INVESTIGATING RISING NITRATE CONCENTRATIONS IN GROUNDWATER IN THE PERMO-TRIASSIC AQUIFER, EDEN VALLEY, CUMBRIA

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Abstract

Groundwater nitrate concentrations in the Permo-Triassic aquifer of the Eden Valley vary from less than 4 mg/l to in excess of 100 mg/l (as NO_3). A significant number of boreholes exhibit rising trends in nitrate concentration which either approach or exceed the CEC Directive 80/778 Maximum Admissible Concentration (MAC) of 50 mg/l. The main source of the nitrate is believed to be the nitrogen applied to grassland, both as slurry and as inorganic fertilizers.

The 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 the travel times for water and solutes to migrate 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, depth of borehole and superficial deposit thickness, amongst other factors.

It is surprising, given the considerable storage within the saturated zone of the 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 close to the abstraction boreholes and the location of the boreholes relative to 'superficial deposit-free windows'. For some scenarios, using realistic superficial deposit geometries and aquifer hydraulic parameters, the proportion of modern water (water that is derived from infiltration that reached the water table since pumping started) could exceed 40 % within 15 years of pumping.

Background

The Eden Valley lies between two upland areas; the Pennines to the east and the Lake District to the west (Figure 1). It 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 aquifer in the region. The Permo-Triassic Sandstones are overlain by superficial deposits which can be up to 30 m thick and include sands, gravels and till. Groundwater in the sandstone aquifer 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 aquifer.

Average annual rainfall is approximately 1000 mm/y in the Eden Valley and is in excess of 1500 mm/y on the surrounding higher ground. Recharge to the sandstone aquifer is estimated to average 150 mm/y. However, this recharge is distributed unevenly with most occurring where superficial deposits are either absent or permeable. Run-off from the adjacent uplands drains to the River Eden, which flows northwards from Kirkby Stephen through Appleby and Penrith into the Carlisle Basin.

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 fertilizers 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 large areas of semi-natural habitat including unimproved grassland and woodland.

A significant number of boreholes that penetrate the Permo-Triassic aquifer have elevated nitrate concentrations (Figure 2). These boreholes include both low-yielding farm supplies and major abstraction supplies.

The source of the nitrate is thought to be agriculture and a consequence of the intensification of farming and an increase in cattle stocking densities. A review of nitrate pollution and livestock farming (Hooda et al. 2000) suggested that spreading of slurry on fields is probably the major source of nitrate in water. Because the spreading of slurry is usually considered a solution to a waste disposal problem rather than a useful source of nutrients, rates of application frequently exceed crop requirements. Rates of nitrate leaching beneath intensively grazed grass can exceed those beneath intensive arable land (Parker et al. 1989; Chilton & Foster, 1991). Intensification of agriculture occurred during the past 20 to 30 years and so high nitrate groundwaters are likely to be associated with modern (post 1970s) recharge. Slurry pits are unlikely to be a major source of nitrate for large abstraction boreholes because of the considerable dilution within the borehole capture zone (Gooddy et al., 2001).

Hydrogeology

The Permo-Triassic Sandstone aquifer comprises two formations, the Penrith Sandstone (Permian) and the St Bees Sandstone (mid-Triassic). These sandstones have moderate intergranular permeability (mean permeabilities are 0.8 and 0.24 m/d respectively (Allen et al 1997)) although pumping test derived hydraulic conductivities are much higher because they include the fracture contribution to permeability (Lovelock , 1972).

Permeabilities used in regional models approach the intergranular value which suggests that the influence of fracture permeability is probably more localised. As a consequence of this and the high porosity of the sandstone, rates of groundwater flow at a regional scale are low. Nevertheless, around abstraction boreholes, groundwater velocities are locally higher because water movement is largely controlled by the fracture permeability (Worthington, 1977).

Ingram (1978) estimated infiltration rates to the Penrith and St. Bees Sandstones, where these outcrop, as 315 and 350 mm/y respectively. Infiltration rates to the drift covered sandstones are lower and were assumed to be 90-100 mm/y. These infiltration rates were checked and a good agreement was achieved by balancing recharge (calculated from these estimated rates) with groundwater discharge to the River Eden, for part of the Eden catchment. However, the distribution of this recharge between areas where the sandstone is exposed and areas where it is covered by superficial deposits is uncertain.

Vines (1984) estimated that the recharge rate through till to Permo-Triassic sandstones 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 till 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 remains the same, then clearly higher rates of infiltration are required in those areas of the Eden Valley where the drift is either permeable or absent. On this basis, rates of infiltration for the exposed sandstone could exceed 480 mm/y; the implications of this are discussed later.

The concept of higher recharge rates in areas where superficial deposits are either absent or permeable would appear reasonable, as run-off from adjacent areas where superficial deposits are thicker and less permeable is likely to contribute to, and significantly increase recharge in these former areas.

There did not appear to be a systematic distribution of the boreholes that pump higher nitrate groundwaters, the implication being that either the source of nitrate for these boreholes 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 prior to the intensification of agriculture (which is the most likely source of nitrate) and thus be of low nitrate concentration.

Scope of investigation

Initially the water quality data from the network of approximately 150 Environment Agency (EA) monitoring boreholes in the area around the Eden Valley was examined. 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 is generally very irregular. The data were plotted, and a brief assessment made of whether any reliable trends in the nitrate concentration could be recognized.

