated by discharge to the River Eden. The River Eden gains over most of its length, although between Langwathby and near Temple Sowerby the river is underlain by the Eden Shale Formation and is not in contact with the aquifer.

The water table is close to the surface near the River Eden but lies at around 50 m below ground level in the north of the basin and may be as much as 100m deep below high ground. The piezometry, groundwater source protection zones, surface water and Environment Agency groundwater monitoring boreholes in the Penrith area are shown in Figure 2.4.

In the Penrith area hydraulic gradients are gentle and predictable, generally towards the rivers Eamont and Eden (Ingram, J. A., personal communication). Steeper hydraulic gradients in the northern part of the Penrith Sandstone Formation may reflect the lower permeability of the sandstone in this area. Locally, perched aquifers may occur where low permeability silicified layers occur above the regional water tables (Ingram, 1978).

Laterally, groundwater may be transferred from the Carboniferous Limestone where the Penrith Sandstone Formation directly overlies the limestone to the south of Penrith. Along the Pennine Fault there are many springs indicating that lateral inflow to the basin may be largely as surface flow rather than between aquifers across the fault zone.

Borehole hydrographs in the Eden Valley demonstrate a limited variation in seasonal groundwater levels, typically less than 1 m in the north of the Vale of Eden. This is consistent with what would be expected in an intergranular aquifer with high storage. Drought periods in the mid 1970s and subsequent recovery to a maximum in 1989 are indicated in some hydrographs (Figure 2.5). The piezometry of the Eden Valley including its longer term trends has not been rigorously investigated during this study. It is possible that some apparent long term fluctuations may represent delayed drainage effects. Milne (1994) investigated the relationship between piezometry and degree of confinement in the aquifer sandstones but no clear correlation was identified.

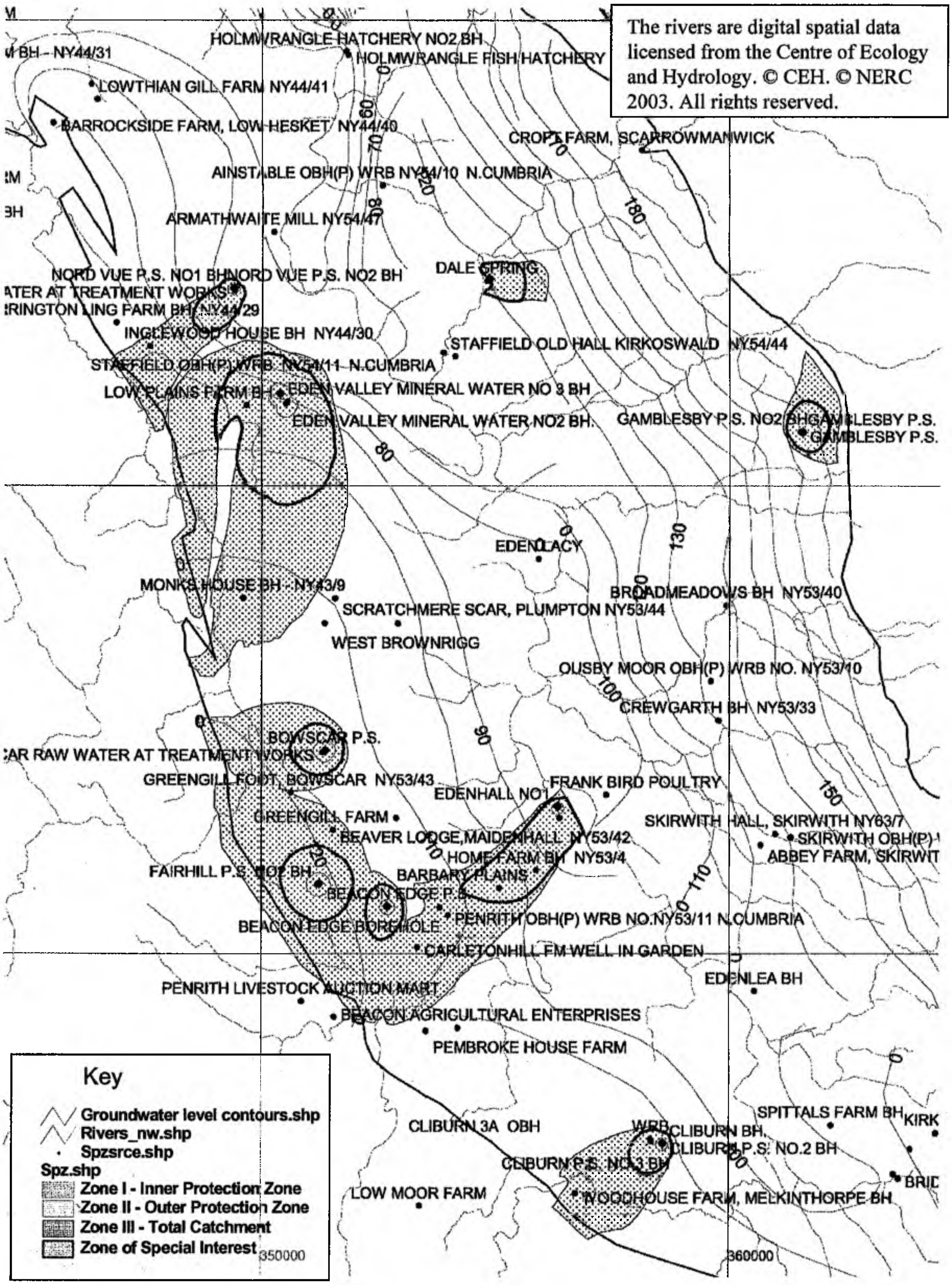

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Figure 2.4 **Water Levels, surface water, EA groundwater source protection zones and groundwater monitoring boreholes in the Penrith Area.**

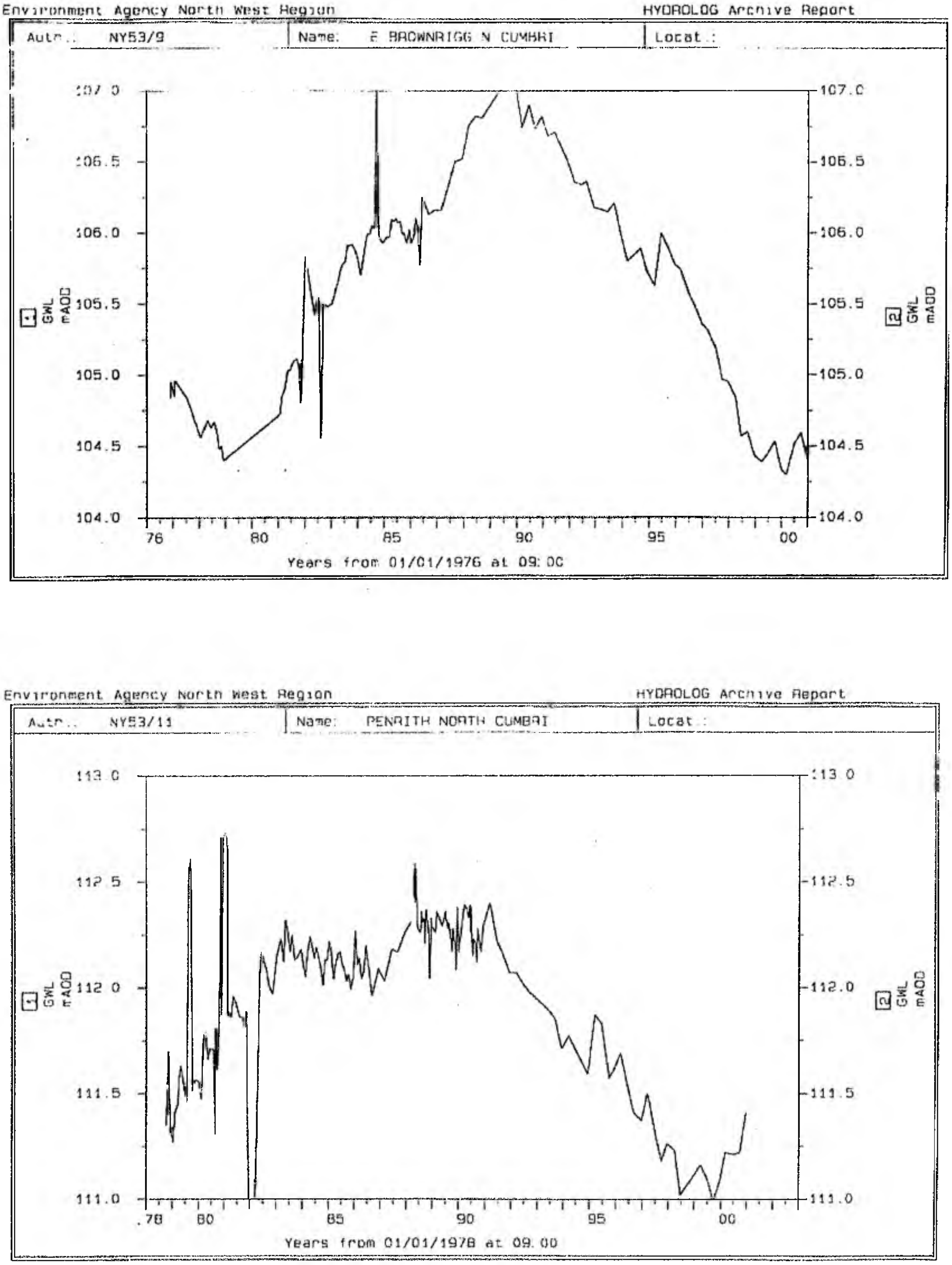


Figure 2.5 Examples of groundwater hydrographs

2.3 Regional aquifer properties

Core data

Comparison of the median core hydraulic conductivity for the different sandstone formations (Table 2.2) indicates that the Penrith Sandstone Formation is more permeable than the St Bees Sandstone Formation. The St Bees Sandstone Formation appears to be more permeable in the north than the south. However, this could however be a function of the depth at which the core samples are taken, as the permeability is likely to decrease with depth.

Horizontal and vertical permeabilities as measured on core samples are generally similar and there appears to be little core-scale anisotropy (Table 2.3). The range of permeabilities: from 5.5×10^{-3} - 4.5m/d in the St Bees Sandstone Formation in the Carlisle Basin and Vale of Eden, indicates that there is potential for larger scale anisotropy within the aquifers because of a high possibility that layers with significantly different permeability likely to be present within any given vertical sequence. This could restrict vertical flow and increase the likelihood of water quality stratification.

Table 2.2. Permo-Triassic sandstone core hydraulic conductivity data, Vale of Eden and Carlisle Basin, northwest England (modified from Allen et al, 1997)

Group or Formation	Range m/d	Interquartile range m/d	Median m/d	Geometric Mean m/d
Penrith Sandstone: Vale of Eden	3.5×10^{-5} - 22.3	0.3 - 3.95	1.35	0.8
St Bees Sandstone: Carlisle Basin and Vale of Eden	5.5×10^{-3} - 4.5	0.14 - 0.39	0.23	0.24

Table 2.3. Horizontal and vertical core hydraulic conductivity data for the Permo-Triassic sandstones, northwest England (modified from Allen et al, 1997)

Group or Formation	Orientation	Range m/d	Interquartile range m/d	Median m/d	Geometric Mean m/d
Penrith Sandstone	Horizontal	2.6×10^{-4} - 22.3	0.28 - 3.9	1.1	0.71
	Vertical	3.5×10^{-5} - 14.7	0.07- 2.8	0.37	0.3
St Bees Sst.: Carlisle Basin & Vale of Eden	Horizontal	5.5×10^{-3} - 4.5	0.16 - 0.41	0.26	0.26
	Vertical	0.01 - 4.5	0.12 - 0.37	0.21	0.21

Porosity, like permeability, varies considerably depending on lithology and degree of cementation. The highest porosities are seen in the north of the region, with an arithmetic mean of 27 % for the St Bees Sandstone Formation in the Carlisle Basin and the Vale of Eden, and an average of 24 % for the Penrith Sandstone Formation (Table 2.4). The Penrith Sandstone Formation has in general a slightly lower porosity than the northern St Bees Sandstone Formation.

Table 2.4. Permo-Triassic sandstone core porosity data, Vale of Eden and Carlisle Basin northwest England (modified from Allen et al, 1997)

Group or Formation	Range %	Interquartile range %	Median %	Arithmetic Mean %
Penrith Sandstone	5.6 - 35.1	21.1 - 27.8	24.1	24.1
St Bees Sandstone: Carlisle Basin and Vale of Eden	19.3 - 34.9	25.3 - 30.1	26.9	27.4

Transmissivity and storage

At relatively shallow depths (of the order of 100 m), both the Triassic Sherwood Sandstone Group (the St Bees Sandstone Formation) and the Permian Penrith Sandstone Formation are good aquifers. Typical values for field transmissivities are 100 to 300 m^2/d but values can be much higher reaching 1000s m^2/d (Lovelock, 1977). The geometric mean of transmissivity for all the aquifers of the whole northwest region is 240 m^2/d (Table 2.5). The large difference between the intergranular and field transmissivities reflects the extent that fractures influence the rate of flow through the aquifers (at least on a local scale).

In the north of the Vale of Eden the St Bees Sandstone Formation has transmissivities of tens to hundreds of metres squared per day. In contrast to the St Bees Sandstone Formation, the Penrith Sandstone Formation in the south of the Vale of Eden has higher transmissivities which are generally up to 1000s m^2/d. Generally the storage values obtained from pumping tests are indicative of 'confined' to 'semi-confined' conditions, with a geometric mean of 1.7×10^{-4} (Table 2.5).

Table 2.5. Summary of aquifer properties data for the Permo-Triassic sandstones in Vale of Eden and Carlisle Basin northwest England from pumping tests (modified from Allen et al, 1997)

Permo-Triassic Sandstones (all data)	Range	Interquartile range	Median	Geometric Mean
Transmissivity m^2/d	8 - 3300	93 - 984	263	240
Storage coefficient	4.5×10^{-8} - 0.12	7.2×10^{-5} - 0.002	4×10^{-4}	1.7×10^{-4}

Established large diameter boreholes in the Penrith Sandstone Formation typically yield 3000 m^3/d compared with 2000 m^3/d in the St Bees Sandstone Formation with drawdowns of 10 to 20 m (Monkhouse and Reeves, 1977).

Summary of aquifer properties

Generally the transmissivity of the St Bees Sandstone Formation depends on fracture intersection, with tighter fractures deeper in the aquifer, resulting in progressively smaller increases in yield with depth. The Penrith Sandstone Formation has greater matrix permeability, except in the silicified horizons, and yields continue to increase with depth: the effect of fracture closure with depth is not generally seen (Ingram, J. A., personal communication).

In both aquifers, the average values of permeability which are obtained from core samples are generally lower than pumping test and packer test derived bulk hydraulic conductivities, because the latter values (but not the former) include the fracture contribution to permeability. Permeabilities used in regional models approach the intergranular value which suggests that fracture permeability is more localised and less influential on a regional scale. The low permeability layers (especially the silicified layers) can have a significant influence on vertical flow and the sandstones may behave as a multi-layer aquifer.

2.4 Water balance

Recharge estimates for the Permo Triassic sandstone aquifers of the Eden Valley have been attempted by Monkhouse and Reeves (1977) and Ingram (1978). In both cases the approaches were similar and were based on multiplying 'residual rainfall' (rainfall – potential evaporation) by a factor to estimate infiltration to both sandstone aquifers (Penrith sandstone and St Bees sandstone) where they were (a) exposed (drift-free) and (b) drift-covered).

Table 2.6. Summary of recharge estimates used by Ingram (1978) for the Eden Valley

	Unit	Penrith Sandstone	St Bees Sandstone	Total
a: Drift-free area	km^2	60	48	108
Infiltration Rate as % of residual rainfall	%	70	70	
Residual Rainfall	mm	450	500	
Direct Recharge	Ml/d	51.8	46	97.8
b: Drift covered area	km^2	250	92	342
Infiltration Rate as % of residual rainfall	%	20	20	
Residual Rainfall	mm	450	500	
Indirect Recharge	Ml/d	61.6	25.2	86.8
Total Recharge	**Ml/d**	**113.4**	**71.2**	**184.6**

Monkhouse and Reeves (1977) estimated the infiltration rates where drift-free to the Penrith and St Bees Sandstones, to be 530 and 515 mm/y respectively. Where these sandstones were drift covered the infiltration rates were significantly lower, 130 and 115 mm/y respectively. However the assumptions used in these calculations were not stated. The total recharge to both sandstone aquifers was estimated to be about 300 Ml/d, which included an unspecified component of indirect recharge.

Ingram (1978) also estimated infiltration rates to the sandstone aquifers (Table 2.6) and these were based on the assumption that 70% of the residual rainfall (ie that available for infiltration or run-off) infiltrates where the sandstones are exposed and only 20% where the sandstones are drift covered. The resulting infiltration rates (i.e. 315 and 90 mm/y respectively) estimated by Ingram (1978) are significantly lower than those of Monkhouse and Reeves (1977). However, the infiltration estimates were checked by balancing recharge estimated from these infiltration rates with groundwater discharge to the River Eden, for part of the Eden catchment; a good agreement was achieved when using Ingram's estimates of infiltration. However, the distribution of recharge between exposed and drift covered areas is open to some doubt. Ingram's estimate of the total recharge to both sandstone aquifers was 184.6 Ml/d.

Vines (1984) estimated that the recharge rate through boulder clay (or till) was closer to 50 mm/y and was based on (a) comparing water balance estimates for the Permo Triassic sandstone aquifer in three adjacent catchments in Lancashire with different degrees of drift cover, and (b) tritium profiles in the unsaturated zone of the sandstones in Cheshire.

If infiltration rates through less permeable drift are as low as 50 mm/y, and assuming the overall recharge rate to the sandstone aquifers of the Eden Valley remain the same, then clearly higher rates of infiltration are required in those areas of the Eden Valley where the drift is permeable or absent. On this basis, rates of infiltration for the exposed sandstone could be as high as 480 mm/y (compared to 315 mm/y in Ingram's estimates). The implications of this are discussed later.

The concept of enhanced recharge through the drift free 'windows' would appear reasonable, as run off from shallow groundwater flow through adjacent drift covered areas is likely to contribute to recharge in these windows; this is discussed later in chapter 6 where more detailed conceptual models are introduced.

The Meteorological Office rainfall and evaporation calculation system (MORECS) is a useful source of data for regional water balance determinations. It is based on a 40 km by 40 km grid. Most of the Eden Valley is contained within MORECS grid square no. 78 with the southern part from Appleby southwards contained in grid square no. 84. The average rainfall for the grid square no. 78 is 1148 mm/y, and for a combination of nos. 78 and 84 it is 1738 mm/y. The potential and actual evapotranspiration rates are very similar at approximately 480 mm/y. The MORECS rainfall figures are clearly much greater than the average annual rainfall in the centre of the Eden Valley (which is more typically 850-900 mm/y). It appears that because the Eden Valley is relatively narrow it is inappropriate to use the MORECS data as this is skewed towards greater rainfall figures found in the higher terrains at the edges of the valley. A better approach (and one used by Monkhouse and Reeves, 1977, before MORECS was available) is probably to consider the water balance at a sub-catchment level.

Abstraction

Licensed groundwater abstractions from the sandstone aquifers in the Eden valley are relatively small although these are increasing. In the 1970s these were around 8000 Ml/y. By 1993 this was estimated as 10730 Ml/y, (Younger and Milne, 1997). This compares with an estimated recharge of 67120 Ml/y, (Ingram 1978). Groundwater abstraction has however only shown a small increase over recent years.

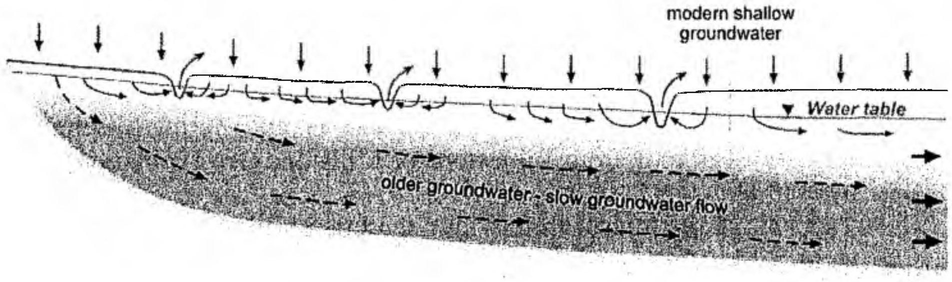
Surface Water – Groundwater Interaction

The River Eden and its tributaries represent the major outflow from the Permo Triassic sandstone aquifer although groundwater contributes less than 10% to the overall flow. The groundwater base flow contribution to the River Eden is significant during periods of drought, and this could have implications for future quality on the surface water; this is discussed in Chapter 3.

Conceptual Model

An initial conceptual model of the groundwater flow system is presented in Figure 2.6. This shows that, prior to major abstraction, the groundwater flow system was characterised by two distinct systems a shallow flow system, of mainly modern waters, discharging to surface water and a deeper, slow flow system with older groundwaters. Vertical-horizontal anisotropy in the sandstones, due to differences in permeability associated with different litho types, would accentuate any stratification.

(a) Groundwater flow system prior to abstraction



(b) Groundwater flow system following abstraction

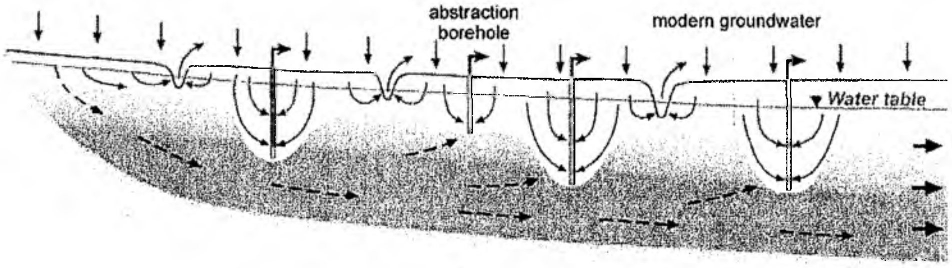


Figure 2.6. **Groundwater flow system schematic pre- and post-abstration (drift excluded)**

Following, the development of the aquifer, mainly in the 1960s and 1970s, when abstraction from major water supply boreholes first began, modern groundwaters would have penetrated deeper into the aquifer in response to this pumping. More detailed conceptual models are presented later and discussed in Chapter 6.

Summary

- The Penrith and St Bees Sandstones are the major aquifers in the Eden Valley. These aquifers are characterised by moderate-high permeability and porosity. Groundwater movement at the regional scale is largely dominated by intergranular permeability whilst inflow into boreholes is predominantly contributed by fractures
- Large areas of the sandstone aquifers (c 65%) are covered by drift deposits of variable lithology and thickness. These have a significant impact on recharge and its distribution; where drift is permeable or absent, rates of infiltration considerably in excess of 400 mm/y, are possible whilst beneath till deposits the infiltration rate may be as little as 50 mm/y.
- Base flow contribution from the Permo-Triassic sandstones is usually significantly less than 10% of the total flow of the River Eden.
    - Other contributions to river flow in the Eden Valley is derived from several sources:
        - Surface water from adjacent upland areas outside the Eden Valley which might originate as runoff and spring discharge from the Carboniferous Limestone or Millstone Grit Formations
        - Direct runoff from within the Eden Valley.

3. WATER QUALITY

3.1 Groundwater Quality

Sources of data

Water quality data were obtained from the EA database held at Warrington. The data include both routine EA monitoring data and data supplied by North West Water. In total, water quality data are available for some 150 boreholes, covering the period 1954 to 2002. However, not all the boreholes have been monitored for the whole of the period. Indeed the EA monitoring network has been enlarged significantly in recent years, giving generally good spatial coverage for the past decade. Further, the frequency of sampling during the past decade has become more regular. This EA dataset was used when considering the distribution of groundwater nitrate and when assessing the influence of various factors on groundwater nitrate concentrations (see Chapter 4).

The monitoring boreholes cover a range of designs and uses, including private farm supplies, industry and public water supply. Borehole depths vary from less than 50 m to nearly 200 m. Abstraction rates range from 25 m^3/d to over 3000 m^3/d. The distribution of the monitoring boreholes is shown in Figure 3.1.

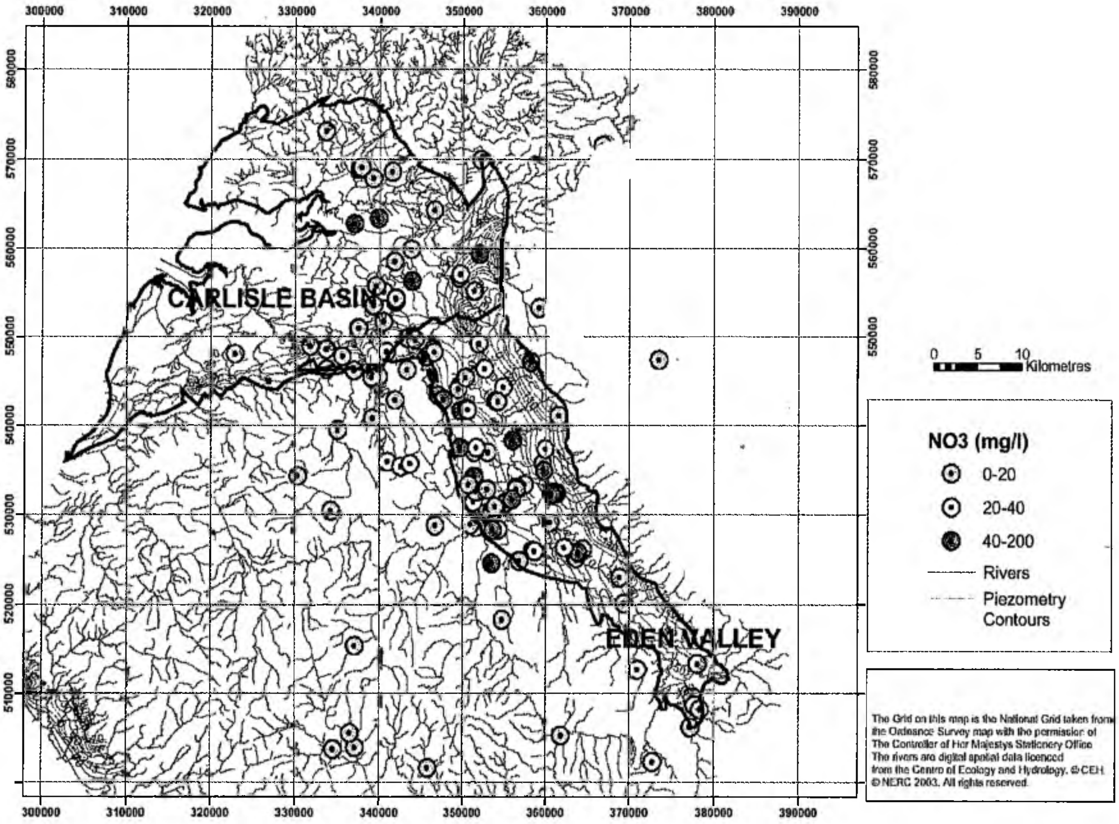


Figure 3.1. Distribution of Environment Agency groundwater monitoring boreholes in the Eden Valley and Carlisle Basin area

Some of the boreholes in this dataset are located in the Carlisle Basin, to the north of the Eden Valley, and others just outside the catchment of the River Eden, however they are included in this report because they provide a useful comparison with data from the Eden Valley. A survey of baseline water quality for the aquifers of England and Wales is being carried out by BGS and the EA. A report on the baseline water quality of the Permo-Triassic sandstone aquifer of Cumbria has already been completed (Shand et al, 1997) which provides a reliable summary of water quality in these aquifers. Data from this baseline water quality report are used here to present an overview of water quality in the sandstone aquifers. Water quality in the Eden Valley (both surface and groundwater) was also reviewed by Milne (1994) as part of an MSc study.