In the early stages of the study it was difficult to identify any pattern to the locations of the high groundwater nitrate boreholes (Figure 3). However, after large-scale geology and land use maps were produced, the proximity of several of the boreholes, which had higher groundwater nitrate concentrations, with ‘windows’ in the superficial (glacial drift) deposits became apparent.

An attempt was made to correlate groundwater nitrate concentrations with selected factors (Figure 4). Although some correlations were observed (e.g. groundwater nitrate concentrations were generally higher and more variable where (a) drift was less than 10 m thick and (b) boreholes were less than 100 m deep), no single controlling factor was apparent (Butcher et al. 2003).

Some deep boreholes (greater than 100 m depth) had relatively high nitrate concentrations. This is surprising as groundwater velocities within the Permo-Triassic sandstone aquifer at the regional scale are low and so it might be anticipated that the residence time of water and solutes arriving at the borehole would be long and likely to originate as infiltration prior to the 1960s/70s and before intensification of agriculture began.

The main purpose of this paper was to investigate how two factors, namely (a) the development of an high permeability fractured zone around the borehole and (b) the influence of varying recharge rates associated with the presence of superficial cover, could influence the fraction of modern water pumped (an by implication the nitrate concentration). It is recognised that other factors, borehole and casing depth, unsaturated zone thickness, and aquifer anisotropy could also influence the fraction of modern water pumped although these factors were not investigated at this stage.

Numerical modelling

An attempt was to assess how travel times for water to migrate from the watertable to an abstraction borehole may vary. Accordingly a relatively simple numerical model was developed to investigate the sensitivity of modelled travel times to two factors:

- The permeability of the sandstone and the development of local fissuring around abstraction boreholes
- The distribution of superficial deposits relative to abstraction borehole.

The conceptual model that underpinned numerical modelling was based on a review of previous studies and existing data (Monkhouse and Reeves 1977; Ingram 1978; Allen et al 1997; Environmental Simulations International (ESI) 1999).

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.

Model structure

The model was 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 shown in Figure 5 is 8 km square and contains five layers. The horizontal hydraulic conductivity of the sandstone aquifer is defined in the model as 1 m/d and compares with a mean intergranular permeability of 0.8 m/d (Allen et al 1997). The porosity value used in the model is 0.25 and is based on core porosity data (Allen et al 1997). 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 is consitent with the regional groundwater level contours observed in the Eden Valley by (ESI 1999).

The model was used to simulate a homogeneous intergranular aquifer and an aquifer that contains a horizontal fractured zone. The fractured zone 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.

The modelled transmissivity varies from 200 m2/d (when no fracturing is present) to 700 m2/d where a fracture zone is included. These values are consistent with field observations

(Lovelock 1972, and Lovelock et al 1975). The total recharge to the aquifer is 55 Ml/d, its distribution varying depending on the extent of the superficial cover. The rate of recharge through the drift is also varied. The different recharge scenarios are shown in Figure 6 and Table 1.

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 varies between model runs); however, at this preliminary stage this was not undertaken. As will be shown, the use of the line of particles was sufficient to enable conclusions to be drawn regarding the influence of superficial cover 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.

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 7. The particle tracking model also calculates the travel time of individual particles. Particle travel times for Model 1 are plotted in Figure 8. These figures are presented as an example of the model output. Conclusions can be made regarding the effect of drift cover and aquifer fracturing by examining the particle travel times. For Model 1 (Figures 7 and 8), 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 9.

Modelling results

a) The effect of fracturing on the percentage of modern water pumped over time aquifer

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).

The influence of fracturing close to the abstraction borehole on the proportion of modern water pumped is shown in Figure 10. This shows that when fracturing is present, the proportion of modern water pumped is normally higher. For example after 15 years of pumping, a borehole in the fractured aquifer, pumps about 40 % modern water compared with 20 % for a borehole where no fracturing is developed.

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.

b) 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.

The influence of superficial cover on the proportion of modern water pumped from a non-fractured intergranular aquifer is shown in Figure 11. Five recharge scenarios were considered; in all cases the total recharge to the model was set at 55Ml/d. The five recharge scenarios were as follows:

Scenario 1: there is no superficial cover and the recharge rate through the sandstone is 314 mm/y.

Scenario 2: superficial deposits cover 35% of the modelled area and the recharge rate through these deposits is 119 mm/y. The recharge rate through the exposed sandstone is 416 mm/y.

Scenario 3: superficial deposits cover 65% of the modelled area and the recharge rate through these deposits is 168 mm/y. The recharge rate through the exposed sandstone is 591 mm/y.

Scenario 4: superficial deposits cover 35% of the modelled area and the recharge rate through these deposits is fixed at 50 mm/y (corresponding to the recharge rate through till estimated by Vines (1984). The recharge rate through the exposed sandstone is 452 mm/y.

Scenario 5: superficial deposits cover 65% of the modelled area and the recharge rate through these deposits is again fixed at 50 mm/y. The recharge rate through the exposed sandstone is 818 mm/y. This is significantly higher than can be realistically expected, although the travel time to the borehole was not affect by this recharge value as the borehole catchment (or capture zone) was restricted to the area overlain by superficial deposits.

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It is clear from figure 11 that the higher recharge rate (thorough the exposed sandstones) close to the borehole (recharge scenaro 2, model run 5) and recharge scenaro 4 (model run 9)) allowed a greater fraction of modern water to reach the borehole more rapidly. This is because the borehole preferentially sources its water from the drift free area where recharge is higher. There is more vertical flow close to the bh and consequently, younger water arrives at the bh 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 areas covered by superficial deposits and the slope of the curve reduces.

In the scenarios where superficial deposits cover 65% of the modelled area , the abstraction borehole is located beneath these deposits. The larger borehole catchment, due to the reduced recharge rate, means that modern water takes significantly longer to arrive at the borehole.

Discussion

Modelling suggests that two factors,

- focussed recharge through permeable windows in the drift cover and
- localised fissure flow to the abstraction borehole,

could have a significant influence on the proportion of modern water pumped from a borehole. The scenarios modelled used realistic parameters that fitted current understanding of the groundwater flow system in the Permo-Triassic sandstone aquifers in the Eden Valley.

In general, the modelling suggests, not surprisingly given the high porosity of the aquifer, that it would take many decades (even centuries) for all the porewater within the borehole catchment to be flushed out by modern water.

The model predicted that groundwater pumped from a deep borehole beneath extensive superficial deposits would have only a small percentage of modern water (during the first 50 years of pumping) and is therefore likely to have low nitrate concentrations. Field data shows that the major abstraction boreholes located beneath thick (more than 10 m) superficial deposits so indeed pump groundwater of low nitrate concentrations. The residence times of the groundwaters are yet to be determined.

The results of the modelling also suggest that, for boreholes located in a ‘recharge window’ or where fracturing is developed close to the borehole, the proportion of modern water pumped could increase rapidly, with time initially (from when pumping started) and then levels off at later times. An implication for pumped nitrate concentrations is that these may increase rapidly once pumping commences but the upward trend may decline later. Thus nitrate concentrations currently observed in the EdenValley are strongly influenced by the pumping history and maximum nitrate concentrations have probably not yet been reached. Tellam and Thomas (2002) reached a similar conclusion for the sandstone aquifer beneath Birmingham.

This investigation suggests that even hen land management practices are introduced to reduce nitrate leaching from soils, the timescales for reversing upward trends in groundwater nitrate concentrations are likely to be many decades. This has clear implications for the implementation of the Water Framework Directive.

Modelling has provided a possible explanation both as to how some relatively deep boreholes can pump water containing a significant percentage of modern water and why there can be differences in nitrate concentration between boreholes in different hydrogeological environments which cannot be explained by differences in land use alone.

Conclusion

Groundwaters in the Permo-Triassic sandstone aquifers in the Eden Valley show a considerable variation in nitrate concentration, from less than 4 mg/l to more than 100 mg/l. The principal source of the elevated groundwater nitrate concentrations is believed to be the spreading of animal slurry to grassland which may be applied at rates in excess of the crop nutrient requirements.

A number of factors appear to influence groundwater nitrate concentrations observed in boreholes.These include, amongst others, surficial geology, the depth of the borehole, the thickness and nature of superficial deposits and the development of horizontal fracturing around the borehole. However, the controls on groundwater nitrate concentration are complex and no single factor dominates.

One surprising observation is the relatively high nitrate concentrations measured in some deep boreholes. Simple numerical modelling suggests that the proportion of modern water pumped by a deep borehole is sensitive to (a) the development of horizontal fracturing close to the borehole and (b) the location of the borehole relative to superficial deposits of low permeability.

One implication from the modelling is that the rising trend in pumped nitrate concentration observed in some abstraction boreholes may level off with time providing nitrogen loadings to the aquifer do not increase, but that these timescales may be very long indeed.

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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 1. ***Details of model runs***