Groundwater quality

Groundwater quality in the Permo-Triassic sandstone aquifers of the Eden Valley is generally good; the groundwaters are dominantly of the calcium-bicarbonate type (Figure 3.2) although calcium-sulphate and calcium-sodium bicarbonate types also occur; the former water type more especially close to the Eden Shales Formation. The SEC of the Permo-Triassic sandstones is usually in the range 200 to 900 µS/cm. Groundwater nitrate in EA monitoring boreholes varies from less than 5 mg/l up to 140 mg/l (N as NO_3); a significant number of boreholes (>40%) have concentrations in excess of 20 mg/l. which compares with the EC-maximum admissible concentration, (MAC) of 50 mg/l (Figure 3.3).

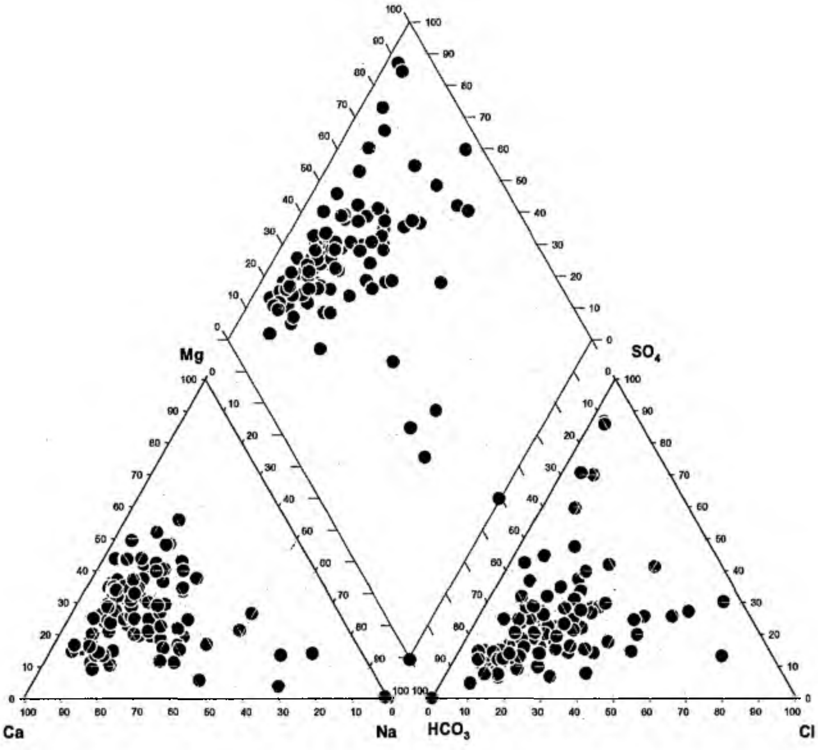


Figure 3.2. Major ion chemistry of Eden Valley groundwater (Piper diagram, Shand et al 1997).

Tables 3.1 and 3.2 present a statistical summary of groundwater quality in the Carlisle Basin and Vale of Eden for the Permian and Triassic sandstone aquifers respectively. The groundwaters are generally oxidising although reducing groundwaters can occur where the sandstone aquifers are confined.

Determinand	Units	Min	Max	Median	Upper Baseline	N samples
pH		6.3	9.55	7.6	8.23	53
Eh	mV	5	461	160	461	7
SEC	µS/cm	245	2170	490	883	53
Ca	mg/l	1.1	458	46	92.8	53
Mg	mg/l	0.3	59.7	19.1	38.2	53
Na	mg/l	5	212.7	17	66.1	53
K	mg/l	0.5	44.9	2.1	4.9	53
Cl	mg/l	7.6	83	19.7	43.6	53
SO_4	mg/l	7.1	1080	24	92.3	53
HCO_3	mg/l	61	430	229	385	53
NO_3	mg/l	0.09	76.13	9.61	49.38	38

Table 3.1 **Statistical summary of groundwater quality in the Triassic Sandstones of the Carlisle Basin and Vale of Eden (from Shand et al 1997)**

Determinand	Units	Min	Max	Median	Upper Baseline	N samples
pH		6.6	8.01	7.3	7.8	40
Eh	mV	220	360	280	357	4
SEC	µS/cm	189	1423	411	953	40
Ca	mg/l	16	231.6	53.7	129	40
Mg	mg/l	3	38.8	10	37.8	40
Na	mg/l	5	135	10	17.5	40
K	mg/l	1.08	8.5	2.1	4.84	40
Cl	mg/l	<5	283	16.1	32.7	40
SO_4	mg/l	9.7	573.4	26.2	146.6	40
HCO_3	mg/l	33	365	170	301	40
NO_3	mg/l	<2.2	73.8	13.51	48.1	407

Table 3.2 **Statistical summary of groundwater quality in the Permian Sandstones of the Carlisle Basin and Vale of Eden (from Shand et al 1997)**

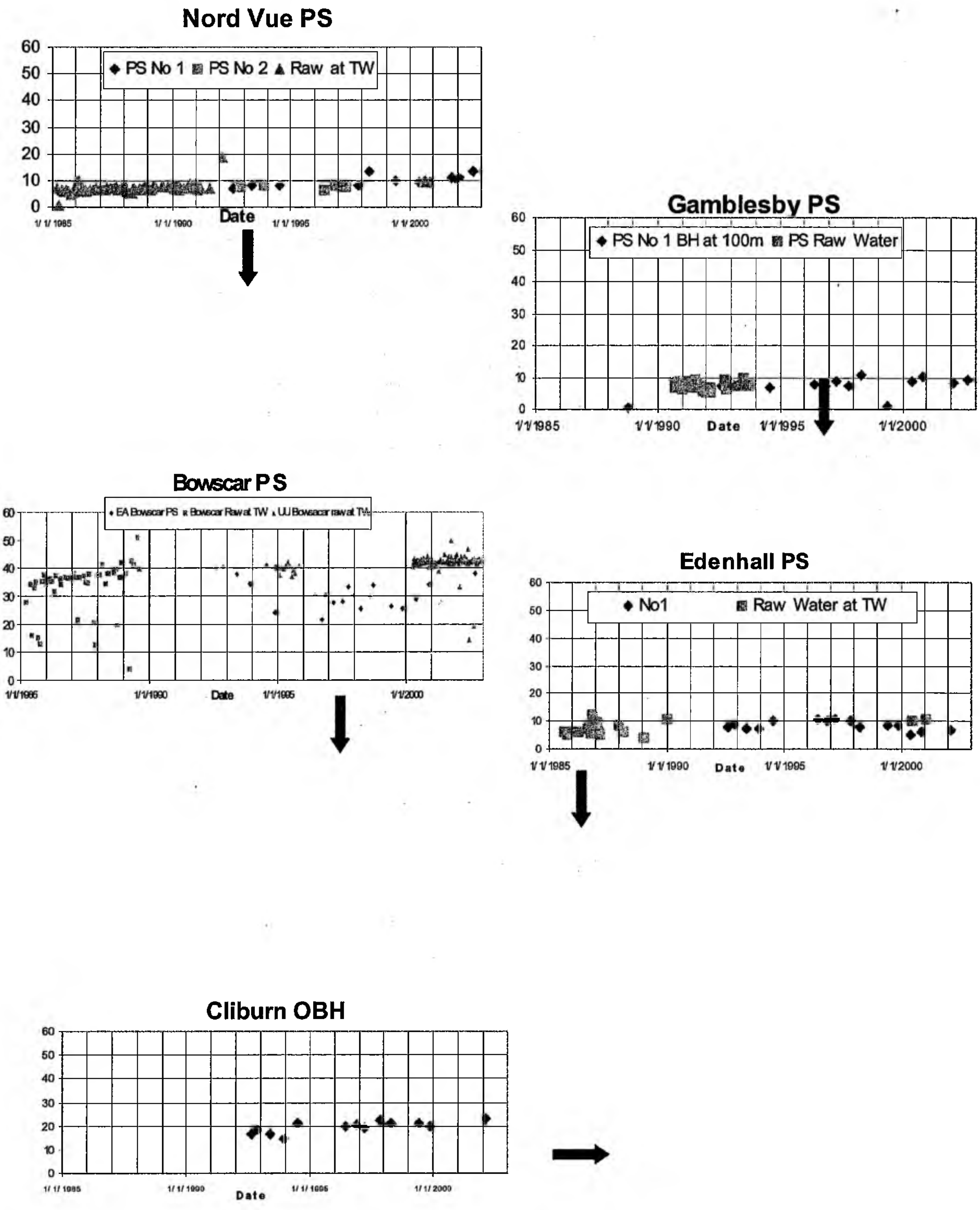


Figure 3.3. Groundwater nitrate concentrations from selected boreholes in the Eden Valley (schematic).

The spatial distribution of groundwater nitrate concentrations is shown in Figure 3.1. Three broad observations can be made using maps produced for the project:

- Groundwater nitrate concentrations are higher in the centre of the Eden Valley around Penrith-Appleby where agriculture is more intense.
- Higher groundwater nitrate concentrations appear to coincide with 'drift free windows' where the underlying sandstone is exposed at the surface and is thus more vulnerable to pollution.
- Groundwater nitrate concentrations in the Carlisle Basin are generally lower, probably because of the more extensive drift cover.

Some of the monitoring boreholes have groundwater nitrate data available for a number of years and can provide a record of the temporal changes in groundwater nitrate concentrations. No universal water quality trend with time is obvious. Some boreholes show a significant rising trend (e.g. Bowscar P.S., and Cliburn), whilst others show very slight or no apparent increase (e.g. Edenhall P.S., Nord View P.S., and Gamblesby P.S.). There is some indication that boreholes exhibiting a rising trend in groundwater nitrate concentration with time also have higher actual nitrate concentrations than those, which exhibit little or no increasing trend with time. This suggests, for those boreholes which pump groundwater with higher nitrate concentrations, that as the proportion of modern pumped water increases with time, the nitrate concentration also rises (because of the increasing intensification of agriculture over the past 50 years). Conversely, for boreholes that pump low nitrate groundwater there are three possible scenarios: (1) the 'front' of modern water has not yet arrived at the borehole, (2) that nitrate is being removed by denitrification, or (3) there is little leaching of nitrate from within the catchment area of the borehole.

No attempt was made to analyse and adjust any nitrate trends with time to allow for seasonal water level fluctuation, as has been suggested elsewhere. This was because (1) the water quality data was rather spasmodic (periods of intensive monitoring interspersed by periods of infrequent sampling), (2) the seasonal water level fluctuation in the sandstone aquifer is relatively small (for instance compared with that typically in the Chalk), and (3) the recharge mechanisms are poorly understood and are complicated by the variability of drift cover (in terms of both lithology and in thickness).

There are no data on residence time for groundwater in the sandstone of the Eden Valley. However, a study of the Permian aquifer of the Dumfries Basin, which has a broadly similar pattern of land use and climate, demonstrated that there is a good correlation between groundwater nitrate concentrations and the percentage of modern water, (Figure 3.4) (MacDonald et. al., 2003). This correlation suggests that, for the Dumfries Basin, travel time was the major control on nitrate concentration (as opposed to differences in land use and/or denitrification). It also suggests that the source of the nitrate concentrations in groundwater was both diffuse and widespread. The controls on groundwater nitrate concentrations in abstraction boreholes and the correlation of various factors with observed groundwater nitrate concentrations in boreholes in Eden Valley is discussed in Chapter 4.

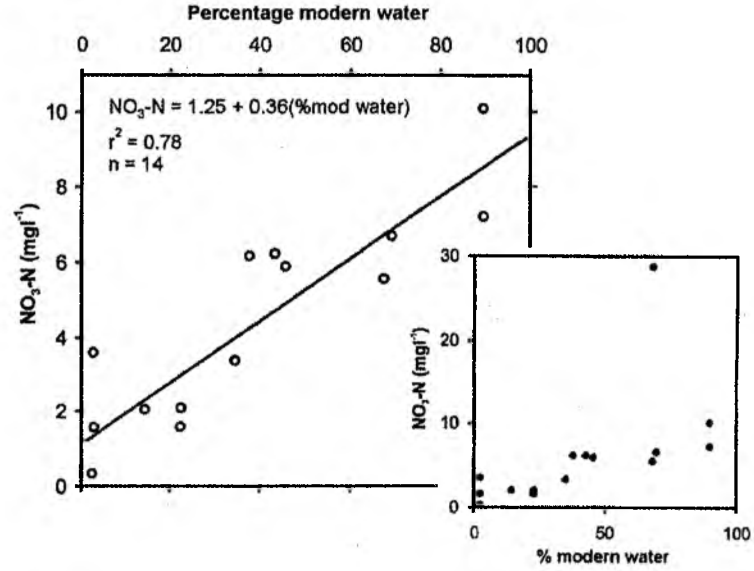


Figure 3.4. Percentage modern water determined by testing for CFCs vs nitrates in the Dumfries aquifer (after MacDonald et al 2003)

3.2 Surface Water Quality

Sources of data

Surface water quality is generally good in the Eden Valley. In 1998 the GQA[1] chemical classification reported that over 85% of the length of the classified watercourse in the Eden catchment was of 'good' quality and less than 3% was of 'poor or bad' quality (Local Environment Agency Plan, 1999). Milne (1994) showed that both the SEC and the nitrate concentration of the River Eden increased downstream and attributed this, at least in part, to the increasing intensity of agriculture in the lowland reaches of the river. Surface water has greater variability in quality than groundwater, which is not surprising given its much shorter residence times. Plots of surface water nitrate verses time and stream flow versus time for the River Eden at Warwick Bridge (Figure 3.5) show this variability. Figure 3.5 also suggests that peak nitrate concentrations usually coincide with peak flows and when runoff from adjacent fields is high. Thus, the bulk of the nitrogen load for the River Eden, at Warwick Bridge, is probably derived from surface water rather than being of a groundwater origin.

As discussed earlier, there are several components that contribute to surface water flow.

- Runoff from adjacent upland areas (e.g. the Pennines)
- Runoff from adjacent land
- Shallow subsurface flow through weathered, permeable drift deposits
- Groundwater baseflow

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[1] General Quality Assessment (NRA 1994, EA 1998)

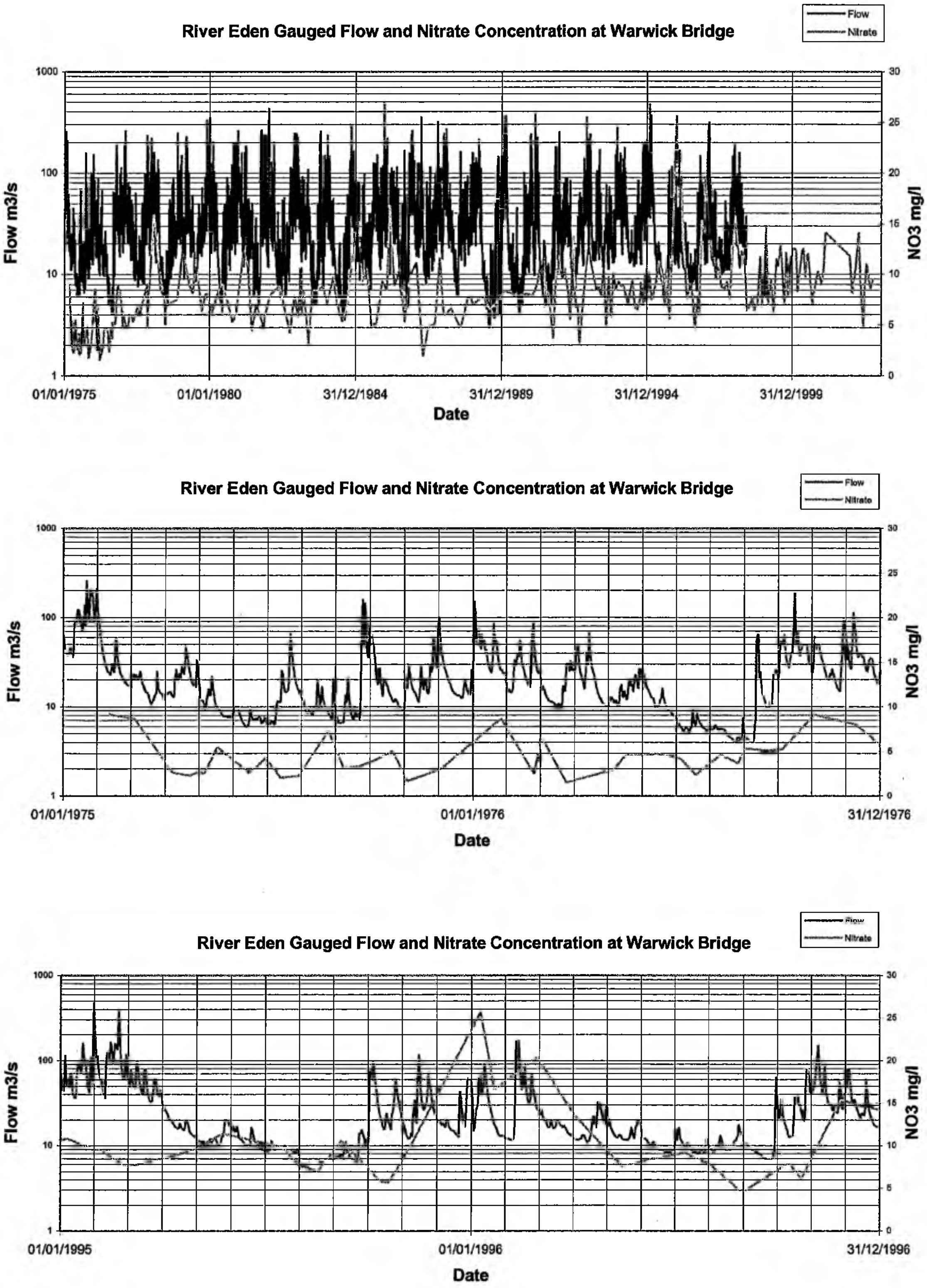


Figure 3.5. **Daily gauged flow and nitrate concentration of the River Eden at Warwick Bridge [NGR NY 470 567] and selected intervals.**

During dry periods, when river flow is low, runoff from adjacent fields is likely to be minimal and changes in the quantity and quality of stream flow over a specific stretch reflects additional input from both tributary streams and groundwater. Where the nitrate flux entering the river from tributary streams is measured, an estimate of the nitrate input from groundwater can be made. This approach was used to provide an approximate nitrate balance for the River Eden between Temple Sowerby and Warwick Bridge (Figure 3.6) for two different dates when river flow was low, (Autumn 1976 and Autumn 1995). Details of the nitrate mass balance calculations and the assumptions made are given in Appendix 4. The estimates suggest that: (1) during very low flows groundwater contributes about 50% of the total nitrate load in the River Eden at Warwick Bridge and (2) the nitrate concentration of groundwater flow entering the River Eden was about 10.5 mg/l (as nitrate) in 1976 and had risen to 44 mg/l (as nitrate) in 1995.

These estimates are approximate only but serve to indicate the likely contribution of groundwater to surface water quality.

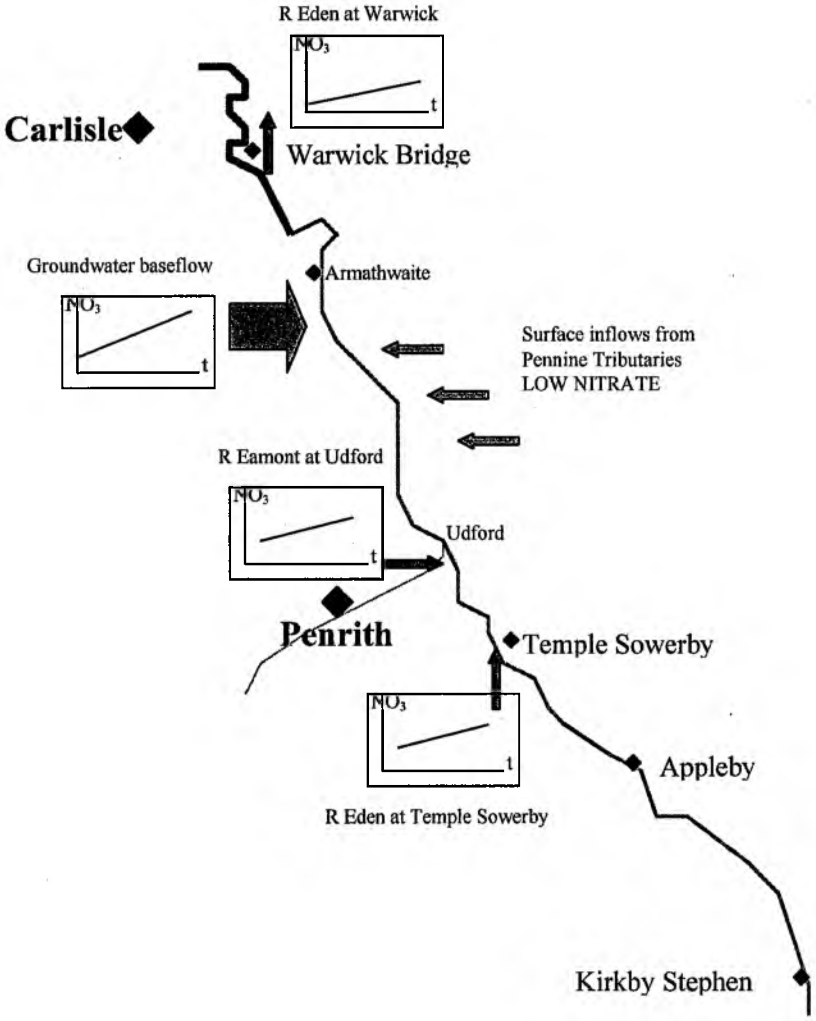


Figure 3.6. **Nitrate balance schematic for the River Eden between Temple Sowerby and Warwick Bridge.**

Summary

- Groundwater nitrate is very variable in concentration and to some extent in its geographical distribution, although higher groundwater concentrations are more commonly found in the lower reaches of the Eden Valley. Boreholes with higher nitrate concentrations quite often occur within or close to drift-free windows.
- Groundwater nitrate trends (with time) are also variable; some boreholes show a fairly steep rise in nitrate concentration; for example pumped nitrate concentrations at Bowscar Pumping Station rose from 9.7 mg/l to 43 mg/l between 1973 and 2002. Other boreholes, especially those with low nitrate concentration, show little or no apparent trend with time (e.g. Edenhall P.S., Nord View P.S., and Gamblesby P.S.).
- A study of the Permian sandstone aquifers of the Dumfries Basin showed that there was a good correlation between percentage of modern water (as estimated from dissolved CFCs in groundwater determinations) and nitrate concentration in groundwater. Land-use and groundwater nitrate concentrations in Dumfries appear to be broadly similar to those observed in the Eden Valley. Thus, if a similar correlation exists for the Eden Valley groundwaters then the higher groundwater nitrate concentrations are likely to be associated with modern waters.
- Surface waters show generally lower nitrate concentrations and, as with groundwater, have lower concentrations in the upper reaches of the Eden catchment. This probably reflects the both less intensive land-use in this part of the Eden Valley and runoff from adjacent upland areas, which receive little or no fertilisers.
- Trends in nitrate concentration of surface waters with time, behave in a similar fashion to groundwaters, that is, show a rising trend where nitrate concentrations are higher but no apparent rise where concentrations are low.
- Nitrogen mass balance estimates for the lower catchment of the Eden Valley suggest that:
    - The bulk of the nitrate in stream flow is derived from surface run-off and higher nitrate concentrations generally coincide with higher flows.
    - In low flow periods, groundwater appears to contribute about half the nitrogen load.
    - Increasing groundwater nitrate concentrations are likely to produce a rising trend in surface water concentrations in low flow periods. However, the overall impact on the nitrogen load of the stream is likely to be small

4. FACTORS INFLUENCING PUMPED GROUNDWATER NITRATE CONCENTRATIONS

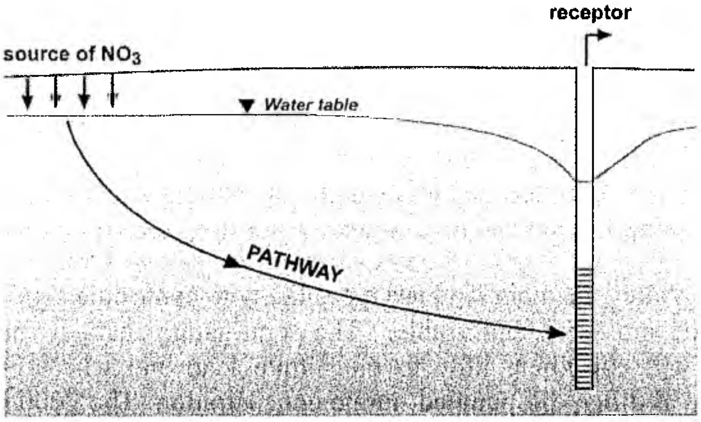
4.1 Groundwater flow and movement of nitrate to abstraction boreholes

Elevated groundwater nitrate concentrations can occur in an abstraction borehole when both a source of nitrate and a pathway, which links the source to the abstraction borehole exist (Figure 4.1). Sources of nitrate are related principally to land use and to activities (including storage of nitrogen wastes) that may release nitrate to infiltration. A pathway exists where the subsurface is permeable and water can move from the source (of nitrate) through the unsaturated zone to the watertable and then through the aquifer to the abstraction borehole. Given that nitrate is mostly associated with modern agricultural processes, an important consideration, is therefore travel time for water containing nitrate to migrate from the land surface to the borehole. Long travel times may delay the arrival of nitrate at an abstraction borehole for many decades. In addition, where the groundwater is anoxic it is possible for nitrate to be reduced by denitrifying bacteria that occur naturally in the subsurface, so that even where a pathway exists, nitrate may never arrive at the borehole.

It is important to recognise that the groundwater pumped from an abstraction borehole is a mix of groundwater with different nitrate concentrations and different ages. These differences reflect variations in land use, geology (especially drift cover) and distance of travel within the borehole capture zone (Figure. 4.2). In detail, factors controlling pumped nitrate concentrations in abstraction boreholes include:

- land use and rates of nitrogen leaching
- shape and dimensions of borehole capture zone
- the geology
- recharge to groundwater
- thickness of the unsaturated zone
- borehole depth and design
- aquifer characteristics

FACTORS CONTROLLING NITRATE CONCENTRATIONS IN PUMPED BOREHOLES



Source - pathway - receptor approach

- need both a 'source' and a 'pathway' for receptor to be affected
- Pathway:
    - hydraulic connection linking source to receptor
    - travel time (travel time <50 years)

Figure 4.1. **Factors controlling nitrate concentrations in pumped boreholes**

PATHWAY FACTORS

Water pumped from a borehole in a mix of water of different ages and derived from different parts of the catchment (with different land uses).

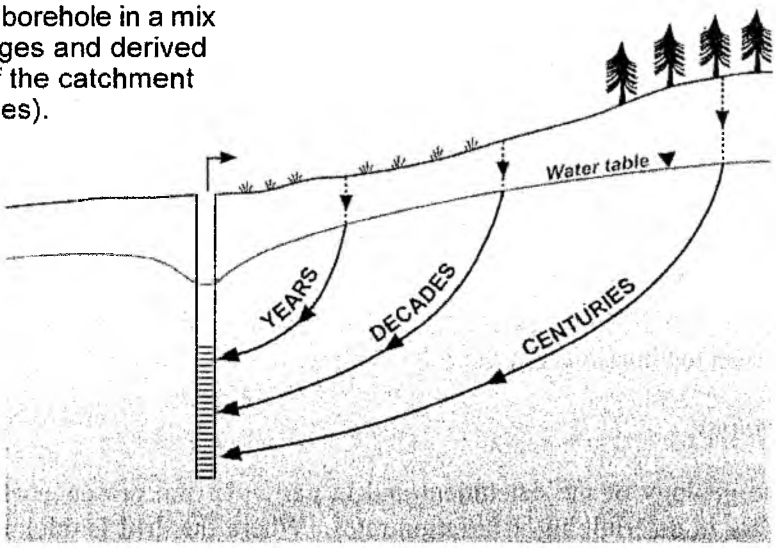


Figure 4.2. **Pathway factors**

Land use and rates of nitrogen leaching

Rates of nitrate leaching from the soil vary considerably with different land use types (as well as soil types and the amount of rainfall). As discussed earlier, there is considerable evidence to suggest that when nitrogen application rates to grassland are high, in excess of 100 kgN/ha/y and especially in excess of 200 kgN/ha/y, then high rates of nitrate leaching from the soil to the watertable can be anticipated (Chilton et al 1991). Conversely, nitrate leaching losses beneath unimproved grassland, (Foster et al 1982) or woodland (Kinniburgh et al, 1999) are low. Slurry pits represent potential point sources of nitrate although earlier research suggests that these are less significant compared with diffuse sources (Gooddy et al 2001) because of dilution and mixing with water from the groundwater catchment.

In the Eden Valley the main land use types likely to contribute significantly to the nitrate load are improved grassland and arable. The semi-natural habitat (unimproved grassland and woodland) will contribute little to the nitrate load and where present within a borehole catchment will dilute the pumped nitrate concentration. The 2000 Land Cover Map (Centre for Ecology and Hydrology (CEH) 2000) for the region is included in Appendix 2. No attempt to correlate land use or nitrogen applications to land with groundwater nitrate concentration was made in this phase of the study due to time and data limitations.

Shape and dimensions of borehole capture zone

The shape and dimensions of the borehole capture zone is important because it will determine: (a) what land use is present within the capture zone (and the sources of nitrate) and (b) the travel time to the borehole. It should be noted that low-yielding boreholes, that draw water from a limited capture zone area, may derive their recharge from land uses atypical of the overall catchment and as a consequence could have unusually high (or low) nitrate concentrations. The shape and dimensions of the capture zone are determined by a number of factors:

- Abstraction pumping rate and regime.
- Recharge within the capture zone. Where the recharge rate is low, for example beneath drift cover, the capture zone will be proportionally larger.
- The width of the capture zone, required to provide sufficient flows to support the pumping rate, will depend on the aquifer transmissivity and hydraulic gradient
- Interference with other nearby abstraction boreholes
- Additional sources of recharge

Figure 4.3 indicates the land use distribution within the catchments (source protection zones) of selected boreholes in the Eden Valley.

Geology

The geology of the catchment and in particular the presence of drift cover, is an important factor in determining infiltration rates. Where the drift is thick and of low permeability then infiltration to the underlying aquifer can be significantly reduced; for example Vines (1984) estimated the recharge rate through 'Boulder Clay' to be as little as 50 mm/y. Recharge is discussed in more detail below.

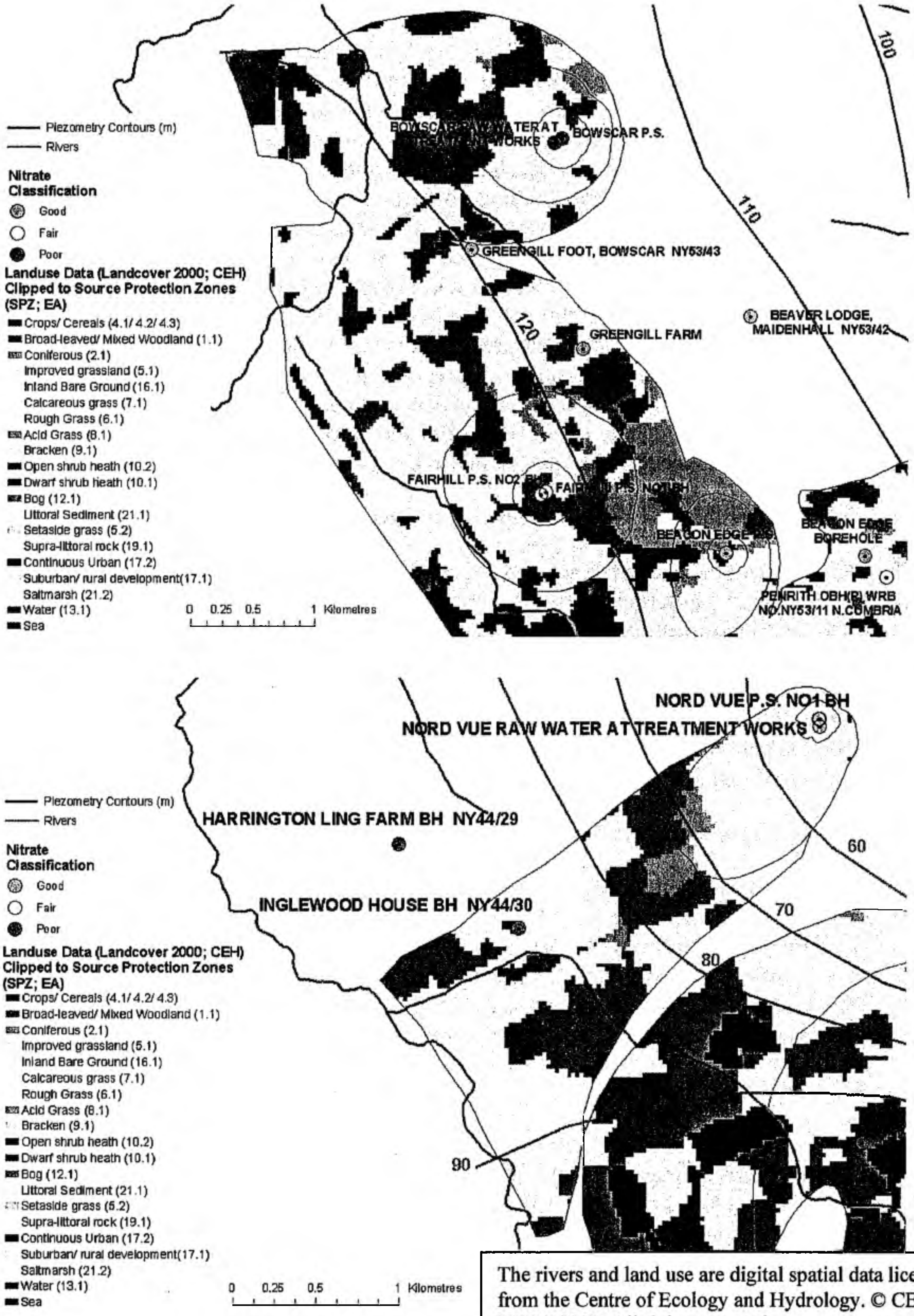


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Figure 4.3. Land use in selected abstraction borehole catchments in the Eden Valley

Recharge

Catchment average rates of recharge for the sandstone aquifers have been estimated earlier based on balancing groundwater recharge with outflows from the aquifer (Ingram 1978). However, assigning different recharge rates between exposed sandstone (i.e. where the sandstone is drift free or covered by permeable drift) and where the aquifer has a significant drift cover is more problematic. Recharge rates through boulder clay (till) have been estimated at 50 mm/y (Vines 1984) although where the till also contains significant sand and gravel, recharge rates could be higher. The till can also exert an influence upon deep infiltration to the sandstone by enhancing recharge at the edge of the till sheet as a result of run off from the clay cover and of interflow within the weathered and more permeable zones in the deposits. Thus recharge through exposed sandstone windows may be appreciably higher than surrounding drift covered areas producing areas of focused recharge within a background of much lower infiltration. Boreholes located within these areas of focused recharge are likely to have a greater proportion of their water derived from close to the borehole and, as consequence, travel time from the surface to the borehole is likely to be shorter (and nitrate concentrations may be higher).

Aquifer characteristics and rates of groundwater flow

The Permo-Triassic sandstone aquifer is characterised by high porosity (c. 0.25) and moderate intergranular permeability (c 0.5 m/d). This produces relatively slow groundwater movement and long travel times. For regional models, an aquifer permeability approaching the intergranular value generally provides the best fit. However, it is widely accepted that for most abstraction boreholes, fissures contribute most of the flow, (typically as much as 90%). These apparently contradictory observations are reconciled by assuming that fissure flow is locally dominant around boreholes. The presence of fissuring is likely to reduce travel time of water moving from close to the borehole (and thus may increase the nitrate concentration).

Thickness of unsaturated zone

Rates of water movement through the unsaturated zone of the Permo-Triassic sandstones are believed to be slow, typically 0.5-3.0 m/y, depending on the porosity of the sandstones and rate of infiltration. Thus where the unsaturated zone extends for several tens of metres, it can impose a significant time lag between leaching from the soil and arrival at the watertable. In the Eden Valley, the unsaturated zone can be up to 50 m thick and so infiltration may take many years or even decades to reach the watertable.

Borehole design

The borehole design can affect the mix of water derived from the aquifer; for example, deep boreholes are likely to pump a greater percentage of deeper groundwater (and probably older water) than a shallow borehole. Likewise, the greater the casing depth, the greater the percentage of deep groundwater that is likely to be pumped. However, the relative contribution of shallow and deep groundwater pumped will also depend on the distribution of both permeability (horizontal and vertical) and head distribution within the aquifer. As mentioned earlier, where low permeability layers occur within the sandstones then stratification of water quality (and residence time) may develop.

4.2 Correlation of pumped groundwater nitrate concentrations with various factors

4.2.1 Method

A spreadsheet was set up to contain all the EA monitoring network data on nitrate and chloride concentrations from pumped groundwater samples in the study area and specific information about the construction of each borehole and geology at the site was added, where the data were available, from the national groundwater archive.

The groundwater nitrate concentrations for the year 2000 were plotted as a frequency histogram (Figure. 4.4) and then against selected factors (borehole depth, drift thickness, casing depth, depth of unsaturated drift and depth of unsaturated bedrock) to see if any significant correlation existed between them. The year 2000 was selected, as this was a year when the majority of the boreholes had been sampled at least once. If there were several dates where samples had been taken in 2000 then the value closest to November 2000 was used. Where no data were available for 2000 then data for 1999 or 2001 were used. If no data were available for these years then the borehole was not included in the graphs.

4.2.2 Results for 2000 data

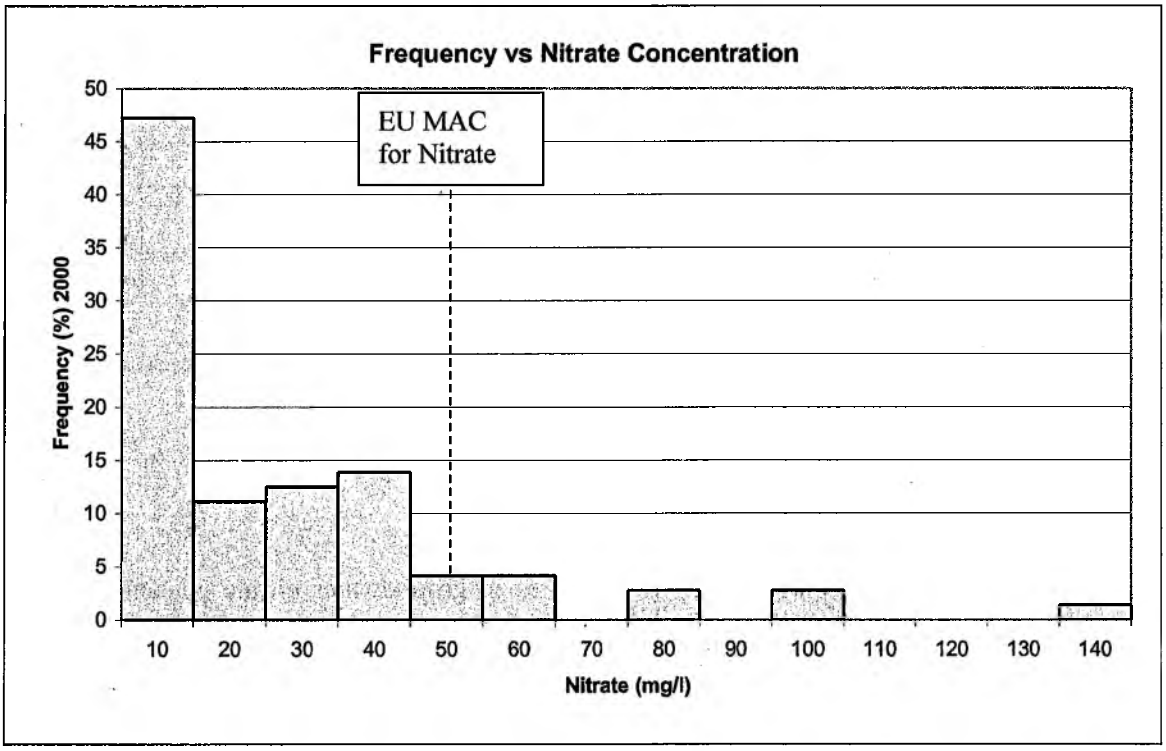


Figure 4.4. Nitrate concentration frequency histogram

Figure 4.4 indicates that groundwater nitrate concentrations are variable within the Eden Valley. Many boreholes (47%) have nitrate concentrations less than 10 mg/l but a significant number have concentrations in excess of 20 mg/l. Groundwater nitrate concentration was plotted against various factors, the conclusions drawn from each of these graphs are described below.

Borehole Depth

Figure 4.5 shows that generally, the highest values of groundwater nitrate concentration are associated with the shallower boreholes. However there is no clear linear relationship between the two. The only obvious pattern is that boreholes less than approximately 80 metres deep show a wide range of nitrate concentrations (1.8 –131 mg/l), however boreholes greater than 80 metres deep, have a narrower range of nitrate concentration of 35 mg/l or less. This suggests that, although borehole depth is a factor where depth exceeds 80 metres, for shallower boreholes other factors are more important.

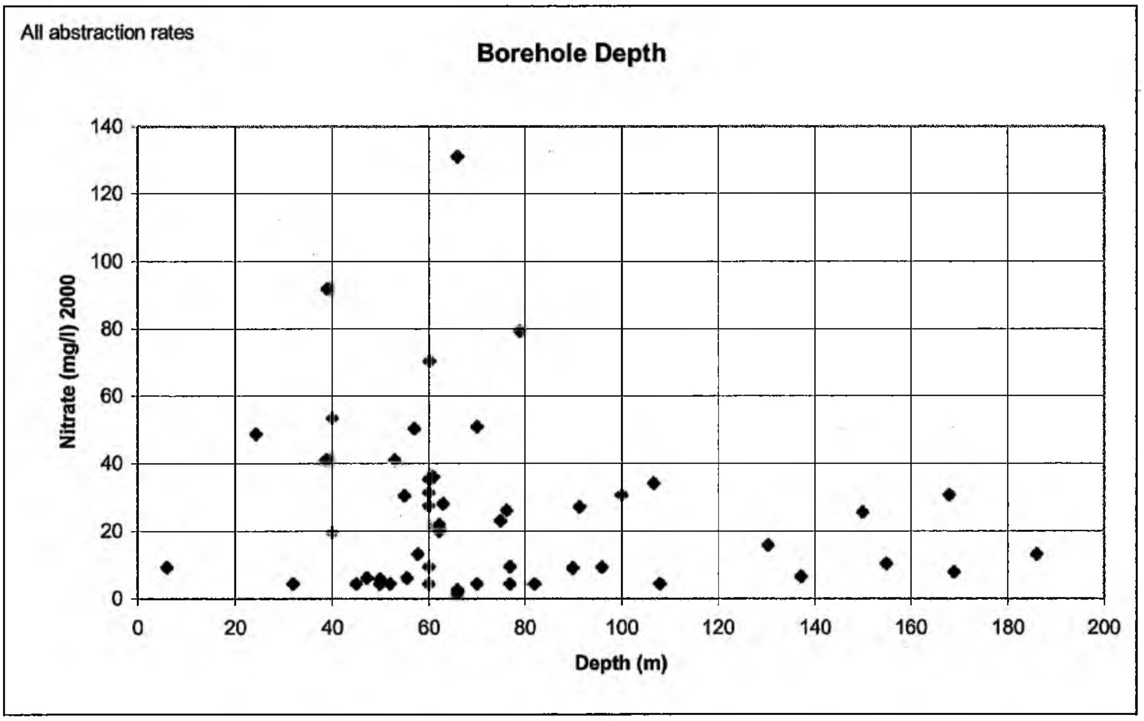


Figure 4.5. Scatter plot of borehole depth and nitrate concentration

Drift thickness

Figure 4.6 shows that generally the higher values of groundwater nitrate concentration are associated with the thin drift cover (<10 m thick), however there are some exceptions. Boreholes with more than 10 m of drift usually have nitrate concentrations below 10 mg/l, although there are some exceptions; for example the nitrate concentration of groundwater from one borehole with more than 20 m of drift was nearly 92 mg/l. Where the drift is less than 10 m the groundwater nitrate concentration is very variable suggesting that other factors are also important.

Casing depth

Figure 4.7 shows a general trend of decreasing nitrate concentration with depth. Where casing depth exceeds 40 m, nitrate concentration is usually less than 20 mg/l although few boreholes have casing depths greater than 40 m.

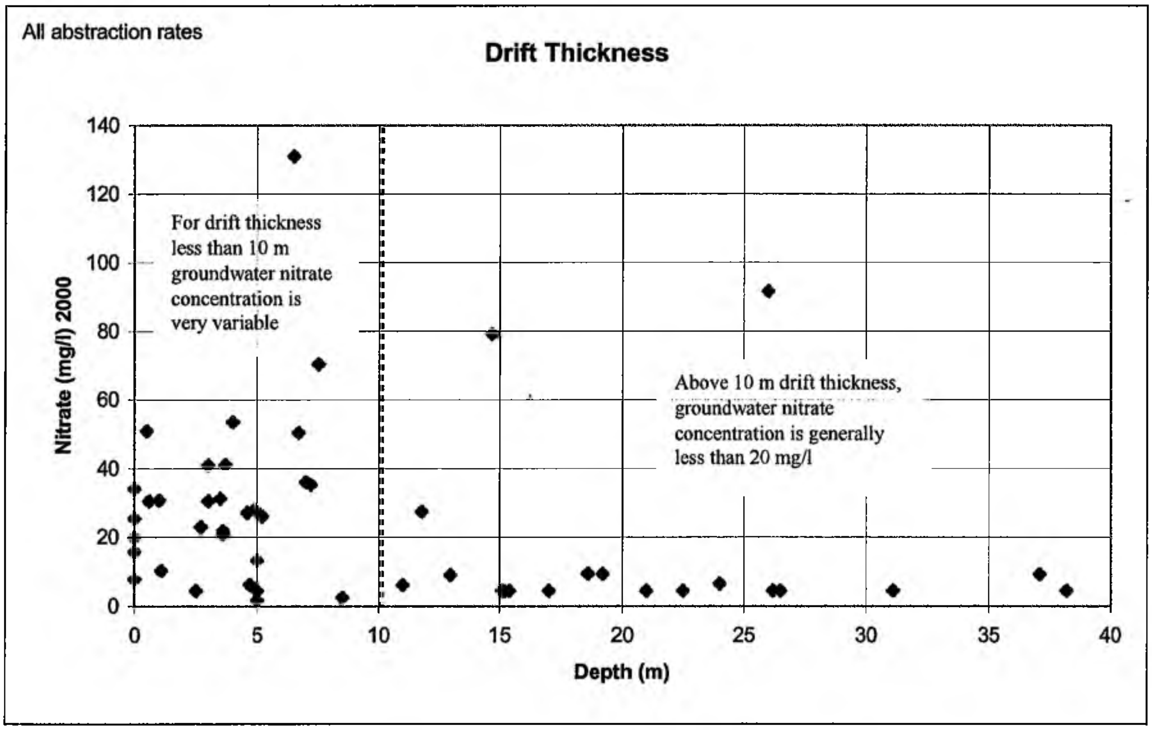


Figure 4.6. Scatter plot of drift thickness and nitrate concentration

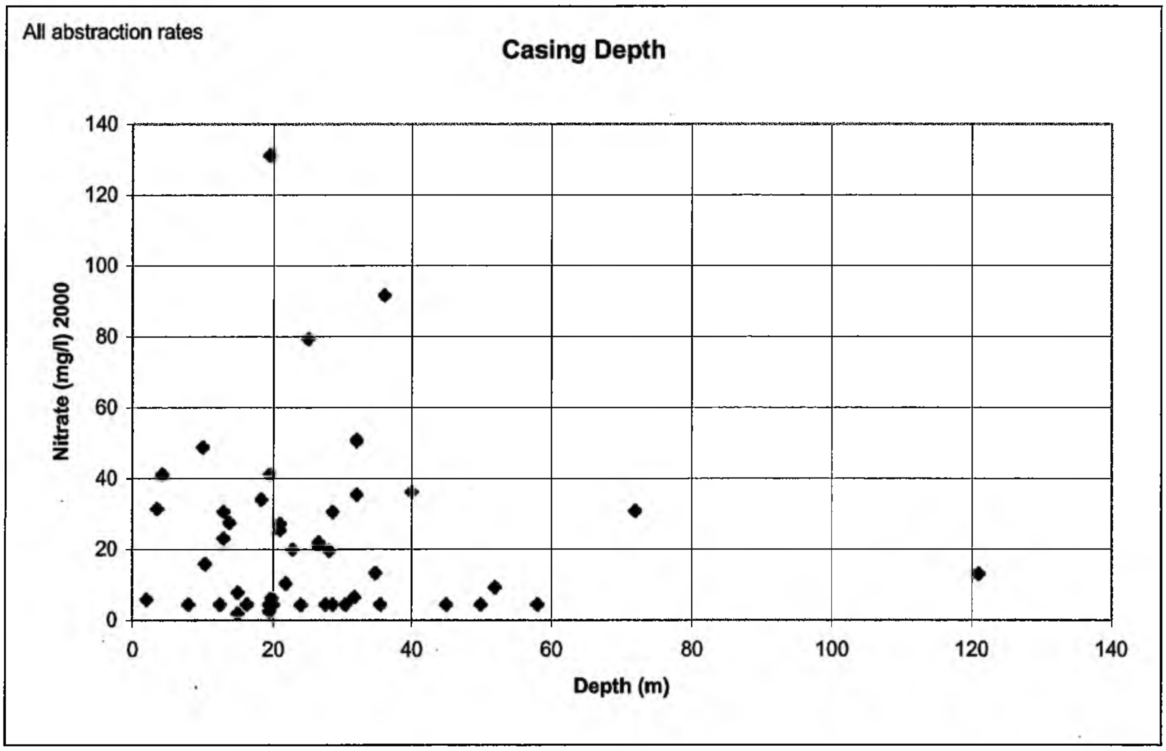
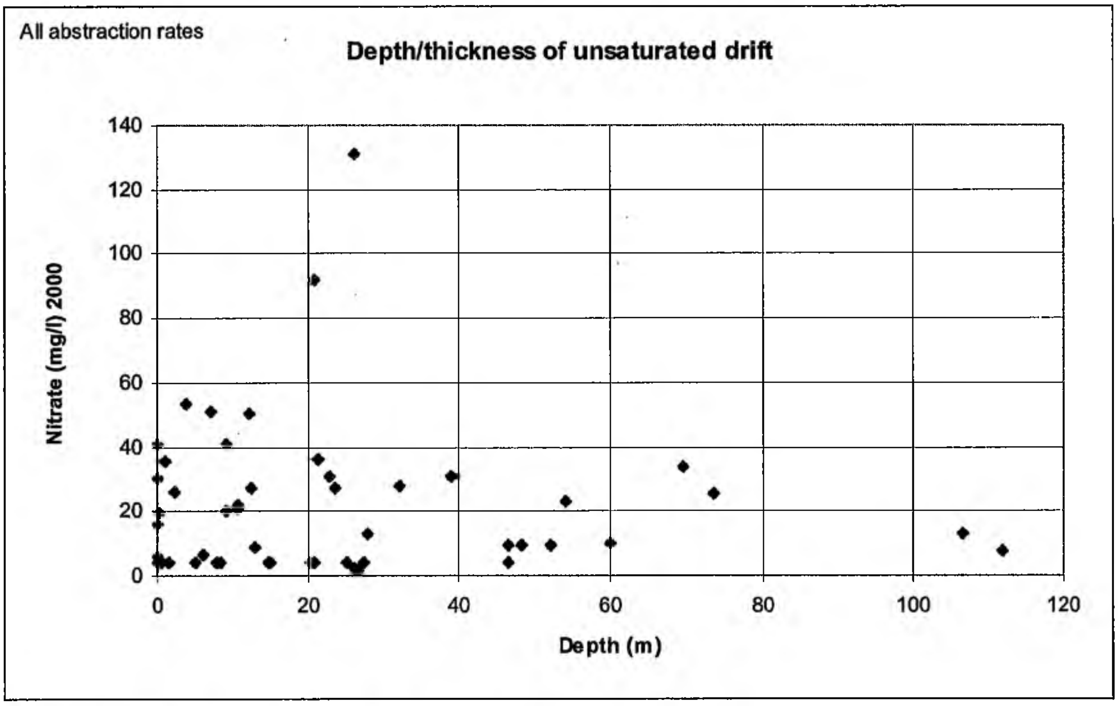


Figure 4.7. Scatter plot of borehole casing depth and nitrate concentration

Depth of unsaturated zone within (a) drift and (b) bedrock

Figure 4.8 indicates that, rather surprisingly, the unsaturated zone thickness does not appear to have a significant influence on groundwater nitrate concentration.