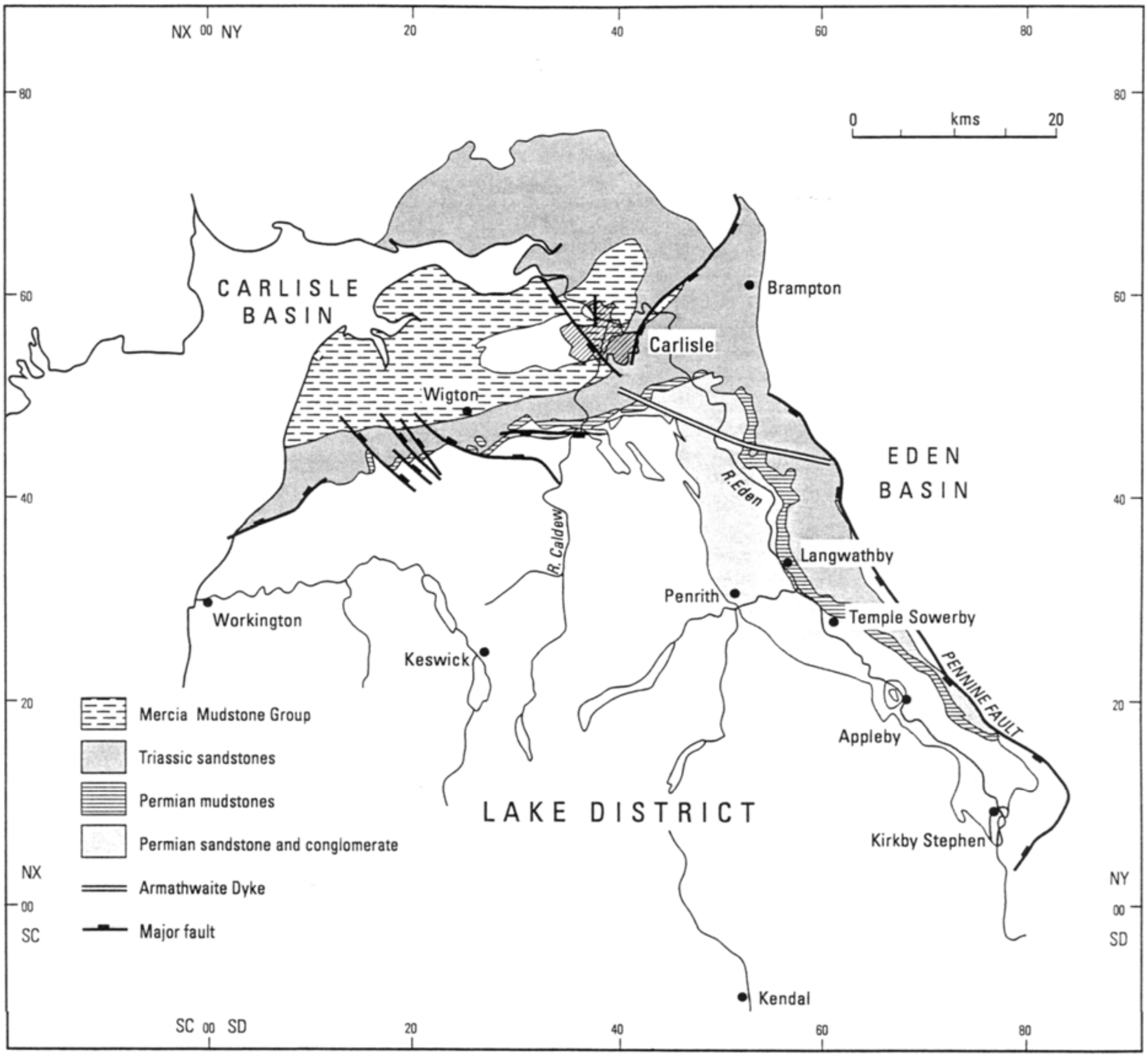

Figure 1. **Location map of the Eden Valley (modified from Allen et al 1997)**

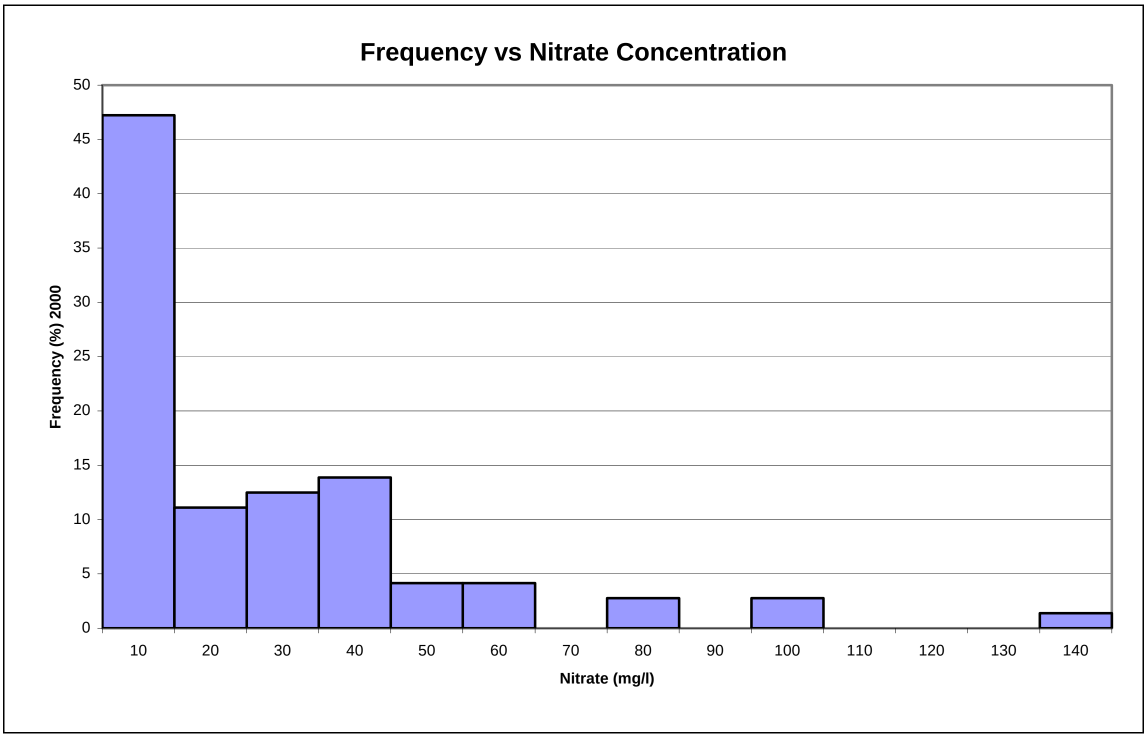

Figure 2 Frequency distribution of groundwater nitrate concentration in monitoring boreholes