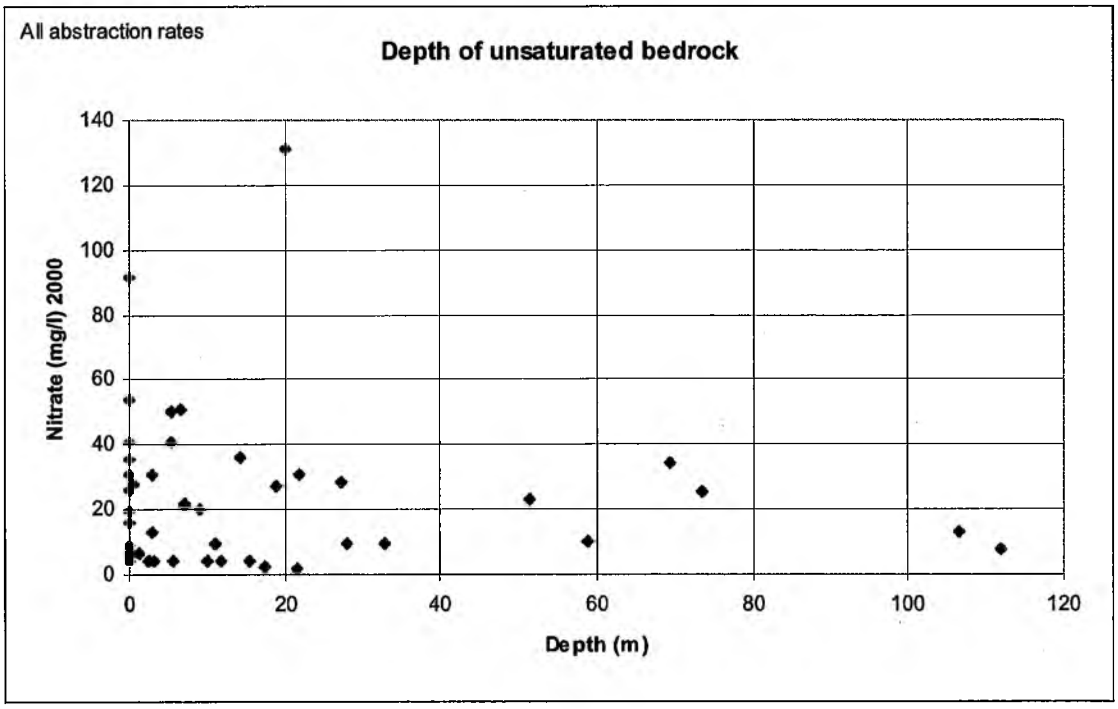


Figure 4.8. Scatter plot of thickness of unsaturated zone (a) drift, (b) bedrock and nitrate concentration

4.2.3 Correlation of various factors with nitrate concentration for large abstraction boreholes (>1000 m^3/day)

It was thought likely that the quantity of water abstracted could also influence the nitrate concentration of the pumped water. This is because low yielding boreholes will have correspondingly small capture zones which could be dominated by land use atypical of the catchment and could produce 'extreme' pumped nitrate concentrations (high or low). Conversely, for higher abstraction rates, the capture zone for the borehole will be larger and the land-use within the zone is likely to approach the catchment 'average'.

The factors described above were correlated with pumped nitrate concentrations for boreholes where the abstractions exceeded 1000 m^3/day.

No correlation with borehole depth or unsaturated zone thickness was observed. There appeared to be a reasonable correlation between pumped nitrate concentrations and both drift thickness and casing depth, however data is rather sparse.

Finally an attempt was made to compare nitrate concentrations with aquifer type. Four aquifer types were identified:

- Unconfined sandstone with either no drift cover or thin permeable cover.
- Unconfined sandstone with drift cover of less than 10 metres[2]
- Unconfined sandstone with drift cover greater than 10 metres
- Confined sandstone (e.g. water level fluctuating within drift cover)

A plot of nitrate concentration for these various aquifer types is shown in Figure 4.9. For these plots, the data used was mainly for the year 2000 although for some boreholes the nearest date was used which in some cases was as early as the mid-eighties.

It is apparent that the nitrate concentration within each aquifer type could vary from less than 4 mg/l to more than 30 mg/l. However, lower concentrations were more frequently encountered in boreholes where the aquifer is confined or where the drift thickness exceeds 10 metres.

Other factors clearly play a role in determining nitrate concentration other than aquifer type alone; for the unconfined with either no drift cover or thin drift, land use may be a significant consideration, especially for low yielding boreholes. However it was beyond the scope of this phase of the project to define individual capture zones and investigate land use within these.

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[2] 10 m used based on previous correlations between groundwater nitrate concentration and drift thickness

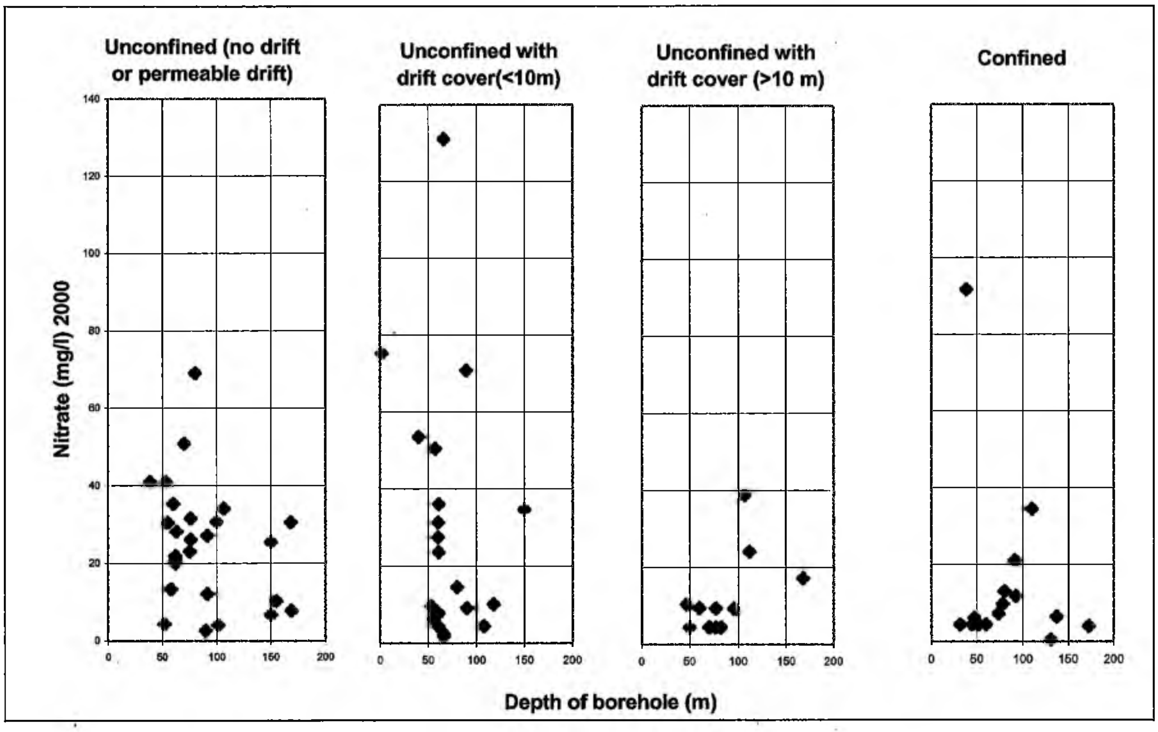


Figure 4.9. **Scatter plot of borehole depth and pumped nitrate concentration (all abstraction rates)**

Two surprising features emerge from the correlation of nitrate concentration with various factors. Firstly, despite the large aquifer storage and the consequent slow travel times in the saturated zone, nitrate concentrations can be high, even when boreholes are deep (greater than 100 metres). Secondly, rates of water movement through the unsaturated zone are likely to be slow (probably less than 2 m/yr) and so the unsaturated zone, which can be up to 50 m deep, is likely to impose a significant time delay for water moving from the soil to the watertable. However, results of groundwater monitoring presented here show that elevated groundwater nitrate concentrations can occur even where a relatively deep unsaturated zone exists. The question of travel time, within the saturated zone, is explored in more detail in the next chapter.

Summary

- Groundwater pumped from a long screened borehole is a mix of water of different ages, of different nitrate concentrations and of different origins from within the borehole catchment.
- Because of the above it is difficult both to predict nitrate concentrations for a specific borehole and to correlate nitrate concentrations in boreholes with individual factors. This is the case in the Eden Valley although there is a trend towards lower nitrate concentrations with increasing depth to water table, casing depth and drift thickness.
- Sandstones in the Eden Valley can be three major aquifer types:
  - Unconfined sandstone with no, or little, drift cover.
  - Unconfined sandstone with thick drift cover (≥10 m).
  - Confined sandstone, groundwater level fluctuates within drift
- The presence of poorly permeable drift deposits does appear to influence nitrate concentrations. The average pumped nitrate concentration for boreholes where drift cover is absent or less than 10 m, is higher than for those boreholes where the aquifer is either confined or overlain by drift cover of more than 10 m.
- Groundwater nitrate concentrations are normally significantly lower in the confined aquifers.
- The relatively high nitrate concentrations of some groundwaters pumped from deep boreholes is surprising, given the high porosity of the aquifer and the consequent relatively long travel times.
- It is anticipated that, as with the Dumfries Basin, groundwater nitrate concentrations are correlated with residence time, (higher nitrate with short residence time). Low yielding abstraction boreholes may be more influenced by very local land-use or by denitrification within till or drift deposits. Larger abstraction boreholes will be recharged from a greater catchment area and consequently have a wide range of land uses and surficial geology.

5. MODELLING

5.1 Introduction

As mentioned earlier, the groundwater pumped from abstraction boreholes is a mix of groundwater with different nitrate concentrations and different ages.

One of the surprising observations when comparing groundwater nitrate concentrations with the various influencing factors is that even in relatively deep boreholes (c.100 m), pumped nitrate concentrations can be appreciable (> 30 mg/l).

This chapter describes how numerical modelling was used to investigate how various factors may influence the travel time (and by implication nitrate concentration) of water arriving at an abstraction borehole.

5.2 Numerical Modelling

Numerical modelling was used to investigate the sensitivity of modelled travel times to:

1. the permeability of the sandstone (including the development of fissuring around the borehole) and,
2. the presence of drift deposits (with different configurations and infiltration rates).

The graphs presented compare the percentage of modern water pumped against time since pumping started. Modern water is defined as recharge that reaches the water table after the abstraction well starts pumping. A high percentage of modern water in the borehole suggests that the nitrate concentration could also be high. Various scenarios were considered, to include a range of aquifer permeabilities and drift geometries. The output from this modelling is used to show that the percentage of modern water pumped is sensitive to these scenarios and provides a possible explanation as to how deep boreholes could pump water with a relatively high percentage of modern water. These models are not used here to predict the percentage of modern water or trends in nitrate concentration with time.

5.2.1 Model structure

The numerical model used to simulate the various aquifer scenarios is shown in Figure 5.1. The model is constructed using the regional groundwater modelling code ZOOMQ3D (Jackson, 2001), which incorporates unconventional local grid refinement. This has been used to simulate the abstraction borehole on a 50 m mesh for improved accuracy. The model is 8 km square and contains five layers. The hydraulic conductivity of the sandstone aquifer is defined in the model as 1 m/d. An abstraction well is located at the centre of the grid and pumps at a rate of 2000 m^3/d. The left hand boundary inflow and right hand bound outflow are specified to approximate a 1:50 regional hydraulic gradient. This gradient has been defined by examining regional groundwater contours presented by Environmental Simulations International (1999) for the Eden Valley.

The model is used to simulate a homogeneous intergranular aquifer and an aquifer that contains a fracture. The fracture is represented using a 5 m thick layer, which has a hydraulic conductivity of 100 m/d. The fracture plane extends 500 m from the abstraction borehole in both horizontal Cartesian directions. The model layer thicknesses differ when simulating an intergranular or a fractured aquifer, however, the total thickness is always 200 m. Further details are given in the appendices.

The total recharge to the aquifer is 55 Ml/d, however, its distribution varies depending on the extent of the drift cover. The rate of recharge through the drift is also varied. The different recharge scenarios are shown in Figure 5.2. In summary they are:

- Scenario 1. No drift is represented and recharge is applied uniformly at a rate of 314 mm/y.
- Scenarios 2 and 3. Drift is included with coverage of 35% and 65%, respectively. The total recharge is maintained at 55 Ml/d. The ratio of the drift recharge rate to the uncovered sandstone recharge rate is 90:315.
- Scenarios 4 and 5. Drift is included with coverage of 35% and 65%, respectively. The total recharge is maintained at 55 Ml/d. Recharge through the drift is specified as 50 mm/y.

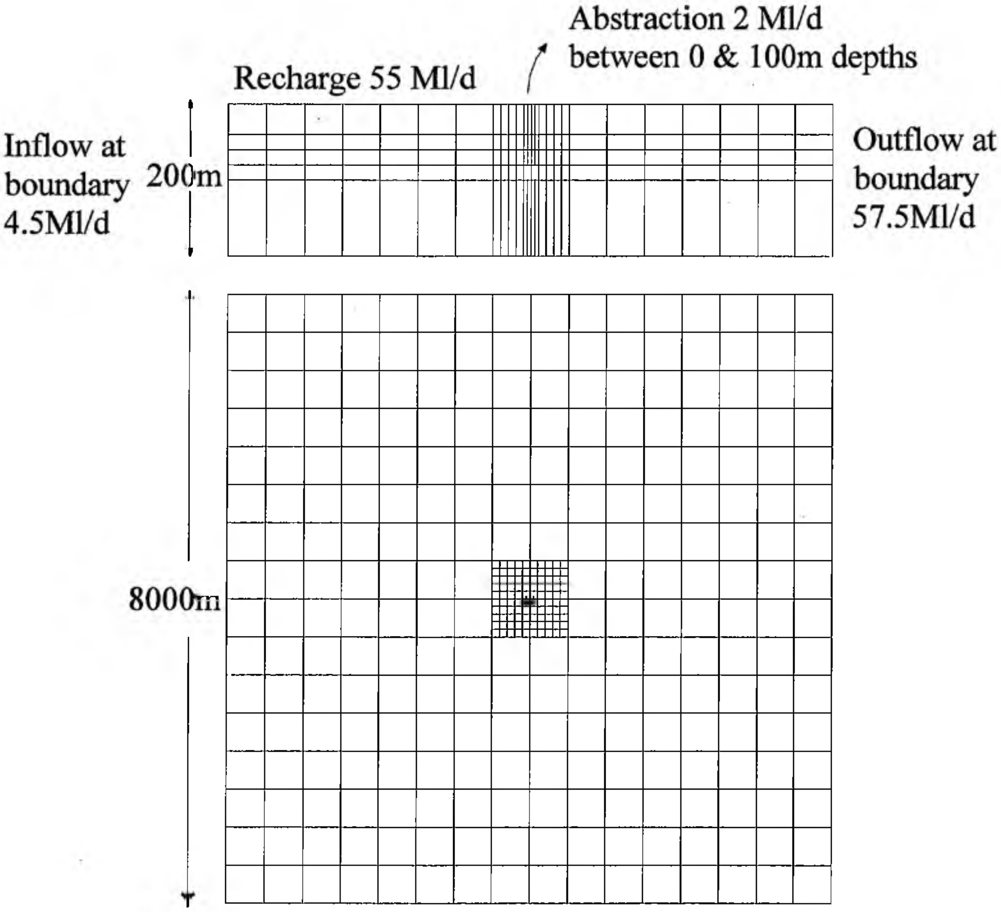
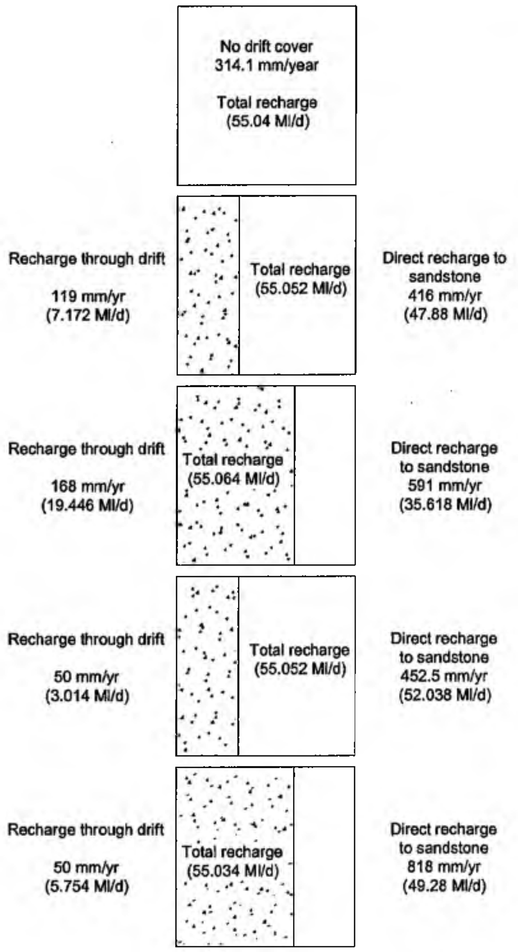


Figure 5.1. Structure of the numerical model (cross section over plan view)

5.2.2 The simulations

In total, twelve steady-state simulations were run in which the different recharge scenarios were applied to the intergranular and fractured aquifer. Particle tracking was then performed to determine the time of travel of particles of water from the water table to the abstraction borehole. Particles are placed on the water table along a line through the centre of the model from the left to the right. A line of particles is used for simplicity. For more accuracy particles could be placed over the full areal extent of the borehole catchment (which vary between model runs), however, time-constraints did not allow this. As will be shown, the use of the line of particles was sufficient to enable conclusions to be drawn regarding the influence of drift coverage and fracturing on the age of the abstracted water.

The spacing of the particles along the water table depends on the recharge rate. For comparisons to be made regarding the percentage of modern water arriving at the abstraction borehole over time, between the different simulations, each particle must represent the same *volumetric* recharge rate. In each model a particle is associated with 0.1075 m^3/day of recharge per metre width of aquifer in the south-north direction. For example, if the recharge rate is 0.5 mm/d the particle spacing will be 215 m. Consequently, when examining the particle tracks (e.g. Figure 5.3 and similar figures in the appendices), fewer particles are located on the water table under the drift than in the areas of uncovered sandstone because the recharge rate is lower where there is drift cover.



Drift Scenario 1
No drift cover

Drift Scenario 2
35% drift cover
Ratio of recharge rates
Drift : No Drift
90 : 315

Drift Scenario 3
65% drift cover
Ratio of recharge rates
Drift : No Drift
90 : 315

Drift Scenario 4
35% drift cover
50 mm/yr through drift
Maintain total recharge of 55 Ml/d

Drift Scenario 5
65% drift cover
50 mm/yr through drift
Maintain total recharge of 55 Ml/d

Figure 5.2. Model recharge scenarios

For scenario 5, the recharge rate to the sandstone aquifer is set at 818 mm/y which appears to be too high, however this may be realistic where focussed recharge occurs within the ‘recharge windows’.

Model No.	**Recharge scenario**	**Intergranular or fractured aquifer**	**Hydraulic conductivity (1 m/d unless given)**	**Porosity (25 % unless given)**
1.	1. (No drift)	Intergranular		
2.	1. (No drift)	Intergranular	K_x=5 m/d	
3.	1. (No drift)	Fractured	K_x=100 m/d for fracture	
4.	1. (No drift)	Fractured	K_x=100 m/d for fracture	5 % for fracture
5.	2. (35 %)	Intergranular		
6.	3. (65 %)	Intergranular		
7.	2. (35 %)	Fractured	K_x=100 m/d for fracture	
8.	3. (65 %)	Fractured	K_x=100 m/d for fracture	
9.	4. (35 %) (50 mm/y through drift)	Intergranular		
10.	5. (65 %) (50 mm/y through drift)	Intergranular		
11.	4. (35 %) (50 mm/y through drift)	Fractured	K_x=100 m/d for fracture	
12.	5. (65 %) (50 mm/y through drift)	Fractured	K_x=100 m/d for fracture	

Table 5.1. Details of model simulation runs

5.2.3 Model output

Particle tracking is used to plot the pathline of each particle from the water table to the abstraction borehole. The particle paths for Model 1, an intergranular aquifer with no drift cover, are shown in Figure 5.3. The particle tracking model also calculates the travel time of individual particles. Particle travel times for Model 1 are plotted in Figure 5.4. These figures are presented as an example of the model output. A full set of these figures is provided in the appendices for each of the simulations.

Conclusions are made regarding the effect of drift cover and aquifer fracturing by examining the particle travel times. In Model 1 (Figures 5.3 and 5.4), 33 particles arrive at the borehole from the water table. The first particle takes 0.81 years to travel from the water table to borehole. Consequently, it can be estimated that 0.81 years after the pump is switched on, approximately one thirty-third of the water abstracted is modern. The second particle arriving at the well takes 1.04 years to travel to the water table. Therefore, after 1.04 years we can assume that 2x100/33 % of the abstracted water is modern. By applying this process, a graph of the percentage of modern water pumped against time can be drawn for each model simulation. For Model 1 this graph is shown in Figure 5.5.

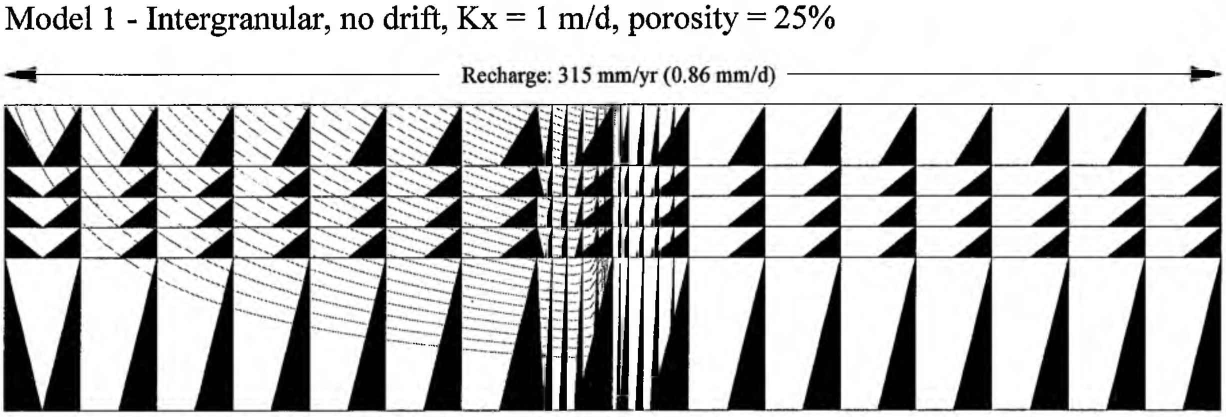


Figure 5.3. Particle pathlines for Model 1, an intergranular with no drift cover

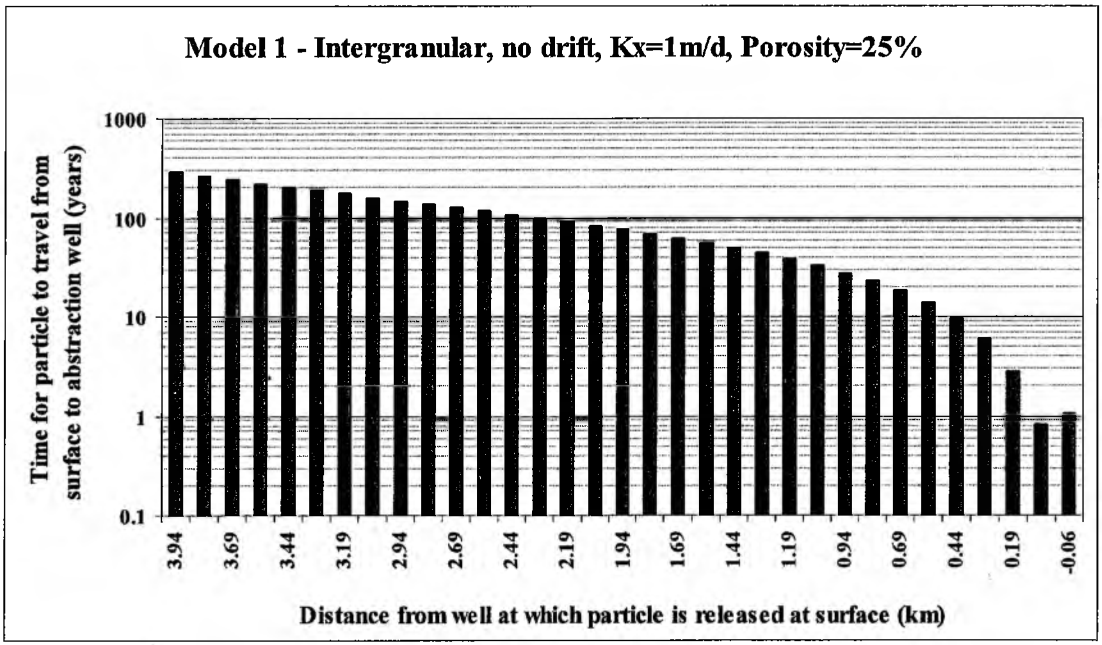


Figure 5.4. Particle travel times for Model 1, an intergranular with no drift cover

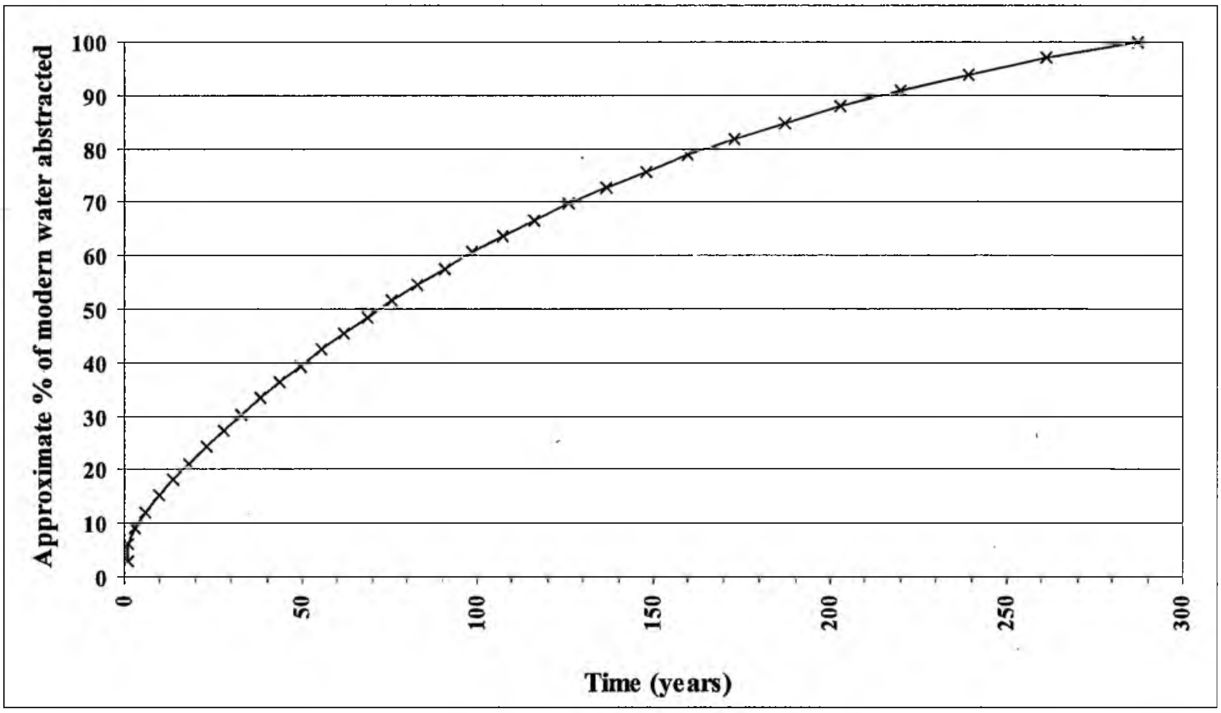


Figure 5.5. **Estimated percentage of modern water pumped since start of abstraction, Model 1**

5.2.4 Modelling results

A. The effect of varying the hydraulic conductivity of the intergranular aquifer

Comparison between Model 1 and 2

Model 1 is taken as the base case for comparison with the other simulations. Model 1 represents an intergranular aquifer with uniform recharge (no drift cover). In Model 2 the hydraulic conductivity is increased five times to 5 m/d (T = 1000 m^2/d). The following conclusions are made with reference to Figure 5.6.