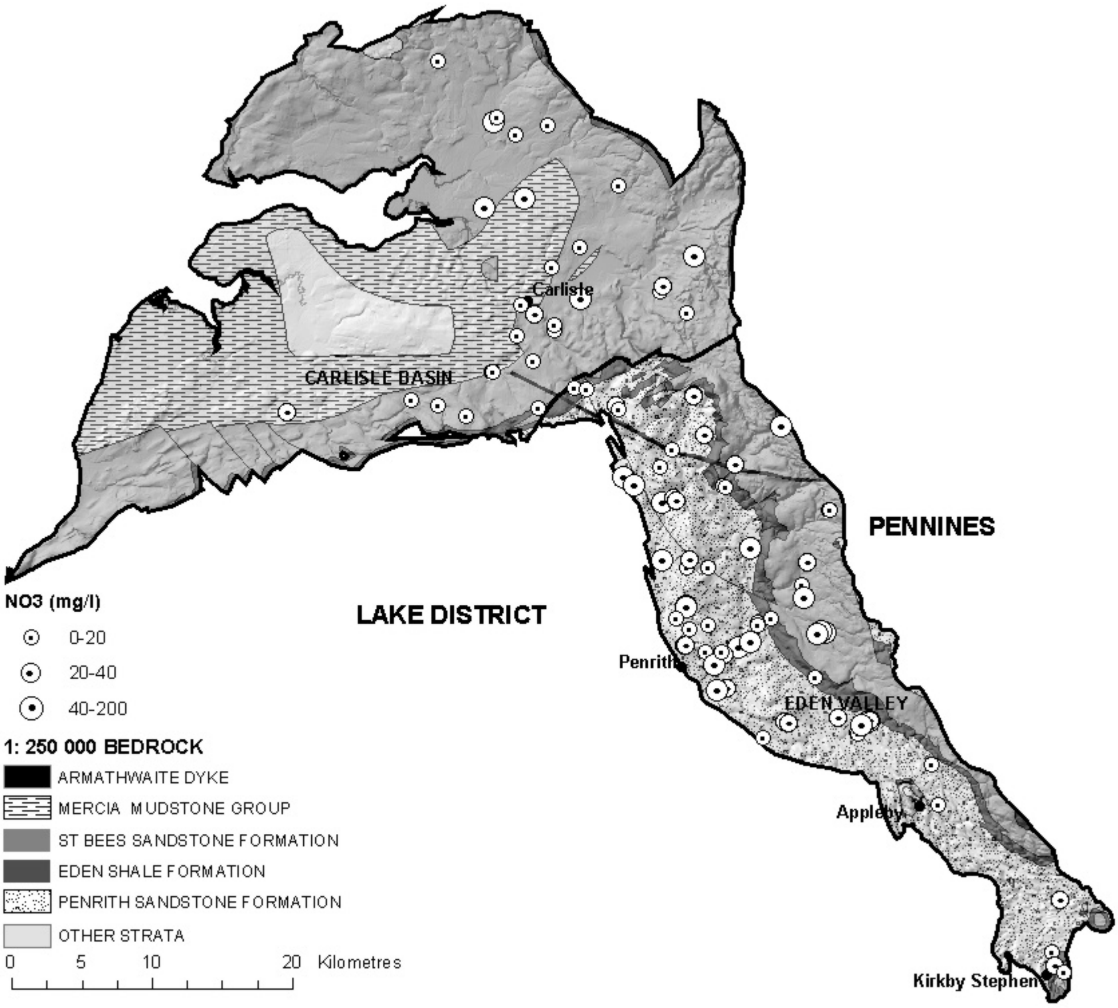

Figure 3. **Distribution of monitoring boreholes in the Permo-Triassic aquifers of the Eden Valley and Carlisle Basin indicating groundwater nitrate concentrations.**