Particle pathlines are very similar (see figures presented in the appendices) even though the horizontal hydraulic conductivity is increased five times in Model 2.

Porosity controls the velocity of the particles. Since porosity is 25% in both models, the particle travel times are also very similar. Consequently, the curves of percentage modern water pumped versus time are nearly identical.

The curves are relatively smoothly varying. This is because the aquifer is homogeneous and particles are uniformly spaced along the water table since recharge is evenly distributed.

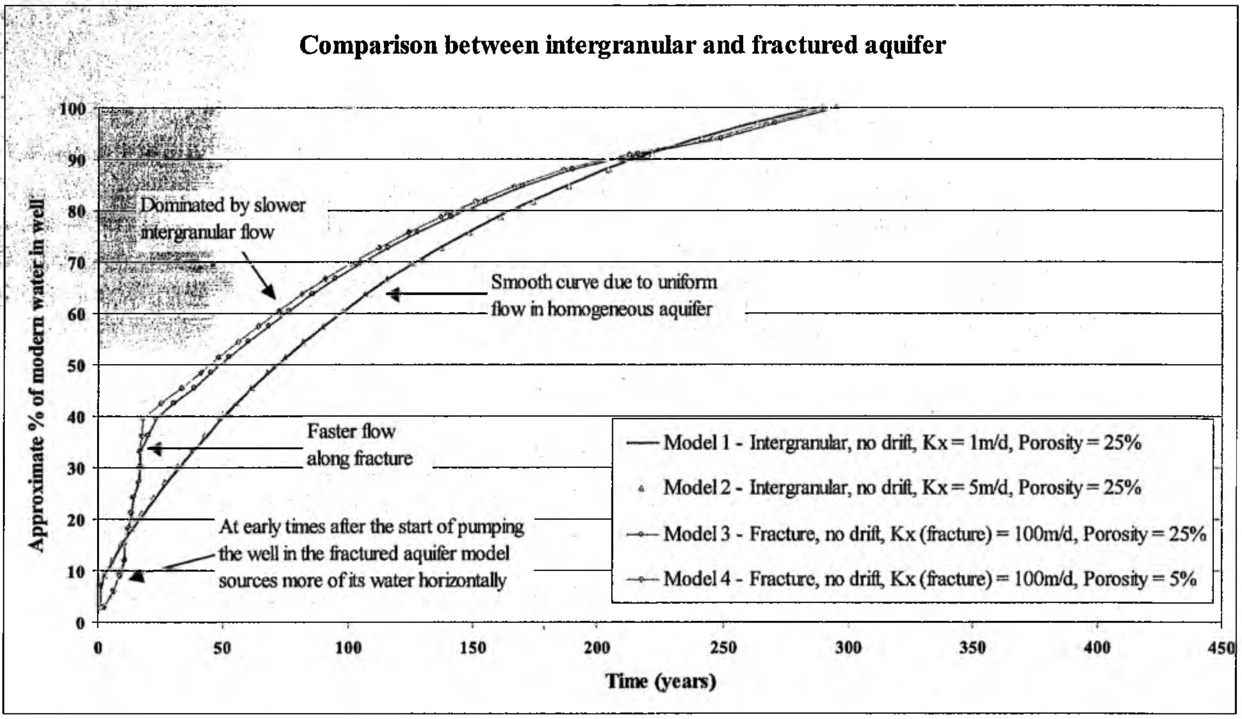


Figure 5.6. Comparison of percentage of modern water pumped against time between intergranular and fractured aquifer

B. The effect of fracturing on the percentage of modern water pumped over time aquifer

Comparison between Models 1, 3 and 4

A fracture is introduced into Model 3 and 4. This is represented by a 5 m thick layer between depths of 20 and 25 m, with an associated hydraulic conductivity of 100 m/d. The porosity of the fracture is 25 % in Model 3 and 5 % in Model 4. The comparison between the models is again shown in Figure 5.6. The following conclusions are drawn from an examination of the graph.

- The fracture transports water rapidly to the borehole. Particles starting approximately 500 m from the well (i.e. over an interval that is similar to the horizontal extent of the fracture) travel vertically down to the fracture and then rapidly to the well. Consequently, a greater percentage of modern water is pumped at earlier times in the fractured aquifer models (Model 3 and 4) than in the homogeneous aquifer model (Model 1).

- The particles that arrive at the well after approximately 20 years, travel for a significant time through the unfractured part of the aquifer (i.e. from greater than 500 m from the well). The introduction of the fracture has less of an impact on the travel times of these particles than those starting closer to the well. Consequently, the curves for the fractured aquifer models are smooth after approximately twenty years since the start of pumping.

- Because the hydraulic conductivity of the fracture is high (100 m/d) water travels rapidly along it. Generally, the length of time that a particle flows within the fracture is much shorter than the time it takes to travel to the fracture. Because of this, only small differences are observed between Model 3 and Model 4, in which the fracture porosity is specified as 25 % and 5 %, respectively. As expected, the decrease in fracture porosity results in a slightly greater percentage of modern water being pumped at earlier times.

C. The effect of varying drift cover on the percentage of modern water pumped over time in an intergranular aquifer. Comparison between Models 1, 5, 6, 9 and 10

In Model 5, 6, 9 and 10 drift cover is simulated. This is represented by reducing the recharge over either the left hand 35 % or 65 % of the model area (Figure 5.2). In Model 5 and 6, the ratio of the drift and drift free recharge rates is 90:315. In Model 9 and 10, the recharge through the drift is reduced further and is specified at 50 mm/y. Total model recharge is always 55 Ml/day. The following conclusions are drawn from an examination of Figure 5.7.

With 35% drift cover, the abstraction borehole is located in a drift free area. The borehole preferentially sources its water from the drift free area where recharge is higher. There is more vertical flow close to the well and consequently, younger water arrives at the well more rapidly. The curves (Model 5 and 9) of the percentage of modern water pumped against time rise steeply compared to the base case (Model 1) for approximately 60 to 70 years. After this time water begins to arrive from the drift covered areas and the slope of the curve reduces.

With 65% drift cover, the abstraction borehole is located beneath the drift. In both such cases (Model 6 and 10) the borehole catchment is completely covered by the drift. The larger borehole catchment, due to the reduced recharge rate, means that modern water takes significantly longer to arrive at the well. Lower drift recharge rates are beneficial if the borehole catchment is contained within the drift covered area.

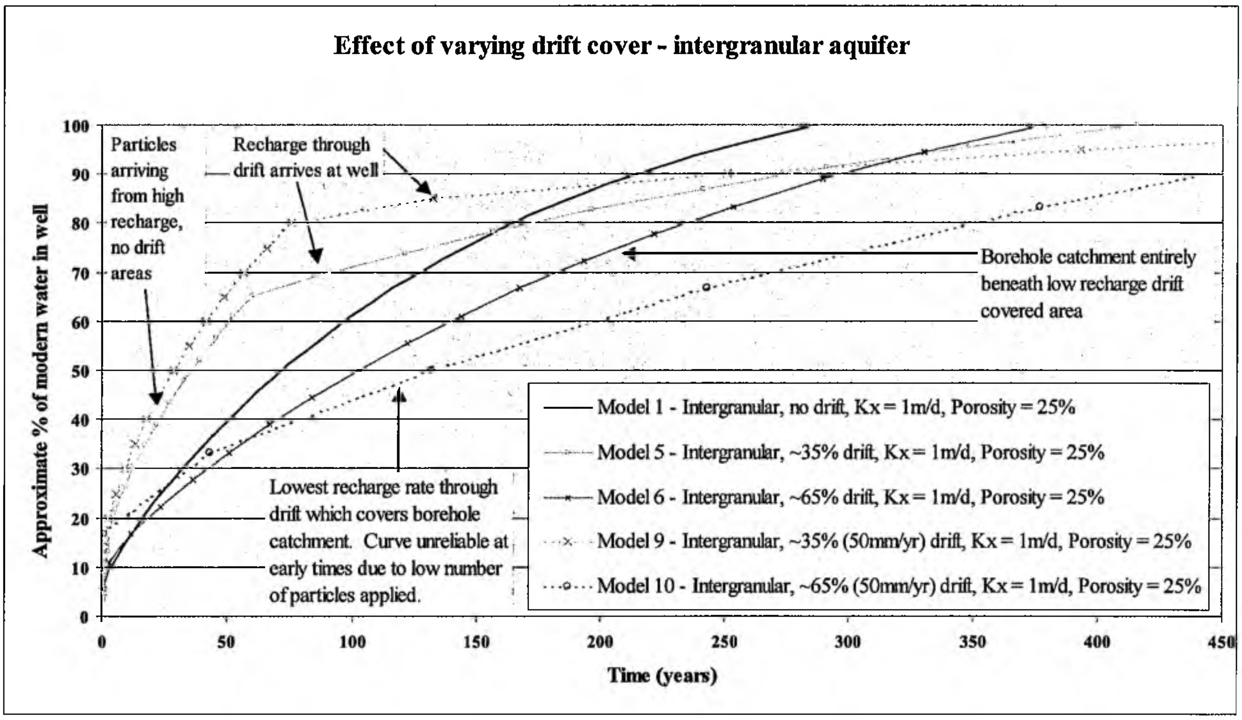


Figure 5.7. **Comparison of the percentage of modern water pumped against time between different drift cover scenarios**

D. The effect of the combination of varying drift cover and fracturing on the percentage of modern water pumped over time in a fractured aquifer. Comparison between Models 1, 3, 7, 8, 11 and 12

In Model 7, 8, 11 and 12 both the fracture and drift are represented. The graphs of percentage modern water pumped against time are shown in Figure 5.8.

With 35% drift cover the well is located in the high recharge drift free area. The introduction of the fracture has the effect of increasing the percentage of modern water arriving at the well. Consequently, in Model 7 and 11, the curve rises sharply soon after the pump is switched on. Approximately, three times the percentage of modern water is pumped after twenty years in a fractured aquifer with 35 % drift cover than in the uniform recharge, homogeneous aquifer case (Model 1).

The effect of the fracture can also be seen where the drift covers 65% of the aquifer. The borehole catchment remains entirely beneath the drift, where the recharge rate is low, however, the fracture still promotes faster flow to the well and thus has a detrimental effect on the percentage of modern water pumped over time.

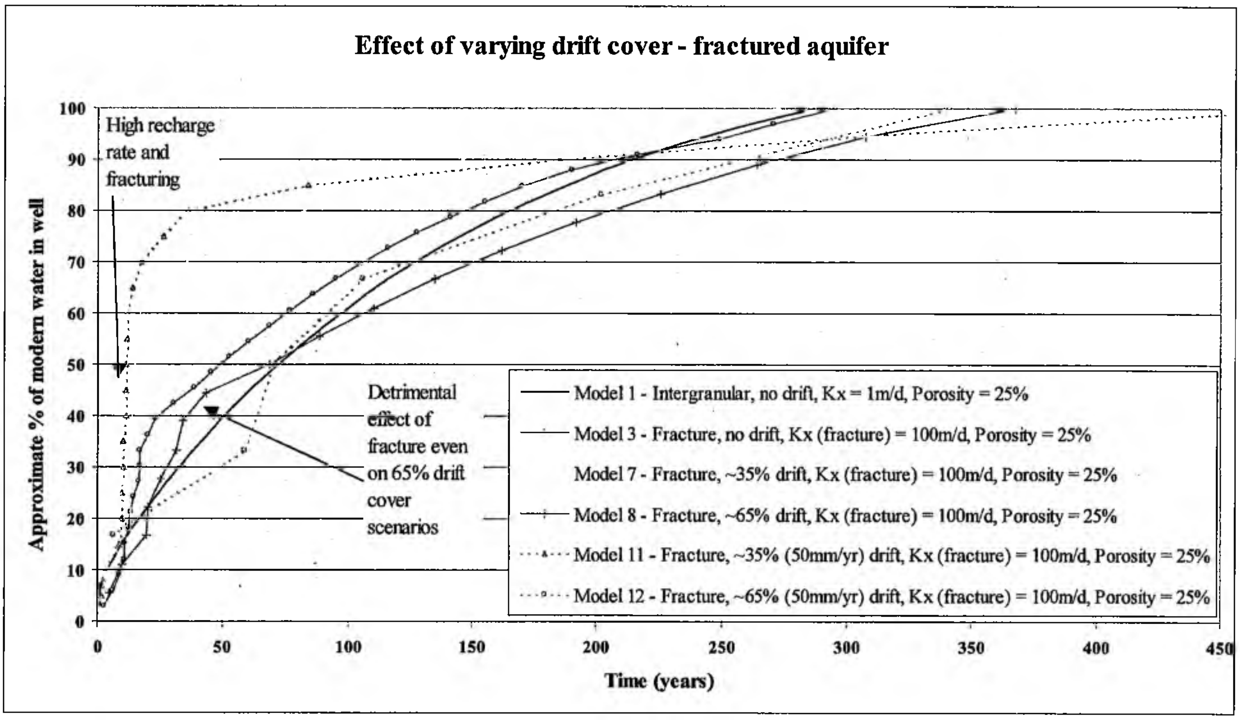


Figure 5.8. Comparison of percentage of modern water pumped against time for a fractured aquifer and different drift scenarios

Summary

- The purpose of the numerical modelling was to provide an explanation for how modern groundwater makes up a considerable proportion of the water pumped from some deep abstraction boreholes, given the considerable storage within the aquifer. The modelling estimates travel time within the saturated zone of the aquifer and modern water is considered to be recharge that arrived at the water table since the start of pumping.
- Modelling suggests that a combination of factors,
    - focussed recharge trough permeable windows in the drift cover and
    - localised fissure flow to the abstraction borehole

  could produce a significant percentage of modern water in the pumped groundwater.

  These scenarios used realistic parameters that fitted current understanding of the groundwater flow system in the Permo-Triassic sandstone aquifers in the Eden Valley.
- Conversely, the model predicted that groundwater pumped from a deep borehole beneath drift cover would have only a small percentage of modern water and is therefore likely to have low nitrate concentrations.
- Modelling has provided an explanation both as to how some relatively deep boreholes can pump water containing a significant percentage of modern water and why there are differences in nitrate concentration between boreholes in different hydrogeological environments. However, it is surprising that some boreholes, where the water table is deep (> 40 m), pump water with a significant fraction of modern water. The recharge mechanism in the Permo-Triassic sandstone is poorly understood and may be more complex than is often assumed so that some rapid bypass flow may occur.

6. DISCUSSION

A conceptual model of the groundwater system within the Eden Valley is summarised in Figure. 6.1. It shows groundwater recharge occurs (1) through drift deposits, (2) where the sandstone aquifer is exposed (drift free windows) and (3) as transfer of water from adjacent aquifers (e.g. Carboniferous Limestone). The main components of groundwater discharge from the system are (1) to river, (2) to abstraction boreholes, and (3) as slower/deep groundwater circulation. Modern, potentially high nitrate groundwater occurs at shallow depths and especially where recharge is concentrated beneath the drift free windows. Within this groundwater system four typical or generic components (Figure. 6.1) have been identified and are discussed below.

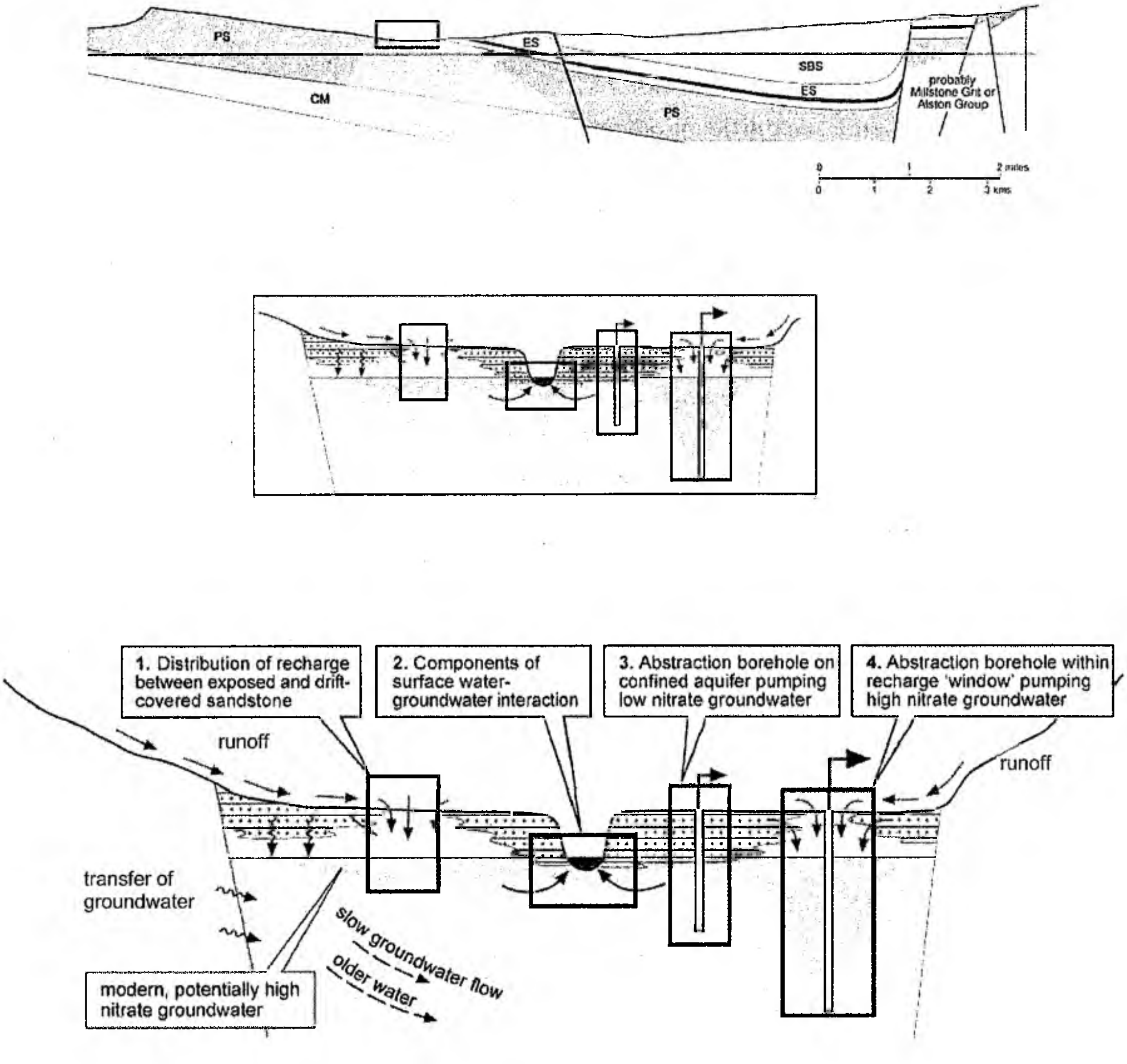


Figure 6.1 Conceptual model of groundwater flow systems in the Eden Valley

Component 1: The influence of drift cover sandstone on recharge distribution

The sandstone aquifer can be conveniently subdivided into areas where the sandstone is covered by drift and areas where the drift is either thin and permeable or absent (referred to as 'drift free windows,' Figure 6.2). It is anticipated that enhanced recharge occurs within the drift free windows because:

- Permeable soils permit high infiltration rates,
- Runoff from adjacent, less permeable drift-covered areas, provides additional recharge
- Shallow interflow/groundwater moving through weathered and/or more permeable lenses within the drift also contributes additional recharge

Differences in recharge rates to the sandstone aquifer between the drift covered and drift free area may be considerable. For example it has been suggested that recharge beneath the drift deposits could be as little as 50 mm/y (Vines, 1984) whereas within the 'drift–free windows' recharge rates are likely to be in excess of 400 mm/y. Where permeable 'windows' are surrounded by extensive drift-covered areas, infiltration rates to the sandstone aquifer within the window may be significantly higher still. The implication of this for pumped water quality in abstraction boreholes is described later in components 3 and 4.

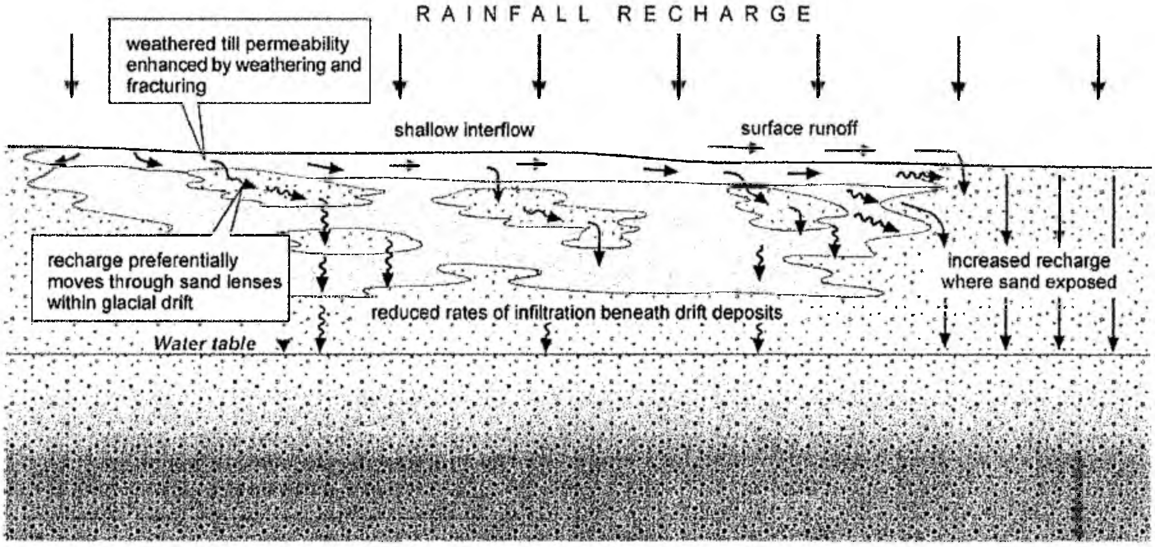


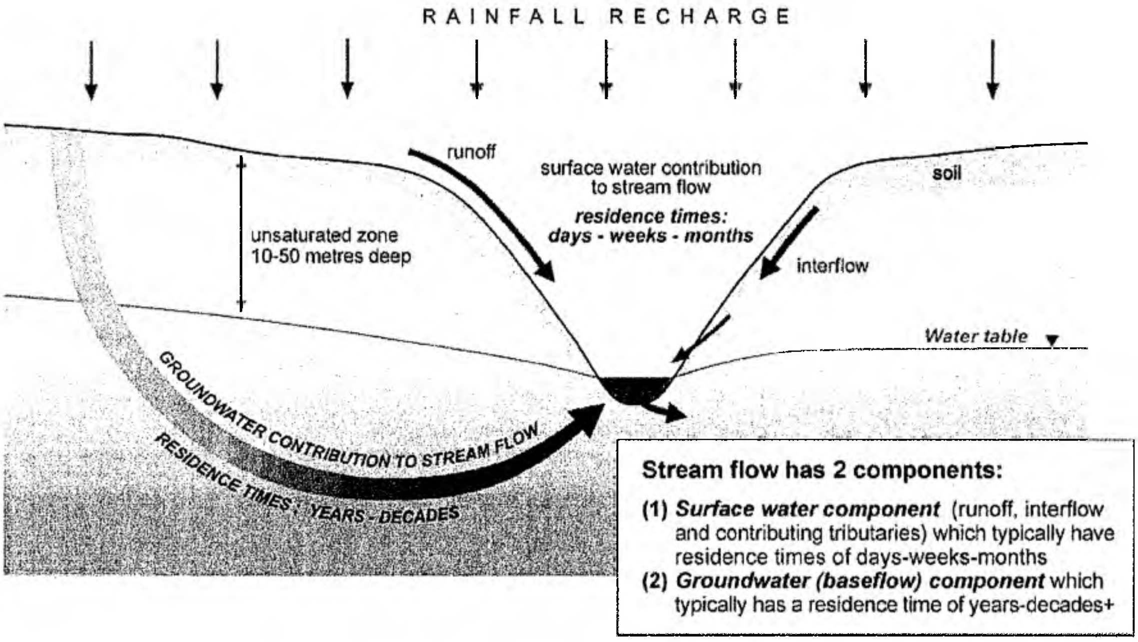
Figure 6.2 Distribution of recharge between exposed and drift-covered sandstone

Component 2: Surface water/groundwater interaction

Surface water courses represent an important part of the overall conceptual model for the Eden Valley Groundwater-Surface Water System. Surface water courses represent areas where groundwater and surface water components discharge and mix. This component conceptual model shows the different components of water flow to the river (Figure. 6.3).

As discussed in Chapter 3, surface water components (runoff, interflow) dominate the overall stream flow in the River Eden catchment. The groundwater component to stream flow becomes relatively more important during periods of drought and a crude nitrogen mass-balance suggested that in periods of drought, groundwater may contribute 50 % of the nitrogen load in the River Eden at Warwick Bridge (see Appendix 4).

It is important to note that the various components to stream flow have very different residence times. Thus changes in land-use or farming practice may have a rapid impact on the quality of the surface water components to stream flow whereas there is likely to be a considerable time lag before a change in land-use will have an impact on the water quality of the baseflow component to the stream.



Stream flow has 2 components:

(1) ***Surface water component*** (runoff, interflow and contributing tributaries) which typically have residence times of days-weeks-months

(2) ***Groundwater (baseflow) component*** which typically has a residence time of years-decades+

Figure 6.3 Components of surface water/groundwater interaction

Component 3: Abstraction borehole in confined aquifer pumping low nitrate groundwater

This component uses the basic conceptual model component 1 but considers an abstraction borehole pumping low nitrate groundwater (Figure 6.4). Three possible explanations for the low nitrate concentrations in pumped groundwater are suggested:

- The long travel times through the confining layer (because of the low permeability of the drift deposits).
- A relatively high percentage of the pumped water is derived from some distance from the borehole (and therefore travel times to the borehole are relatively longer) because of a low recharge rate through the confining layer. This situation was modelled and discussed in Chapter 5 (scenarios 6,8 and 10) and indicated that the fraction of modern water pumped would be significantly less than for a borehole located within a drift-free window.
- Denitrification which may occur within the drift deposits.

This component conceptual model thus provides possible explanations for the generally lower nitrate concentrations observed in boreholes that pumped from aquifers which were either confined or had a drift cover in excess of 10 m as discussed in Chapter 4

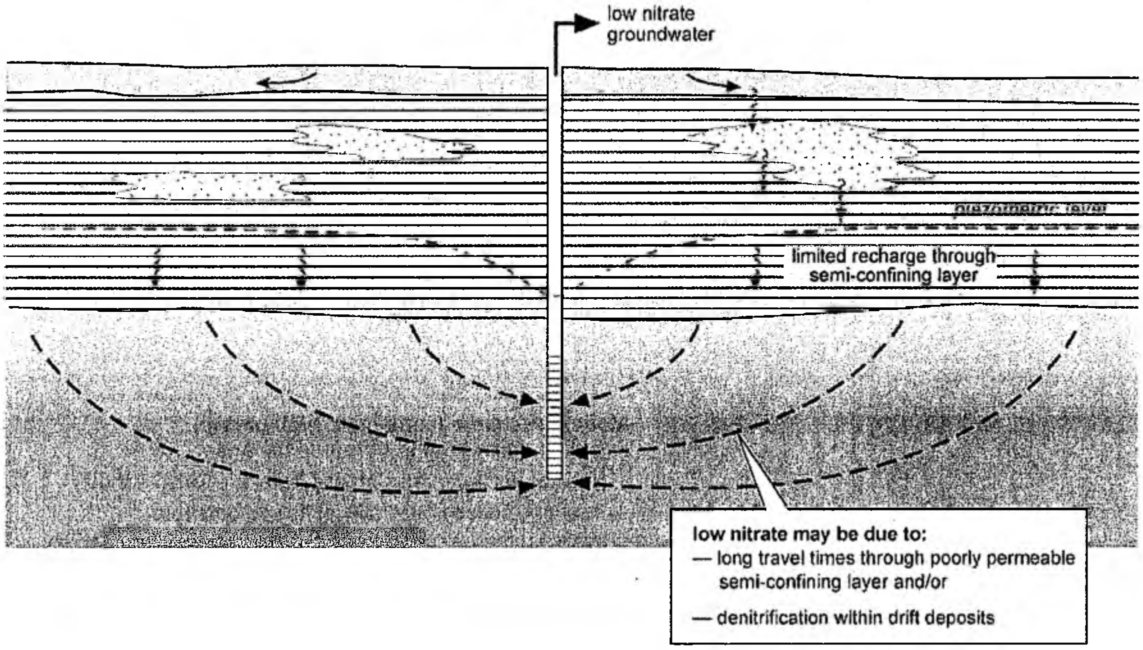


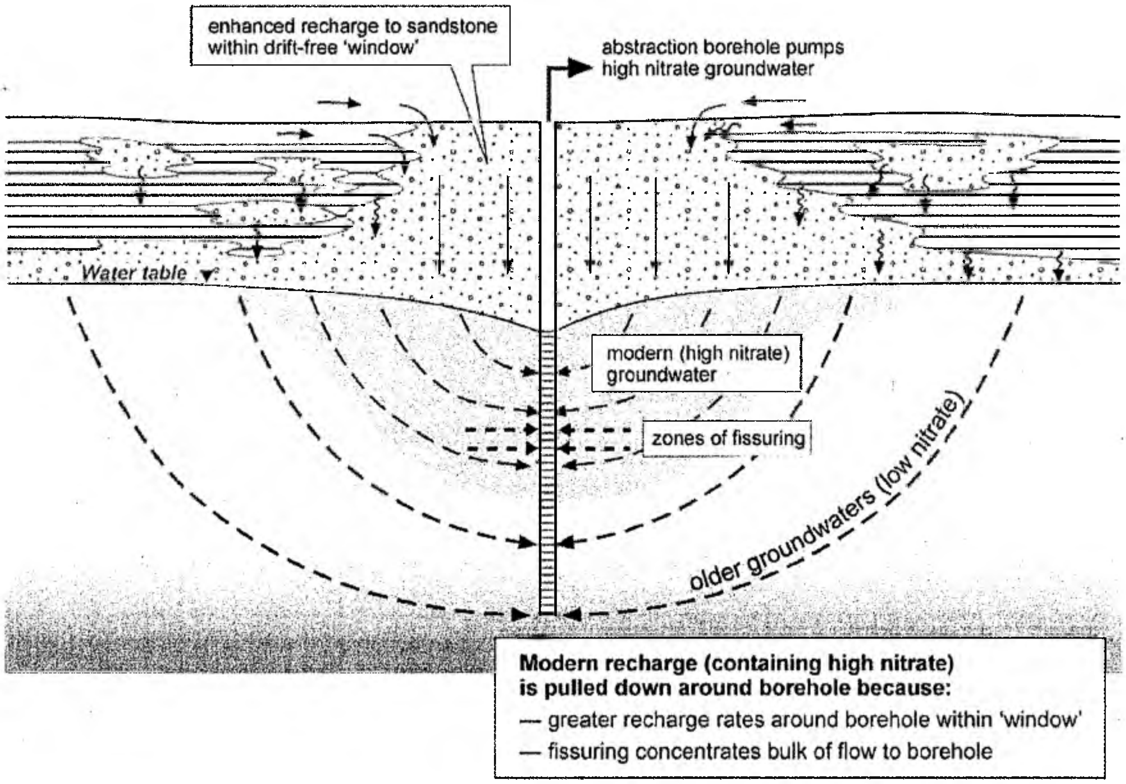
Figure 6.4 **Abstraction borehole in confined aquifer pumping low nitrate groundwater**

Component 4: Abstraction borehole within recharge window pumping high nitrate groundwater

This component conceptual model also uses the basic conceptual model component 1 but considers an abstraction borehole within a permeable recharge window where a high percentage of modern (potentially high nitrate) groundwater is pumped by the borehole (Figure. 6.5). Two explanations are suggested:

- A greater fraction of the water pumped is derived from close to the borehole due to the higher rates of recharge within the 'window'.
- Fracturing reduces travel time to the borehole.

A simple numerical model was used to illustrate this (see Chapter 5).



Modern recharge (containing high nitrate) is pulled down around borehole because:
— greater recharge rates around borehole within 'window'
— fissuring concentrates bulk of flow to borehole

Figure 6.5 Abstraction borehole within recharge window pumping high nitrate groundwater

7. SUMMARY

Nitrate concentrations in groundwater from the Permo-Triassic aquifer of the Eden Valley show considerable variability. Concentrations range from less than 4 mg/l to in excess of 100 mg/l (as NO_3); a significant number of boreholes have nitrate concentrations approaching or exceeding the EC MAC limit of 50 mg/l.

The main source of the high concentrations of nitrate found in some boreholes is almost certainly the high rates of nitrogen applied to grassland (up to 250 kgN/ha/y), both as slurry and as inorganic fertilisers. Previous research (Parker et. al. 1989) has shown that significant leaching of nitrate from grassland can be anticipated when rates of nitrogen application exceed 100 kgN/ha/y.

The spatial variability in groundwater nitrate concentrations is thought to be due in part to land use, particularly where low-yielding boreholes derive their water from a limited/localised area, and in part due to the variability in travel times of the flow paths from the soil to the water table and then to the borehole. This variability (in travel times) is a function of surficial geology, depth to water table and depth of borehole and drift thickness amongst other factors. As a broad generalisation boreholes in unconfined aquifers with thin (or no) drift cover have higher nitrate concentrations than boreholes in aquifers which are either overlain by thick drift cover or where the aquifer is confined (by the drift deposits). However there are frequent exceptions and this suggests that the system is complex and that a number of factors exert a control on groundwater nitrate concentrations.

A further factor which might explain some of the low nitrate concentrations observed is the removal of nitrate by denitrifying bacteria within the subsurface. This is most likely to occur within the organic-rich drift deposits that overlie the sandstone aquifers. However there is no direct evidence that denitrification does occur.

The considerable depth to water table (at least in some areas of the Eden Valley) is likely to impose a significant delay in the arrival of high nitrate infiltration at the watertable. This delay within the unsaturated zone could be many years or even decades. Thus groundwater nitrate concentrations are likely to increase in the short term whatever restrictions on land-use activities at the surface are imposed. It is likely that for some water supply boreholes, where current nitrate concentrations approach the EC (MAC) of 50 mg/l, that this value could be exceeded in the future. It is important to obtain a better understanding of the relative importance of land-use, as opposed to travel time or denitrification as the cause of the variability in the groundwater nitrate concentrations in the Eden Valley. A survey of groundwater quality to determine groundwater residence time (using CFCs) and to provide evidence, or not, for denitrification (using the ratio of N_2/Ar in dissolved gases) may help resolve this.

In general, elevated groundwater nitrate concentrations can represent a potential problem both for groundwater abstraction and for surface water quality. In the Eden Valley, the possible impact on groundwater abstraction is of greater concern because the bulk of the nitrogen load in stream flow appears to be derived from surface runoff. Nevertheless a rise in the nitrate concentration of the River Eden, during low flow conditions, can be anticipated as the nitrate concentration of shallow groundwater is likely to rise, at least in the short-term.

It is surprising, given the considerable storage within this aquifer and the slow groundwater movement, that some relatively deep boreholes pump groundwater with nitrate concentrations in excess of 20 mgl^{-1}. Simple numerical modelling suggests that the fraction of modern water pumped is sensitive to the presence of fissures and the location of "drift-free windows" relative to the abstraction borehole. For some scenarios, using realistic drift geometries and aquifer hydraulic parameters, more than 60% of the water pumped could be 'recent' (that is derived from infiltration that reached the water table since pumping started).

These models were used to asses how sensitive 'the percentage of modern water pumped' is to a few key aquifer scenarios and the models were not used to predict future pumped nitrate concentrations. Numerical models could be developed (to predict pumped nitrate concentrations) but for these models to have any validity, they would need to incorporate a good understanding of both the groundwater flow system to the borehole and the nitrogen fluxes within the borehole catchment. This in turn may require specific, detailed and potentially costly hydrogeological investigations depending on the level of confidence needed.

8. CONCLUSIONS

1. Leaching of nitrate from soils receiving high applications of nitrogen fertilisers appears to be the principal cause of high nitrate groundwater observed in some boreholes in the Eden Valley.

2. Groundwater nitrate is likely to continue to increase, at least in the short term, whatever land-use changes or agricultural practices are introduced because of the considerable time-lag between leaching of nitrate from the soil and arrival at the abstraction borehole. Therefore some water supply boreholes are at risk of not meeting the EC maximum allowable concentration.

3. Since groundwater contributes to surface water flow, the nitrate concentrations in surface water may rise. However the groundwater contribution to the nitrate load (in surface waters) appears to be significant only during periods of low river flow.

4. Predicting the likely rise in groundwater nitrate concentrations requires a knowledge of the nitrate flux within the unsaturated zone for both the exposed and drift-covered sandstone aquifer.

5. It is possible to develop numerical models to help predict future nitrate concentrations in abstraction boreholes although it is essential that there is a good understanding of the groundwater flow system and the nitrogen fluxes within the borehole catchment. The data requirements which includes rates of nitrate leaching from different land uses, recharge rates beneath drift and non-drift covered areas, permeability distribution within the aquifer etc., may make this prohibitively costly depending on the degree of confidence that is needed.

9. RECOMMENDATIONS

Phase 1 has provided a broad understanding of the groundwater flow system which helps explain some of the nitrate trends observed. However, a number of questions remain which will need to be addressed if the impact of rising nitrate concentrations in groundwater and surface water are to be fully assessed and if appropriate measures are to be introduced to alleviate, where necessary, any detrimental impacts.

It is recommended that further work is undertaken which will attempt to:

1. estimate the nitrate flux moving through the unsaturated zone to the watertable
2. identify the origin/cause of the low nitrate groundwaters
3. estimate future trends in nitrate concentrations in groundwater and surface water.

It is possible to develop numerical models to help predict future nitrate

9.1 Estimating the nitrate flux in the unsaturated zone

This report has shown that there is a considerable time-lag between leaching of solutes (eg nitrate) from the soil and their arrival at the watertable. Thus it is crucial to know how much nitrate is present in the unsaturated zone and its rate of downward movement so that the likely future impact on water quality (both groundwater and surface water) can be assessed.

As a first step it will be necessary to collect more information on the range of nitrogen applications to agricultural land in the Eden Valley over the past 50 years and attempt to identify any spatial correlations (perhaps related to soil types) or temporal trends. This would also help guide where to locate cored boreholes to investigate nitrate fluxes in the unsaturated zone.

A second step will be to obtain solute profiles though the unsaturated zone (by extracting porewaters from sandstones cores) at sites representative of key land-use types. Dating of these porewaters by tritium (or other indicators) will be required. Borehole sites should include both drift-free and drift-covered areas.

9.2 Identify the origin/cause of the low nitrate groundwaters

This report has suggested that the variability in pumped groundwater nitrate concentrations could be due to one or more reasons, namely:

1. difference in solute travel time from the soil to the borehole
2. differences in land-use
3. denitrification

It is recommended that a regional water quality survey is undertaken using the Environment Agency monitoring network and analysing for a) major ions, b) nitrate (and ammonium), c) dissolved N_2 and Ar, d) CFCs and e) occasional oxygen and hydrogen isotopes.

This survey should enable a determination of which of the above factors are mainly responsible for the low nitrate concentrations in groundwater and for what setting. This is important because it would help to identify those settings where the nitrate concentrations are likely to increase (because the front of modern/higher nitrate water will eventually arrive at the borehole) or remain stable (and low) because of denitrification. Further, where land-use is seen as a critical factor in maintaining low nitrate groundwater then future policy should be directed at restricting land-use changes in order to protect important groundwater sources.

9.3 Estimating future trends in nitrate concentrations in groundwater and surface water.

Predicting likely generalised changes in groundwater nitrate concentrations with time can be attempted by considering the flux of nitrate moving through the unsaturated zone (see 9.1 above). However, predicting nitrate concentration for individual groundwater sources would require considerably more site specific information (pumping rate, capture zone, permeability distribution etc.) depending on the level of uncertainty permitted.

Water quality in streams depends both on surface processes (eg runoff from adjacent farmland) and on subsurface processes (baseflow contribution from shallow groundwater). The former respond rapidly to changes in land-use practices and it is anticipated that, with the introduction of measures under the Nitrate Vulnerable Zones Scheme, nitrate concentrations in runoff may stabilise or reduce. However, because of the considerable storage within the unsaturated zone there will be a significant lag between the introduction of land use practices (to reduce nitrate leaching) and the arrival of low nitrate recharge at the water table. As a consequence the nitrate concentration of surface water is likely to increase at least in the short term.

Predicting future trends in nitrate concentration of surface water will require: (a) estimating the current nitrate contribution to surface water from groundwater, and (b) predicting future nitrate contribution to surface water (by groundwater) based on estimating the nitrate flux within the unsaturated zone (see above).

The current nitrate contribution to surface water from groundwater will be estimated by nitrogen mass balance approach for different catchments using existing EA data on stream flow and nitrate concentrations. It may be appropriate to supplement these existing data on surface water nitrate concentrations by additional monitoring for short periods.

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APPENDICES

Appendix 1 Data Sources

Geology	BGS Maps Memoirs and Reports Listings BGS Single Online Borehole Index (SOBI)
Hydrology	River Catchment Basin Summary Data Flow Gauging EA CEH/IH Flow Accretion Profiles: modified from above with local estimates Water quality monitoring and trends EA GQA network (10 year dataset) EA SWAD network water quality monitoring Eutrophication Reports / History
Hydrogeology	National Water Well Archive / Wellmaster Borehole construction Peizometry inc. seasonal variation and response to storm events EA datasets Aquifer Properties Manual Temporal hydrochemistry of bulk/blend and depth sampled water. EA (any others?) Any existing trend or other statistical analyses of the above Reports and reviews Ingram/Monkhouse/Milne/Price,Tate & Robinson/Younger & Milne NWWA/EA Source & Monitoring reports Source/OBH Test pumping, flow logging, bh geophysics Downhole hydrochemical sampling (flow through cell testing)
Meteorology (Rainfall/Recharge/EVT Data)	Met Office MORECS British Atmospheric Data Centre (BADC Rutherford Appleton Lab)* (most significant for v. spikey temporal NO_3 data)
Water Balance	Existing recharge determinations or models with abstraction
Baseline Hydrochemistry:	Exisitng Baseline Report. Groundwater/Surface Water/Rainfall
Models/Source Protection Zones	Proformas and reviews of existing examples
Simplified Vulnerability Assessment for sources under study	Existing NVZ bearing particular attention to Superficial deposits examples
Nitrate Research Literature	BGS/EA MAFF/DETR/DEFRA ADAS USEPA EU Others
Land Use	Classification/Database (CEH*) Nitrate Loading Data (past and present) and timing Cropping or stock type and density MAFF/DEFRA/ADAS Literature Nitrate Loading Methodology/Practices Slurry injection or airborne spreading
**These may have cost implications*	

Appendix 2 Land Cover Map for Eden Valley

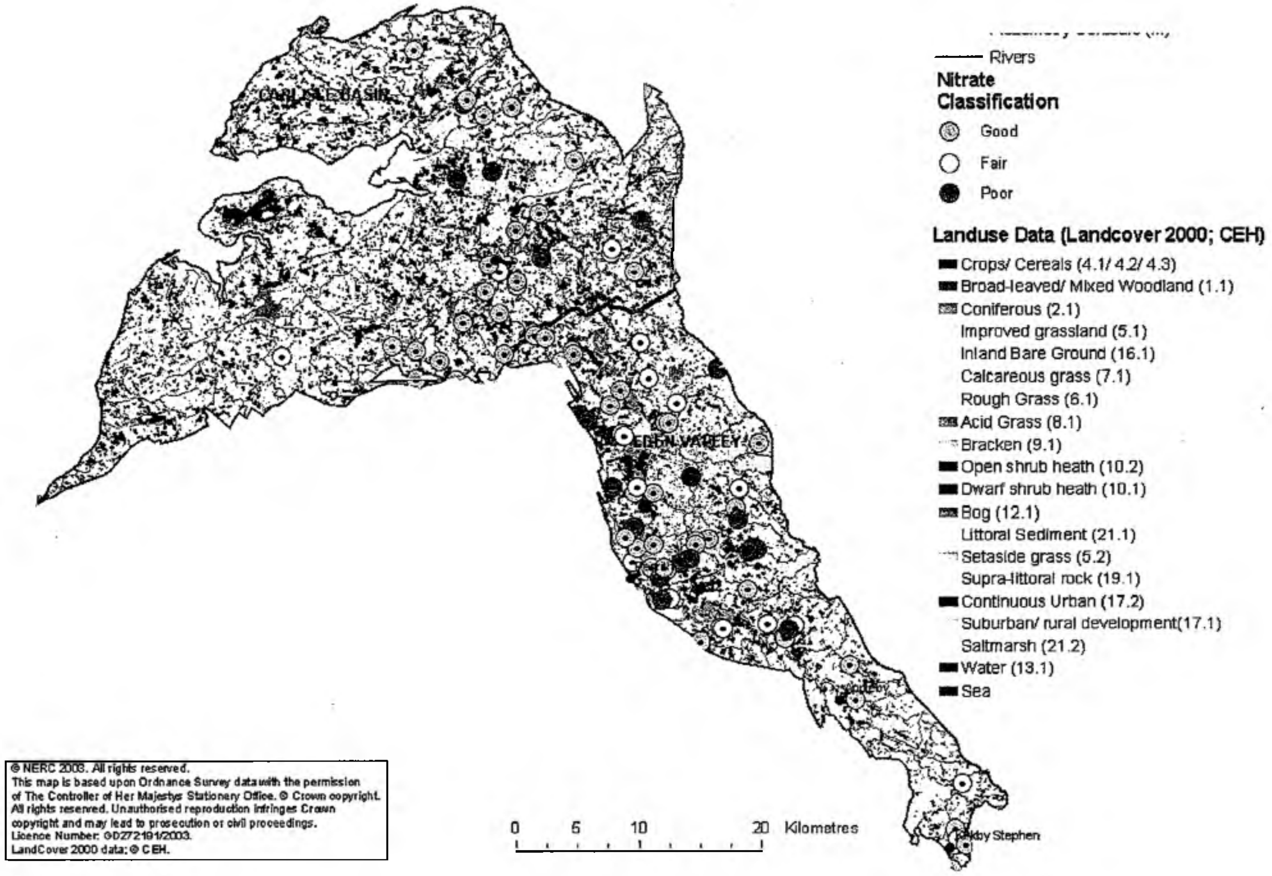


Figure A2. **Land Cover Map for Eden Valley area with EA groundwater sampling sites used in the study.**

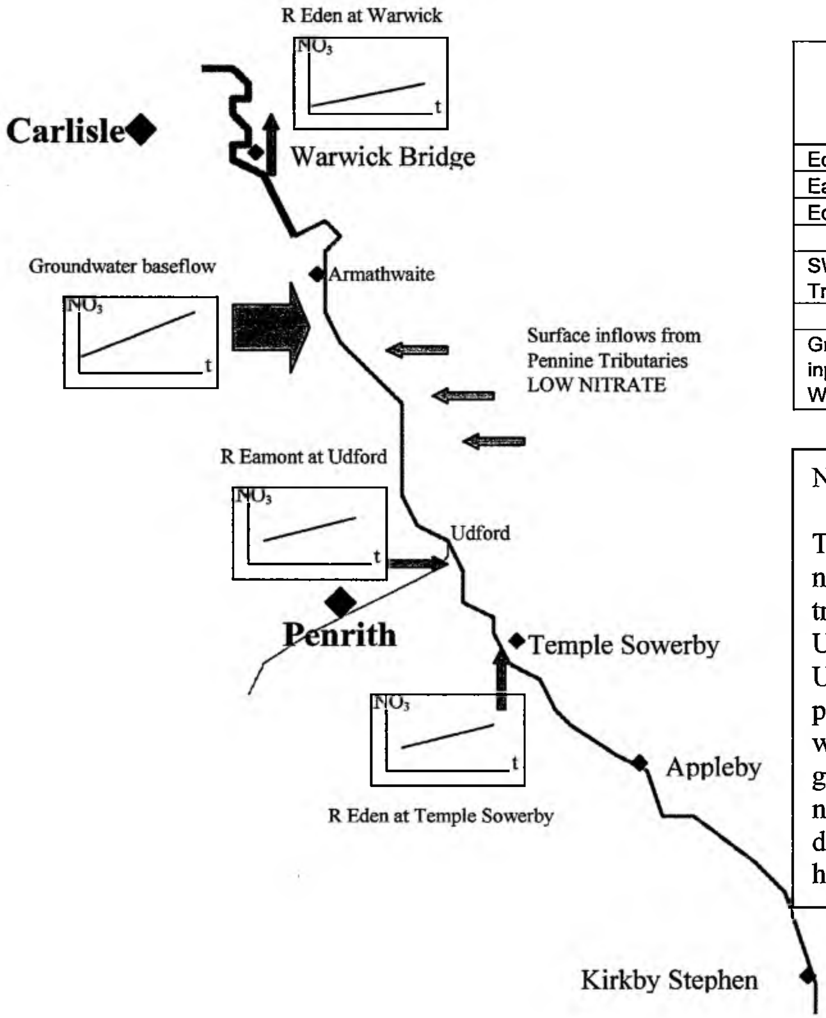
Appendix 3 Project Gantt Chart

Gantt Chart for Eden Valley Nitrates Project Tasks/Activities

Task	Task Description	2002											2003													
		O	O	O	N	N	N	N	D	D	D	D	J	J	J	J	F	F	F	F	M	M	M	M	A	A
		42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Project Planning**																									
	MOU Pricing and Contract Preparation		▨	▨	▨	▨																				
	Work Plan and Scoping Report		▨	▨	▨																					
	Project Flyer			▨			▨																			
	Project Meetings			▨																						
2	**Review of Existing Information and Data Sources**																									
	Review					▨	▨																			
	Fieldwork					▨	▨	▨	▨																	
	Data Gathering and Validation						▨	▨	▨	▨	▨															
	Preparation of Report								▨	▨																
3	**Application to Specific Sites or Sources**																									
	Data Handling									▨	▨		▨	▨												
	Development of Source-Receptor Conceptual Models												▨	▨	▨	▨										
	Preparation of Graphics																	▨	▨	▨	▨	▨	▨			
	Preparation of Report																			▨	▨	▨	▨			
	Preparation of Summary Document/Media																								▨	▨
4	**Design and Preparation of Scoping for Phase 2**																									
	Develop Key Requirements for Phase 2 Scoping															▨	▨	▨								
	R & D Technical Capabilities & Requirements for Field Investigations																	▨	▨	▨						
	Technical Programme for Feld Investigations																			▨	▨	▨				
	Preparation of Phase 2 Scoping Section of Report																			▨	▨	▨	▨	▨		
	Preparation of Phase 2 Proposal?																								▨	▨

Figure A3. Project implementation timetable (Gantt chart)

Appendix 4 Nitrate balance for the River Eden between Temple Sowerby and Warwick Bridge



Site/Source	1976 Low Flow M3/s	1976 Nitrate Concentration. mg/l	1995 Low Flow M3/s	1995 Nitrate Concentration mg/l
Eden At WB	4.0	3.63	6.89	7.04
Eamont at Udford	1.40	4.00	1.20	6.90
Eden at T. Sowerby	1.18	0.44	1.33	2.94
SW inflow from Pennine Tributaries	0.83 d	1.0 e	3.7 d	2.0 e
Groundwater baseflow input between Udford & Warwick Bridge	0.6 e	10.5 d	0.65 e	44.3 d

Nitrogen mass-balance for the River Eden

The nitrogen load for the River Eden at Warwick Bridge is the sum of the nitrogen fluxes contributed by (a) the River Eden at Temple Sowerby, (b) tributaries flowing from the Pennines to the east, (c) the River Eamont at Udford and (d) groundwater baseflow from the sandstone aquifer between Udford and Warwick Bridge. In these examples (taken for drought periods during 1976 and 1995) the nitrate concentrations of the surface waters and their flow rates were either measured or estimated. The groundwater baseflow contribution was estimated (Ingram 1978). The nitrate concentration in the baseflow contribution was determined by difference and suggests that in 1976 it was about 10.5 mg/l and by 1995 it had risen to 44.3 mg/l.