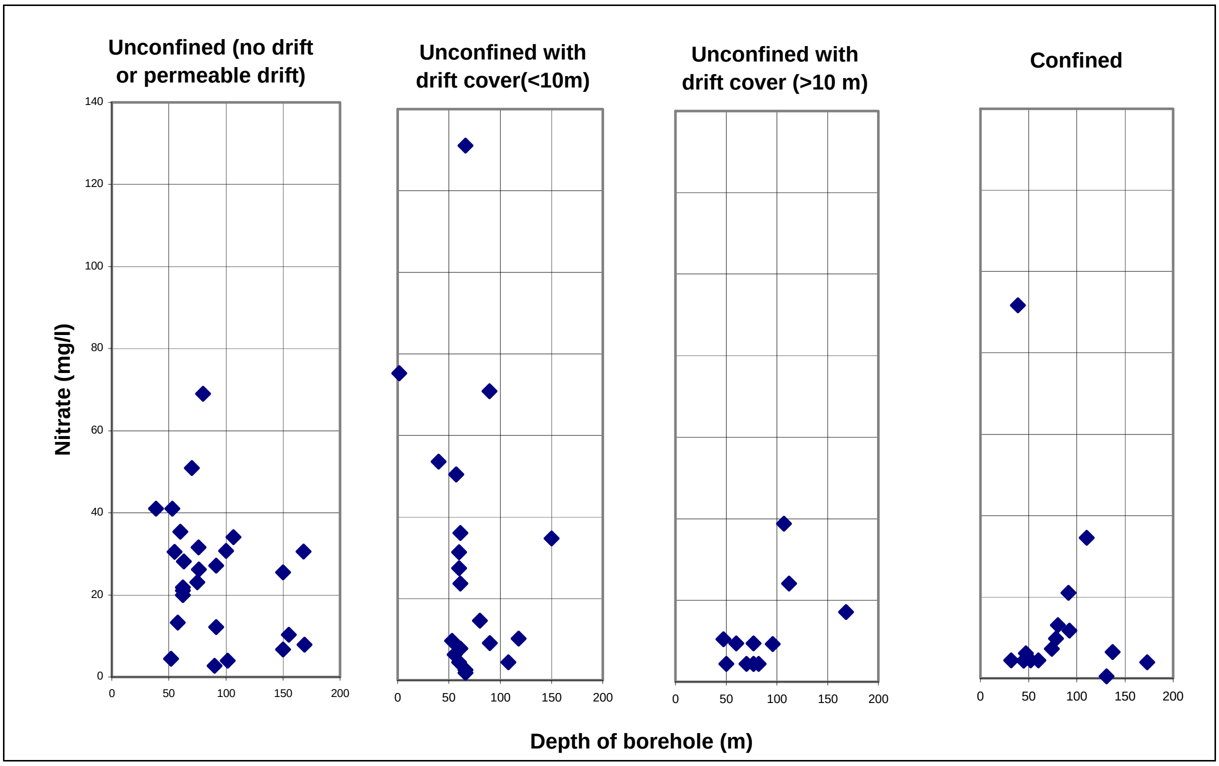

Figure 4. **Scatter plot of borehole depth and pumped nitrate concentration for the year 2000**

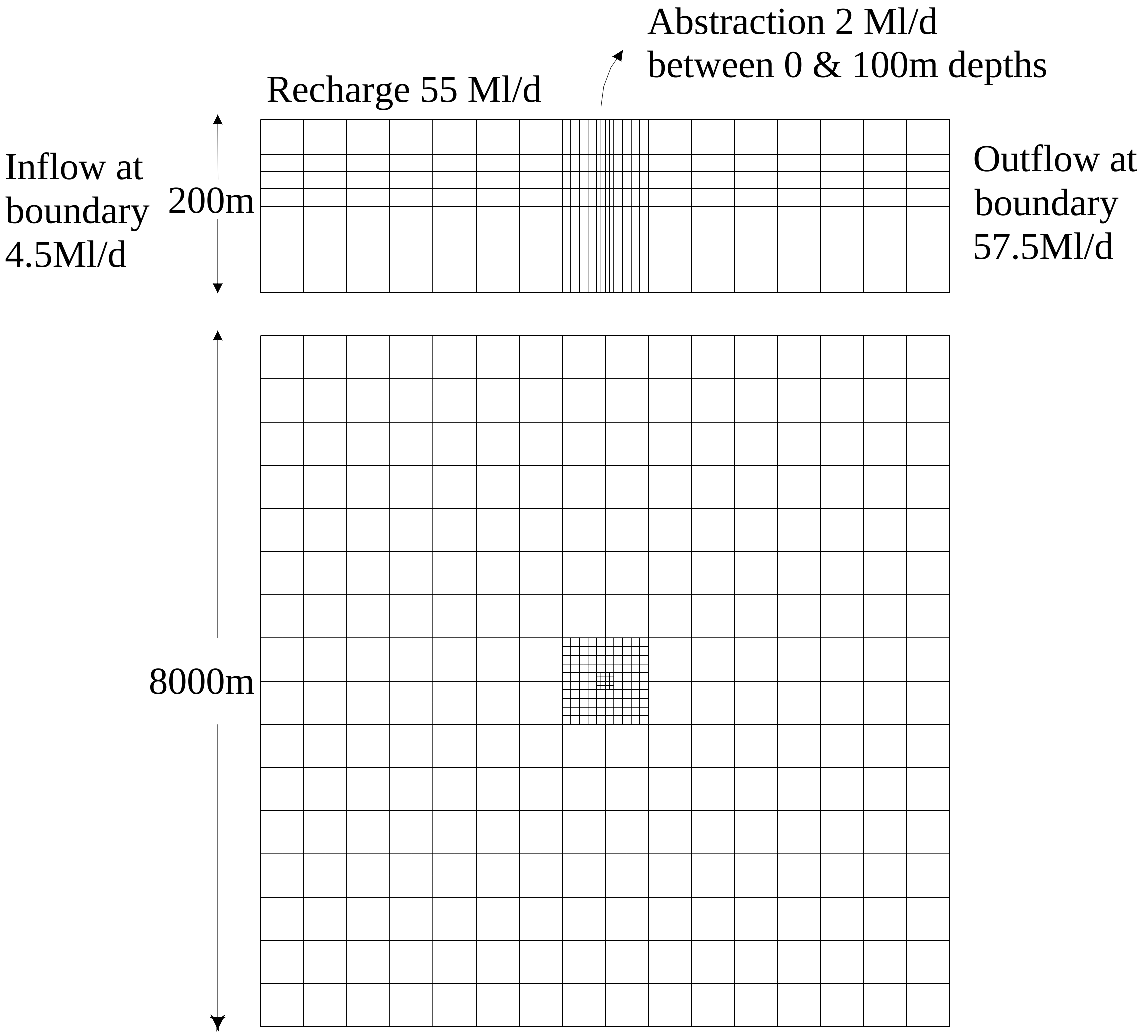

Figure 5 Structure of the numerical model (cross section over plan view)

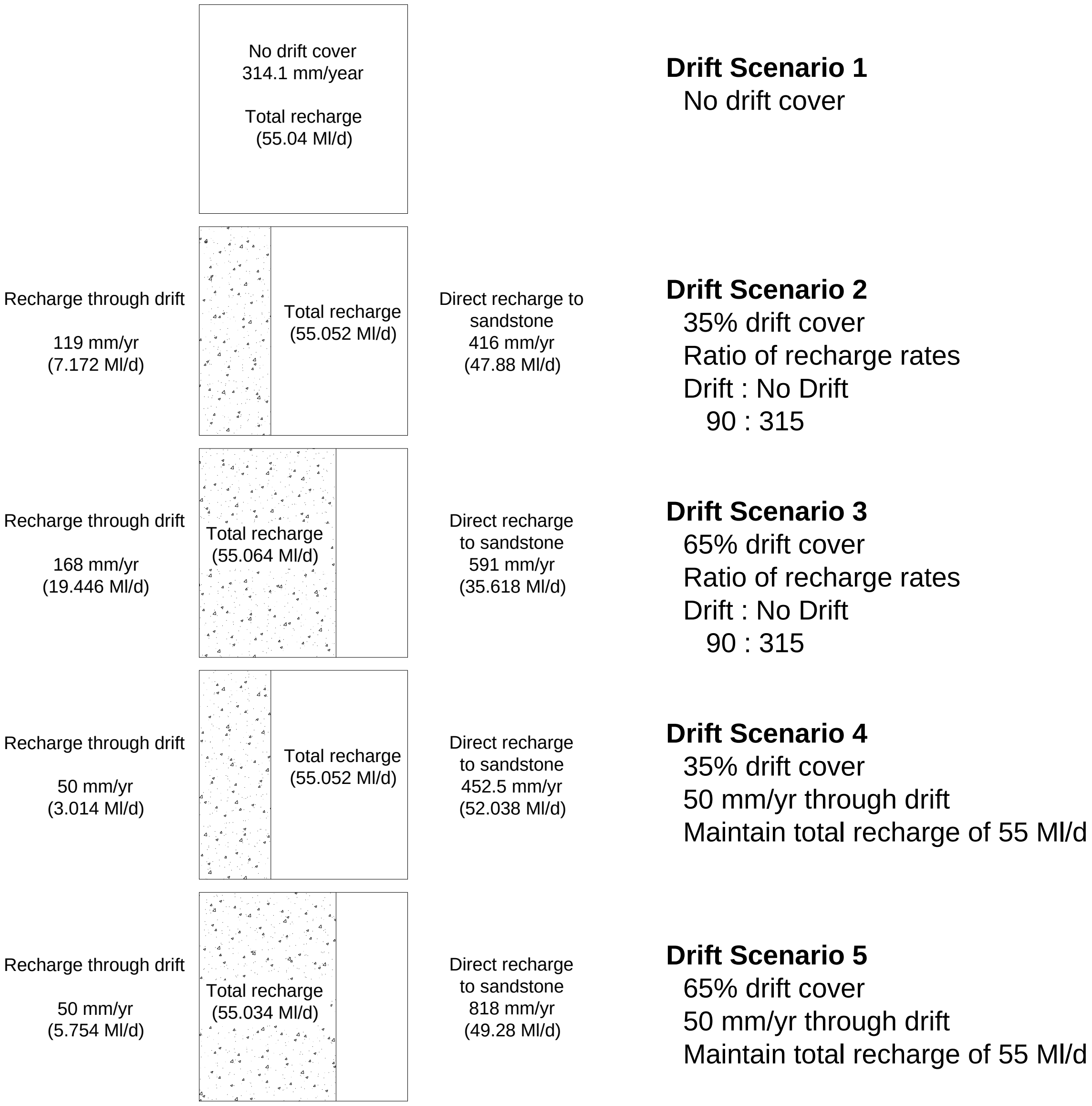

Figure 6. **Model recharge scenarios**

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’.

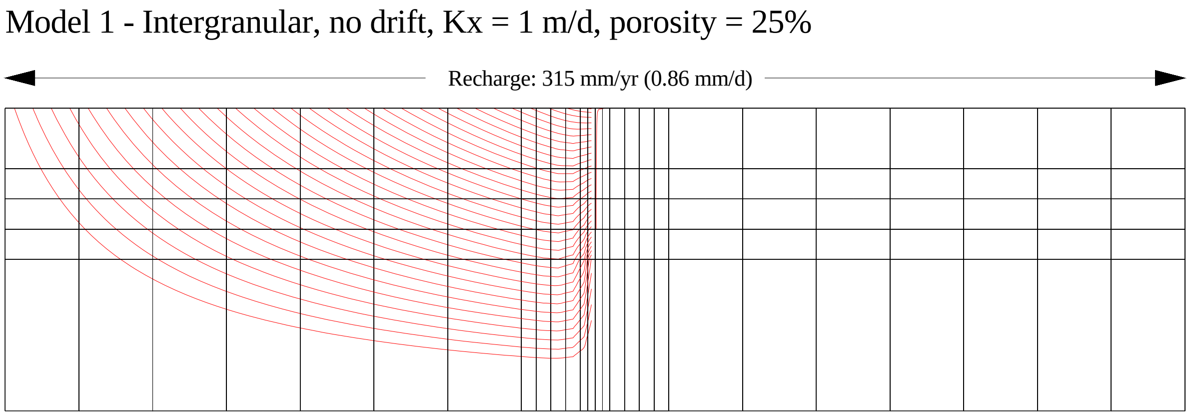

Figure 7. **Particle pathlines for Model 1, intergranular aquifer with no drift cover (***particles down the hydrogeological gradient from the borehole are omitted***)**