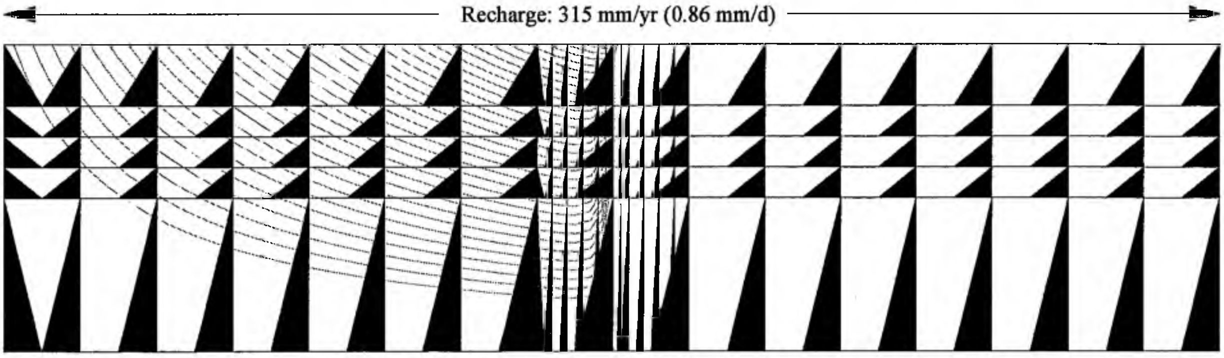
Appendix 5 Numerical Modelling

Model layer thickness

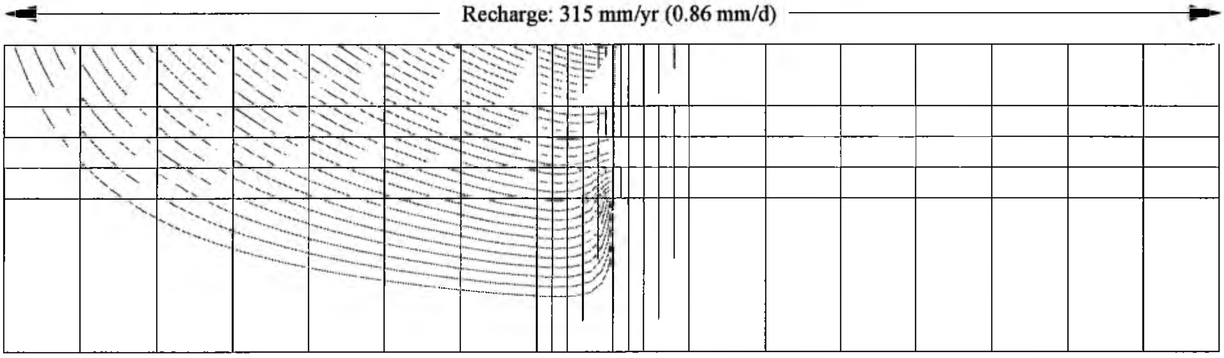
Layer	Intergranular aquifer models	Fractured aquifer models
1	40 m	20 m
2	20 m	5 m
3	20 m	25 m
4	20 m	25 m
5	100 m	100 m

Particle pathlines (in some models, not all pathlines are indicated)

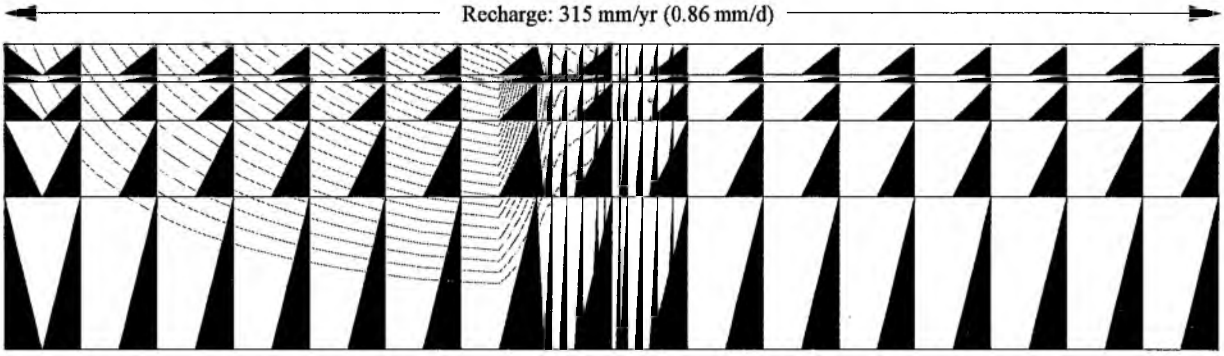
Model 1 - Intergranular, no drift, Kx = 1 m/d, porosity = 25%



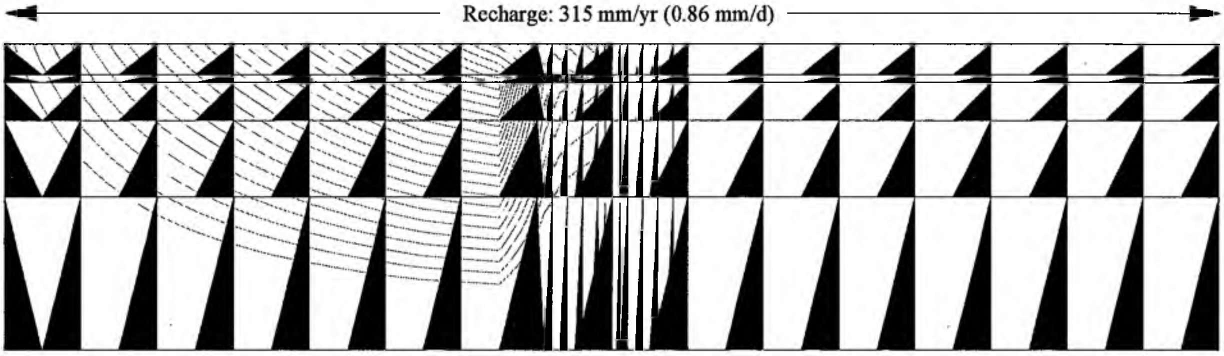
Model 2 - Intergranular, no drift, Kx = 5 m/d, porosity = 25%



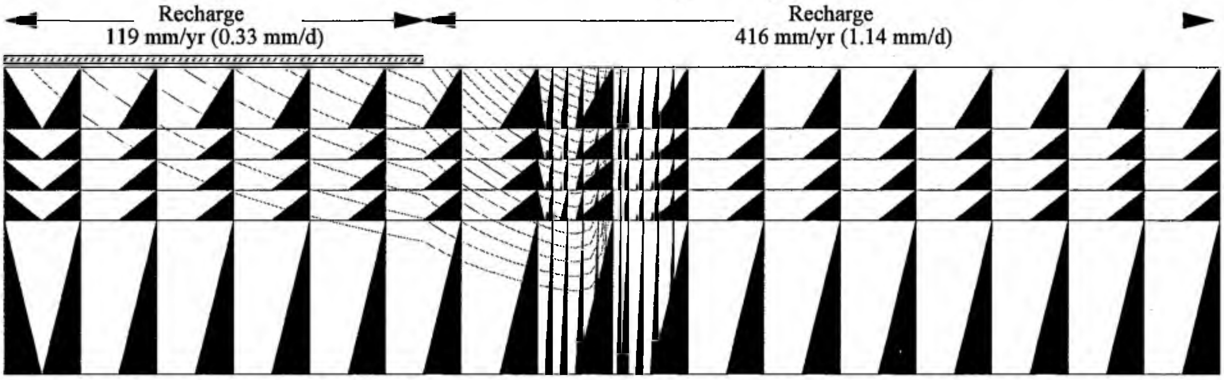
Model 3 - Fractured, no drift, Kx (fracture) = 100 m/d, porosity = 25%



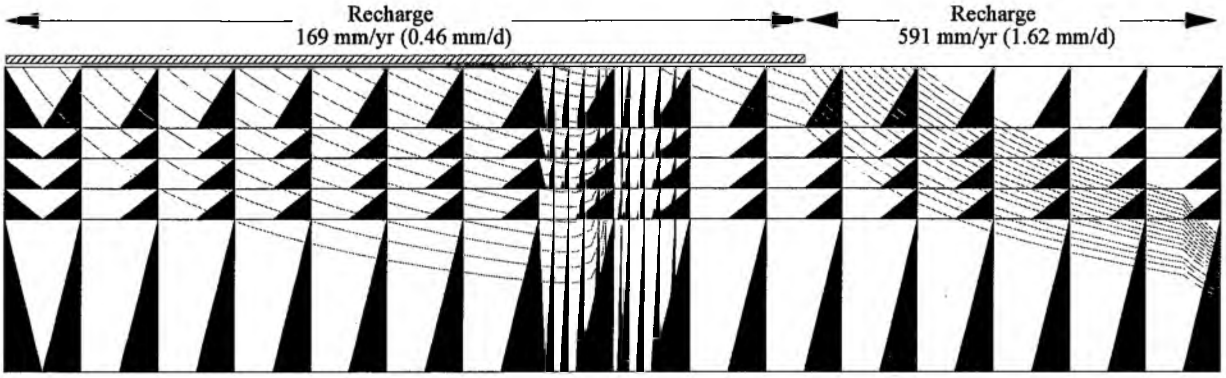
Model 4 - Fractured, no drift, Kx (fracture) = 100 m/d, porosity = 5%



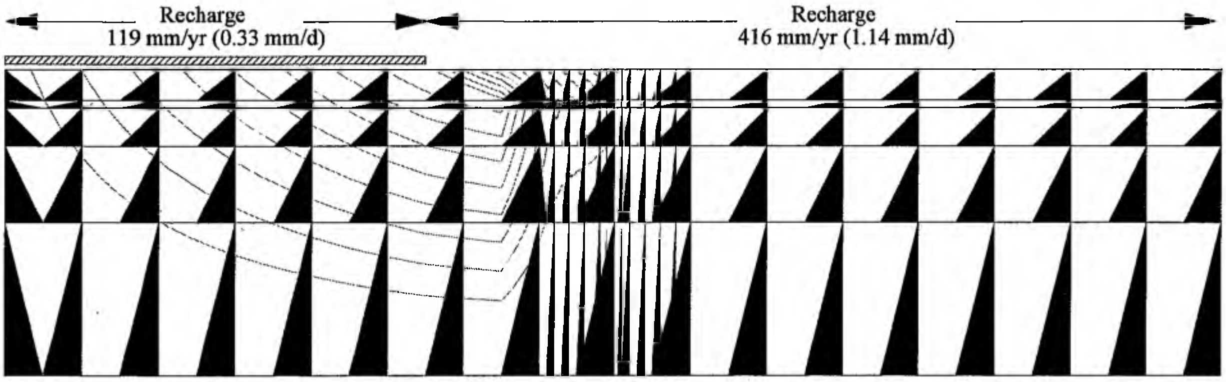
Model 5 - Intergranular, ~35% drift, Kx = 1 m/d, porosity = 25%



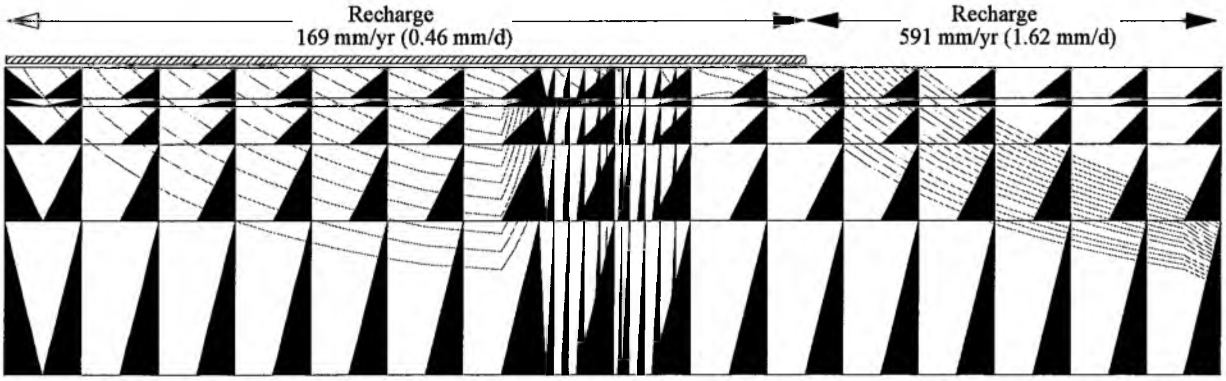
Model 6 - Intergranular, ~65% drift, Kx = 1 m/d, porosity = 25%



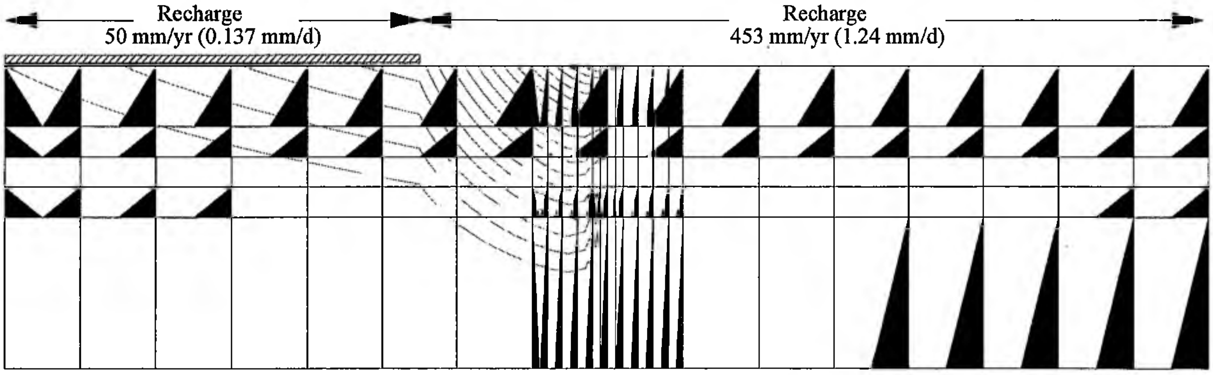
Model 7 - Fractured, ~35% drift, Kx (fracture) = 100 m/d, porosity = 25%



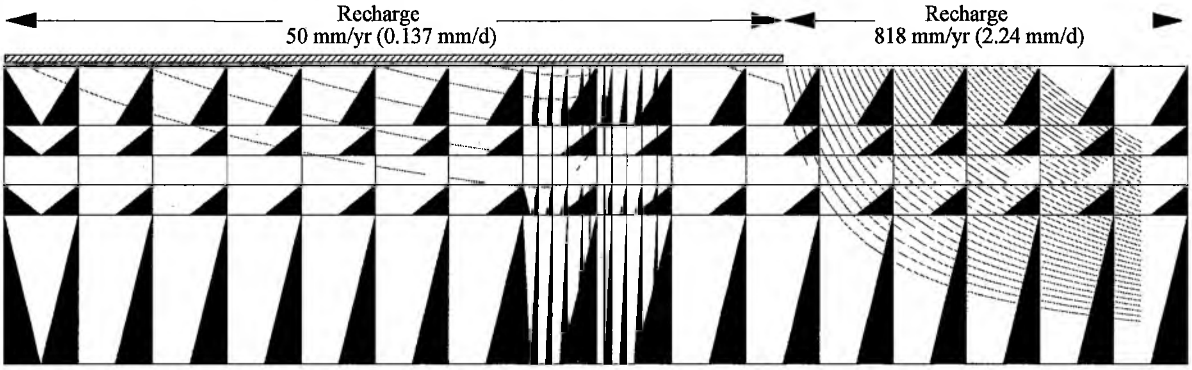
Model 8 - Fractured, ~65% drift, Kx (fracture) = 100 m/d, porosity = 25%



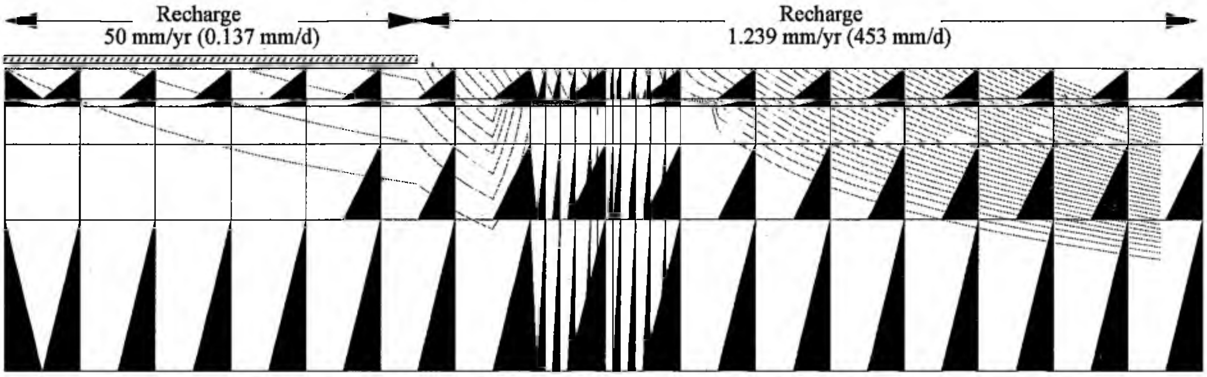
Model 9 - Intergranular, ~35% drift, Kx = 1 m/d, porosity = 25%



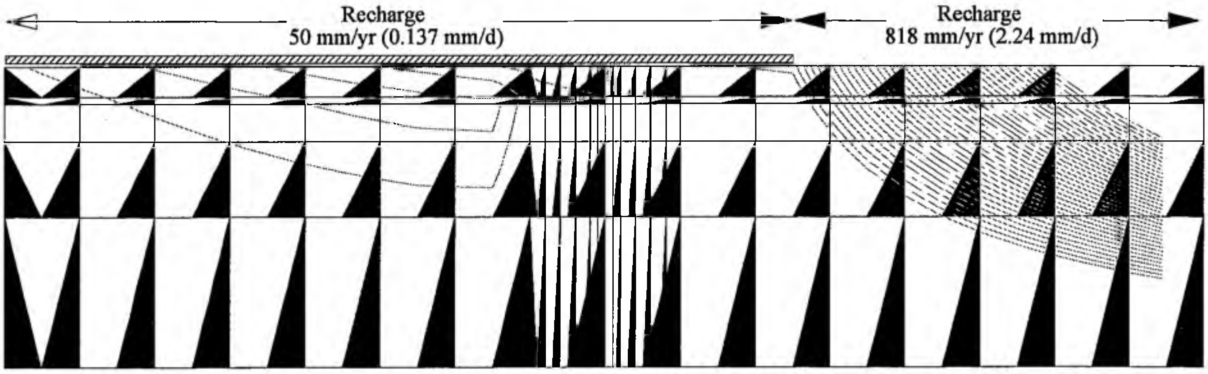
Model 10 - Intergranular, ~65% drift, Kx = 1 m/d, porosity = 25%



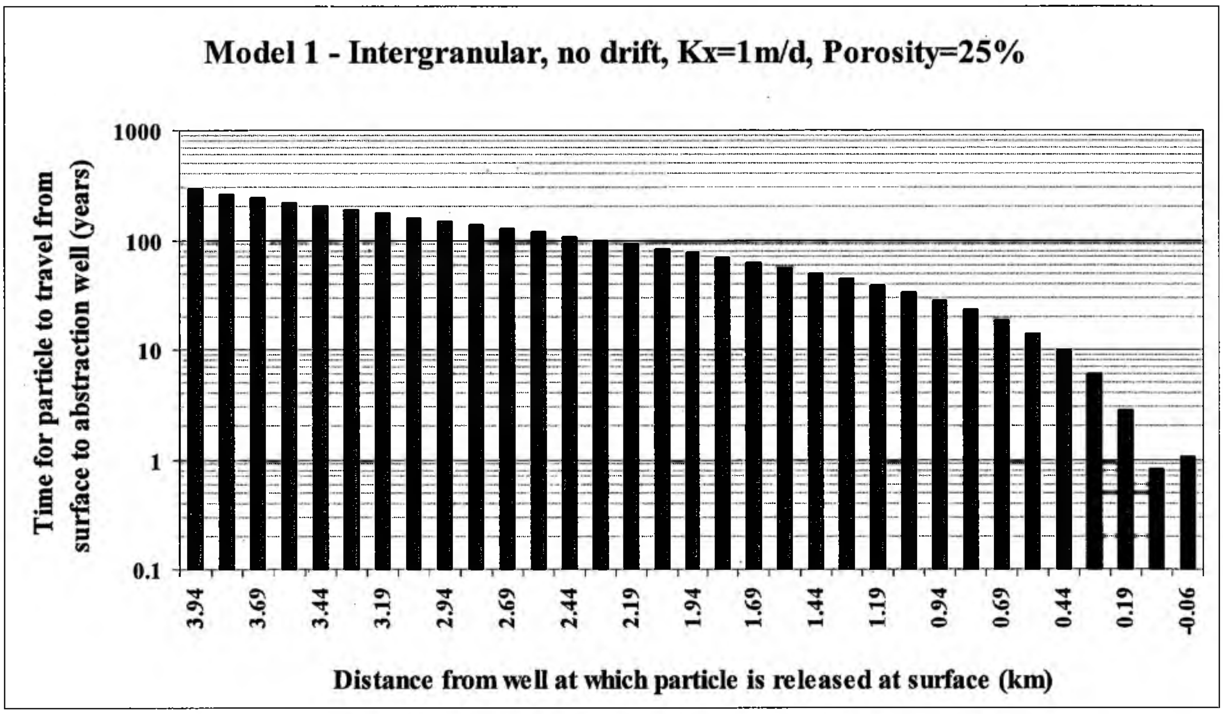
Model 11 - Fractured, ~35% drift, Kx (fracture) = 100 m/d, porosity = 25%

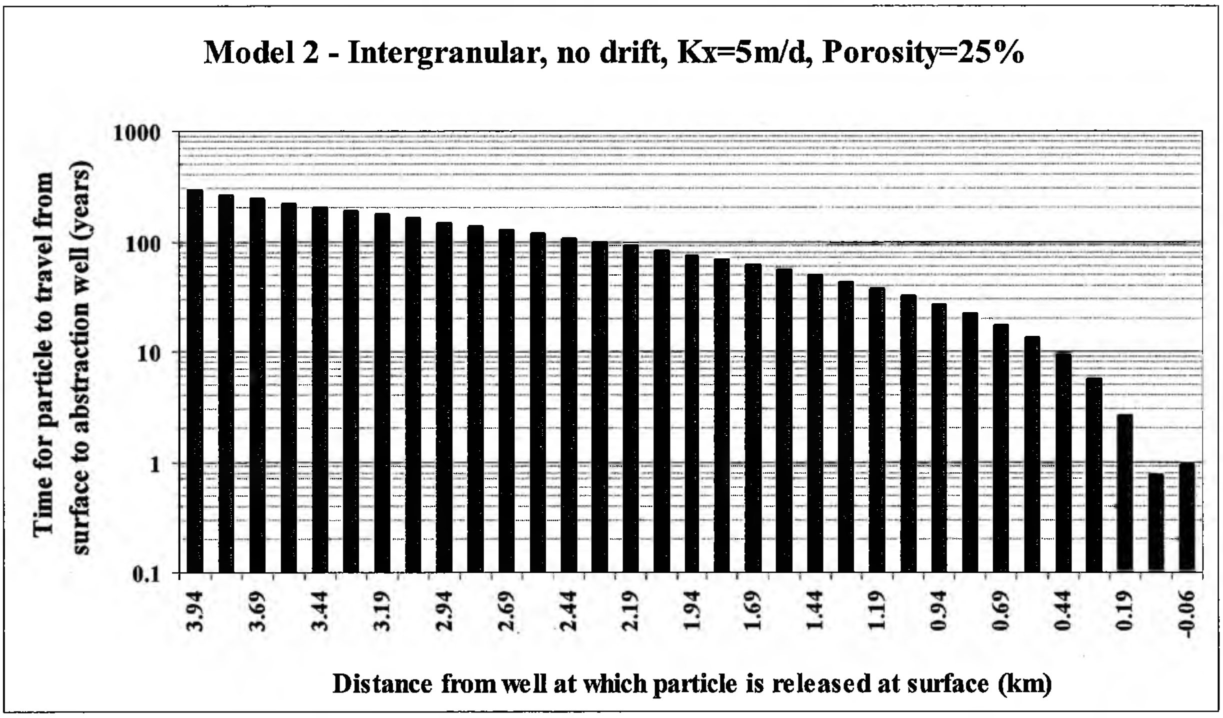


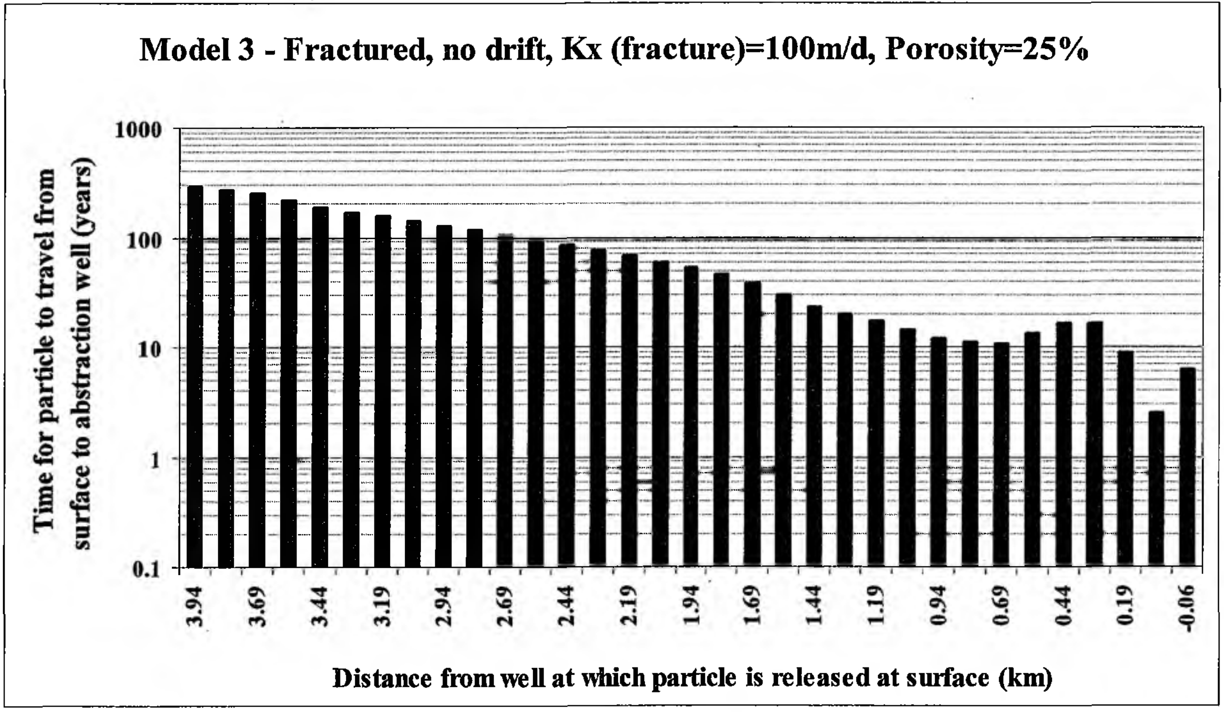
Model 12 - Fractured, ~65% drift, Kx (fracture) = 100 m/d, porosity = 25%

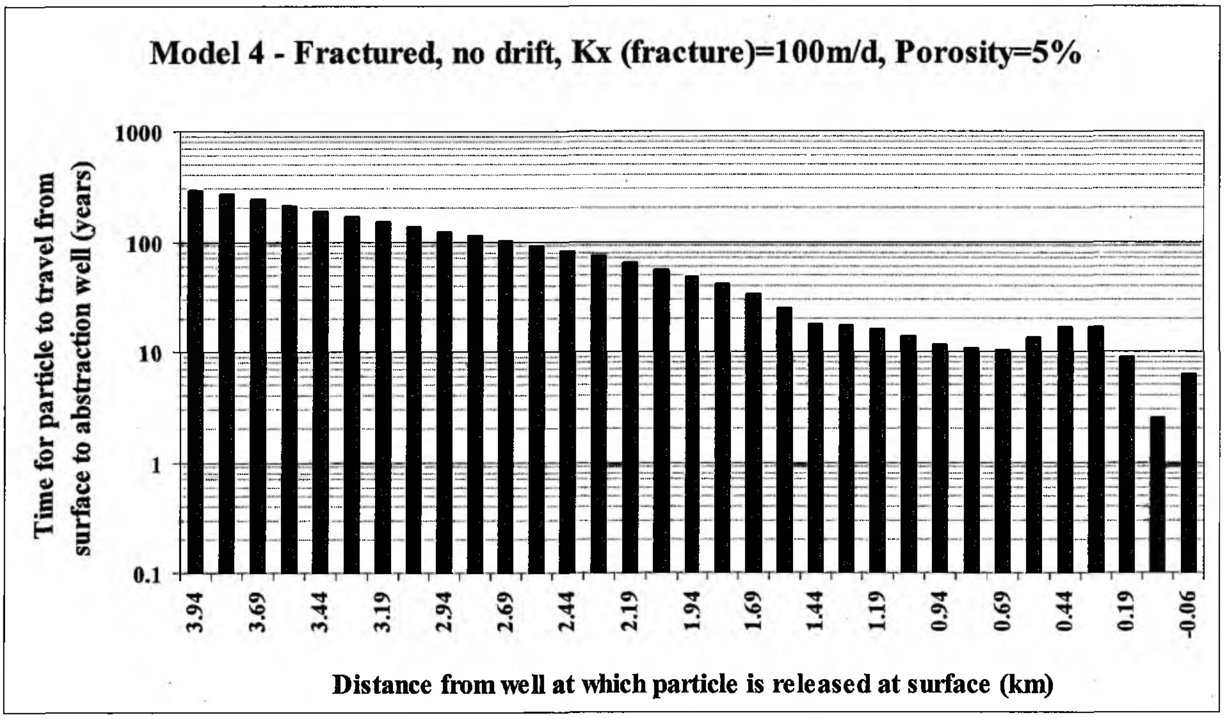


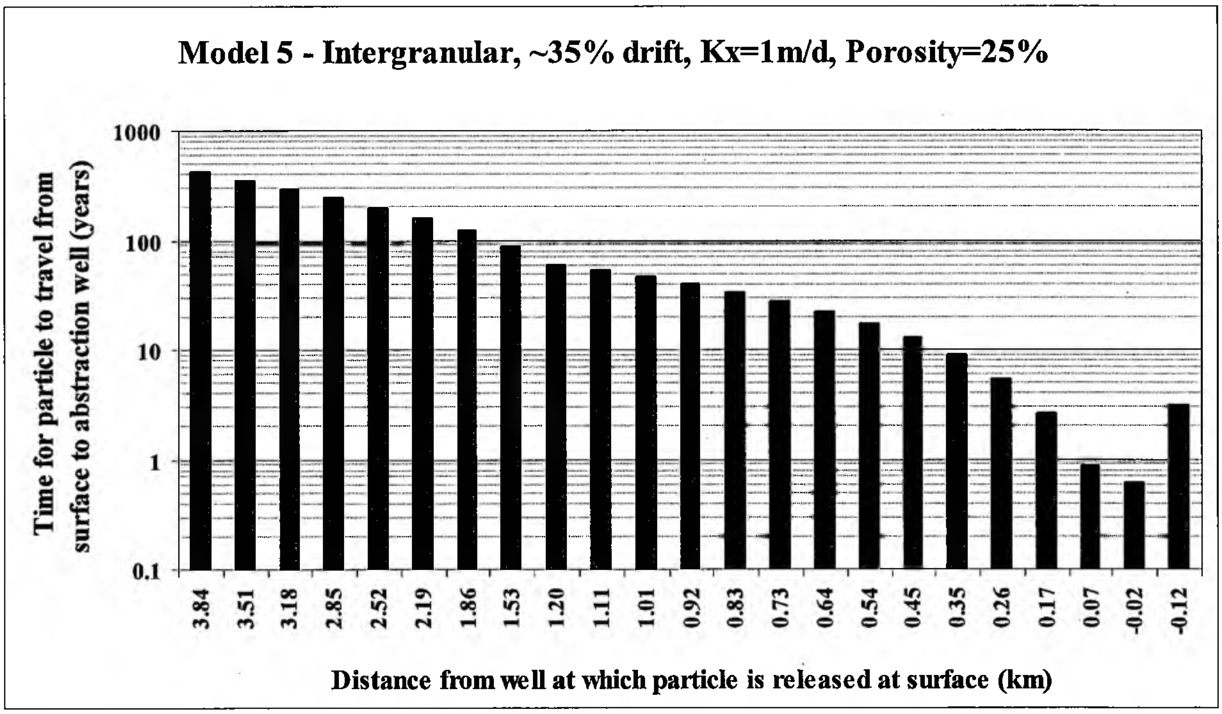
Particle time of travel plots for each model run

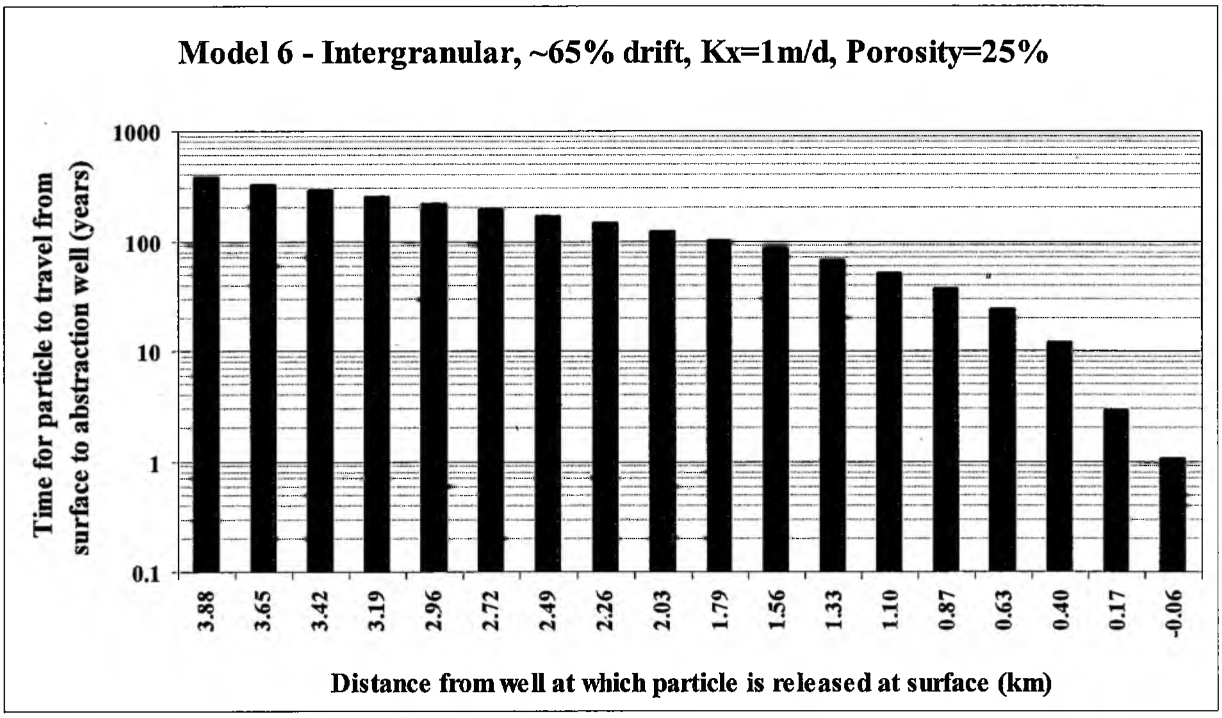


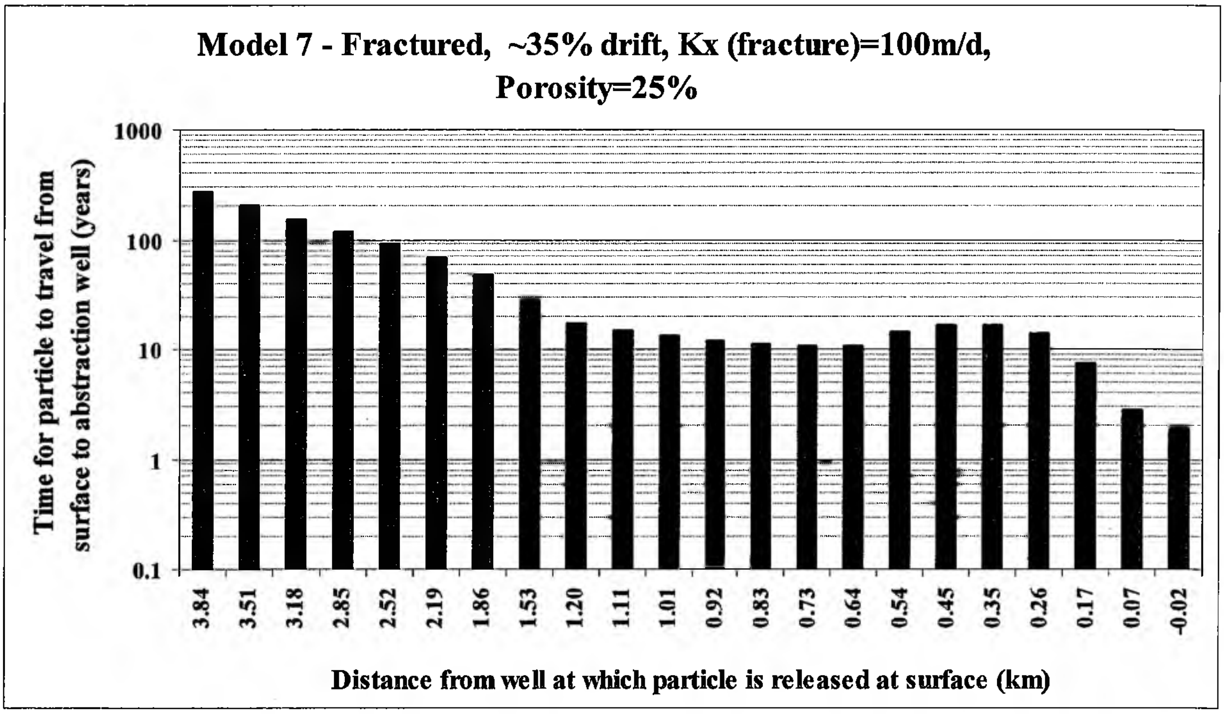


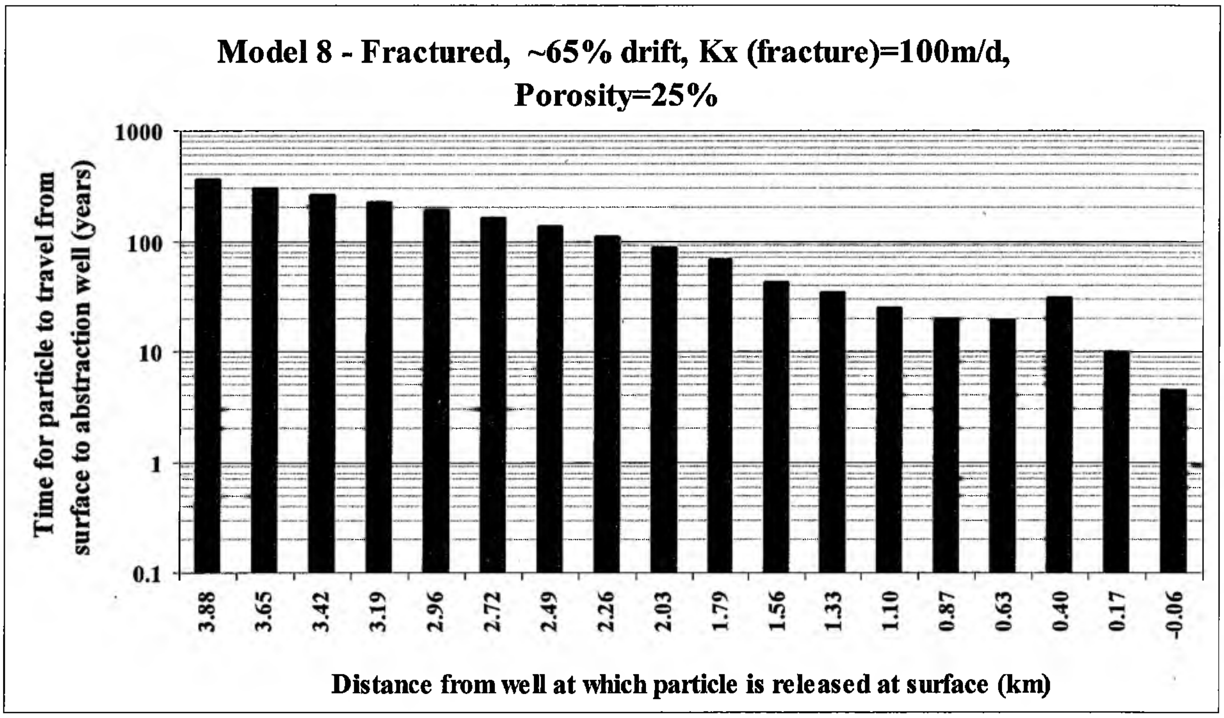

Model 3 - Fractured, no drift, Kx (fracture)=100m/d, Porosity=25%
Time for particle to travel from surface to abstraction well (years)
1000
100
10
1
0.1
3.94
3.69
3.44
3.19
2.94
2.69
2.44
2.19
1.94
1.69
1.44
1.19
0.94
0.69
0.44
0.19
-0.06
Distance from well at which particle is released at surface (km)

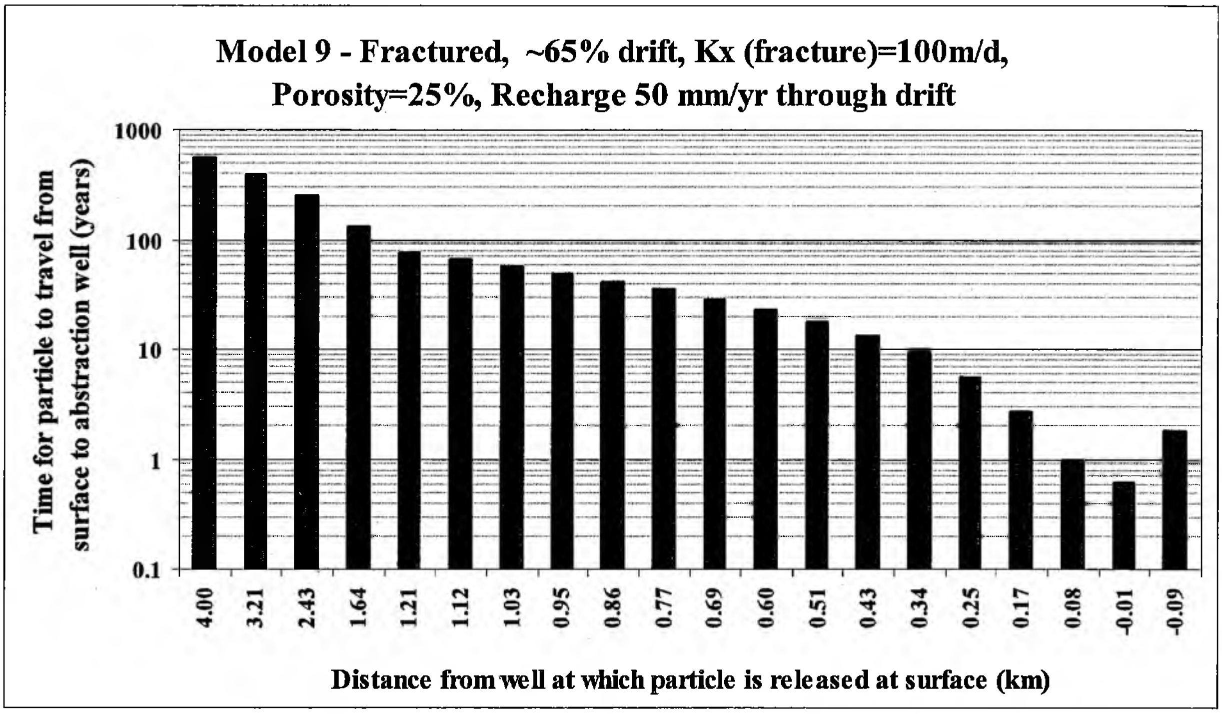

Model 4 - Fractured, no drift, Kx (fracture)=100m/d, Porosity=5%
Time for particle to travel from surface to abstraction well (years)
1000
100
10
1
0.1
3.94
3.69
3.44
3.19
2.94
2.69
2.44
2.19
1.94
1.69
1.44
1.19
0.94
0.69
0.44
0.19
-0.06
Distance from well at which particle is released at surface (km)

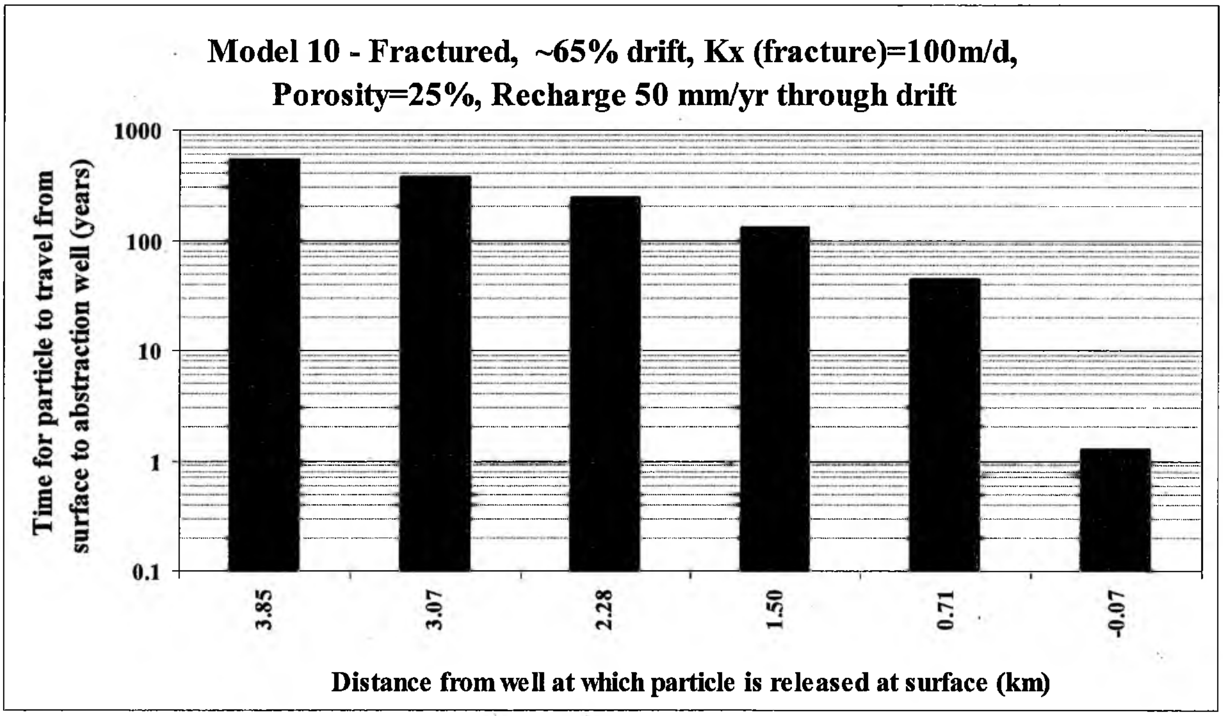

Model 5 - Intergranular, ~35% drift, Kx=1m/d, Porosity=25%
Time for particle to travel from surface to abstraction well (years)
1000
100
10
1
0.1
3.84
3.51
3.18
2.85
2.52
2.19
1.86
1.53
1.20
1.11
1.01
0.92
0.83
0.73
0.64
0.54
0.45
0.35
0.26
0.17
0.07
-0.02
-0.12
Distance from well at which particle is released at surface (km)

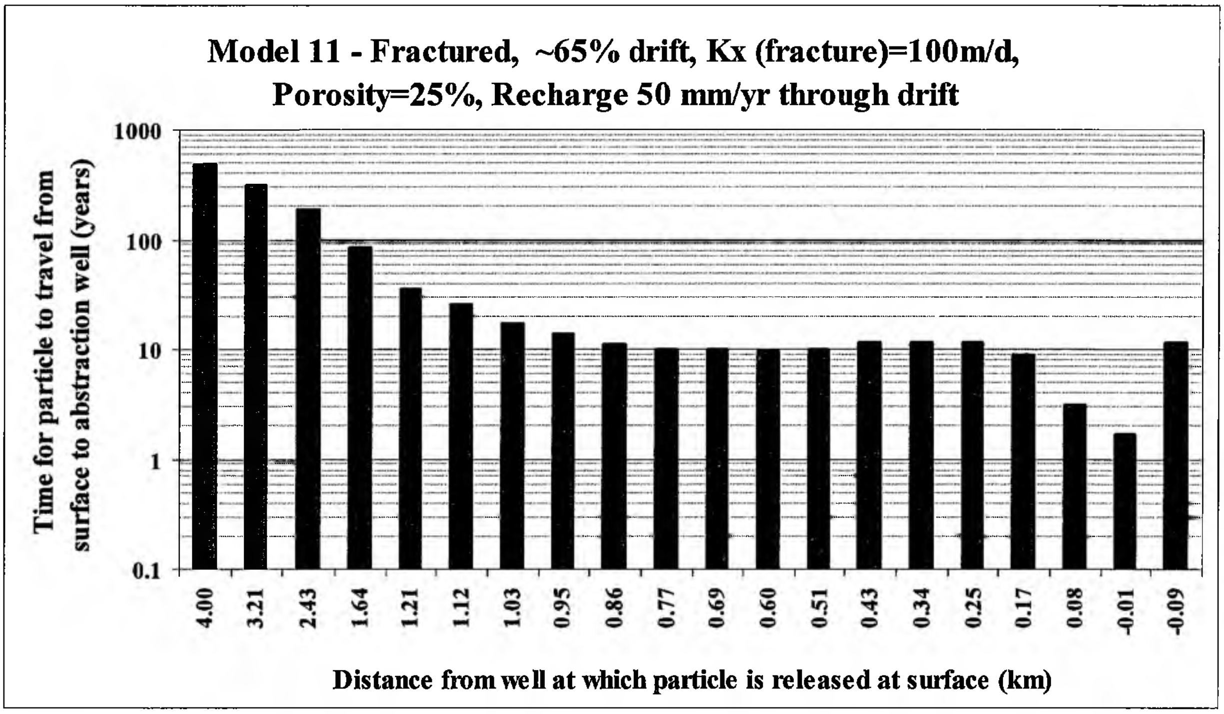

Model 6 - Intergranular, ~65% drift, Kx=1m/d, Porosity=25%
Time for particle to travel from surface to abstraction well (years)
1000
100
10
1
0.1
3.88
3.65
3.42
3.19
2.96
2.72
2.49
2.26
2.03
1.79
1.56
1.33
1.10
0.87
0.63
0.40
0.17
-0.06
Distance from well at which particle is released at surface (km)

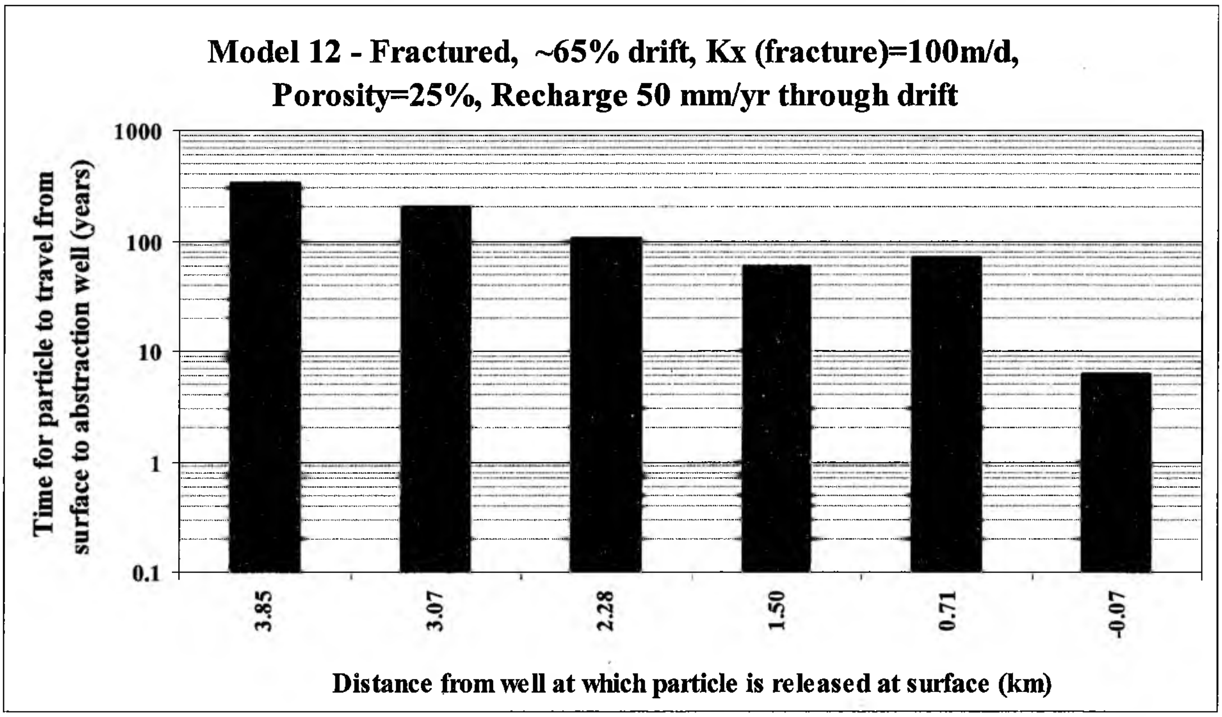

Model 7 - Fractured, ~35% drift, Kx (fracture)=100m/d, Porosity=25%
Time for particle to travel from surface to abstraction well (years)
1000
100
10
1
0.1
3.84
3.51
3.18
2.85
2.52
2.19
1.86
1.53
1.20
1.11
1.01
0.92
0.83
0.73
0.64
0.54
0.45
0.35
0.26
0.17
0.07
-0.02
Distance from well at which particle is released at surface (km)


Model 8 - Fractured, ~65% drift, Kx (fracture)=100m/d, Porosity=25%
Time for particle to travel from surface to abstraction well (years)
1000
100
10
1
0.1
3.88
3.65
3.42
3.19
2.96
2.72
2.49
2.26
2.03
1.79
1.56
1.33
1.10
0.87
0.63
0.40
0.17
-0.06
Distance from well at which particle is released at surface (km)


Model 9 - Fractured, ~65% drift, Kx (fracture)=100m/d, Porosity=25%, Recharge 50 mm/yr through drift


Model 10 - Fractured, ~65% drift, Kx (fracture)=100m/d, Porosity=25%, Recharge 50 mm/yr through drift


Model 11 - Fractured, ~65% drift, Kx (fracture)=100m/d, Porosity=25%, Recharge 50 mm/yr through drift


Model 12 - Fractured, ~65% drift, Kx (fracture)=100m/d, Porosity=25%, Recharge 50 mm/yr through drift