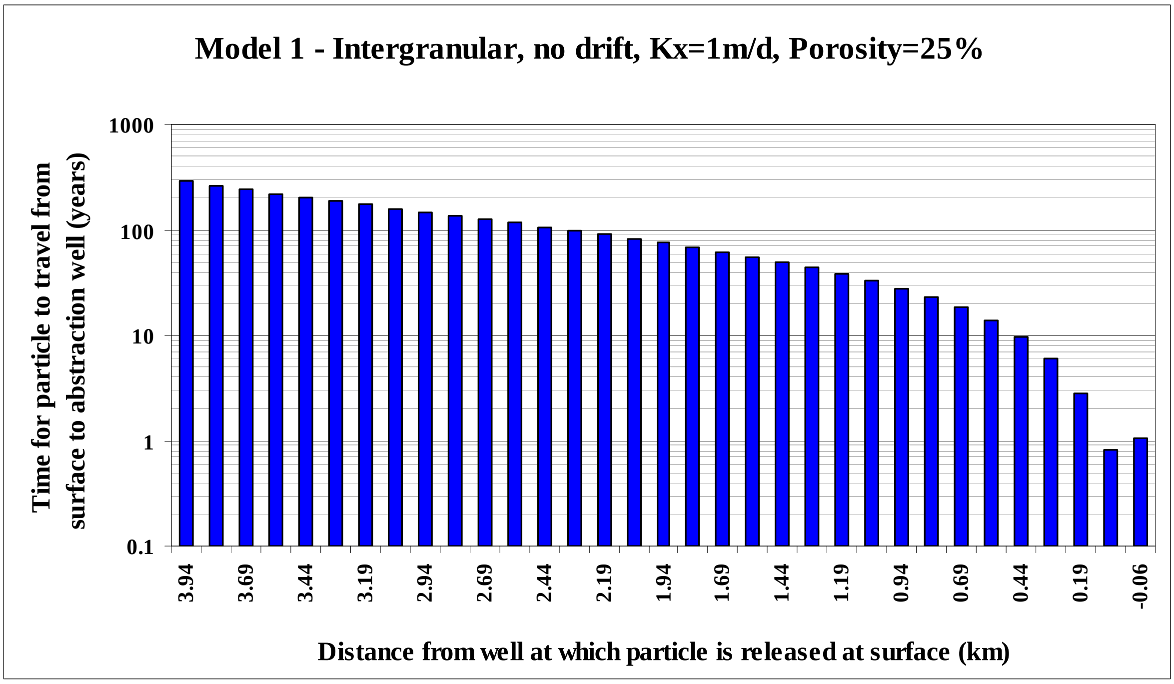

Figure 8. **Particle travel times for Model 1, an intergranular with no drift cover**

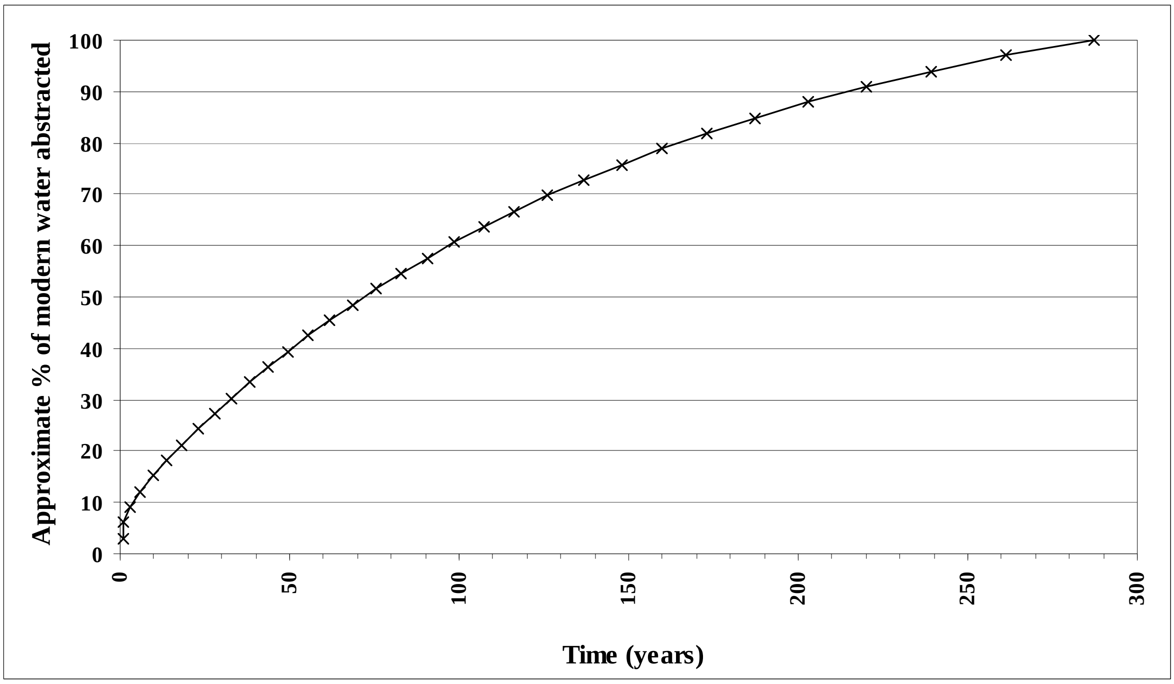

Figure 9. **Estimated percentage of modern water pumped since start of abstraction, Model 1**

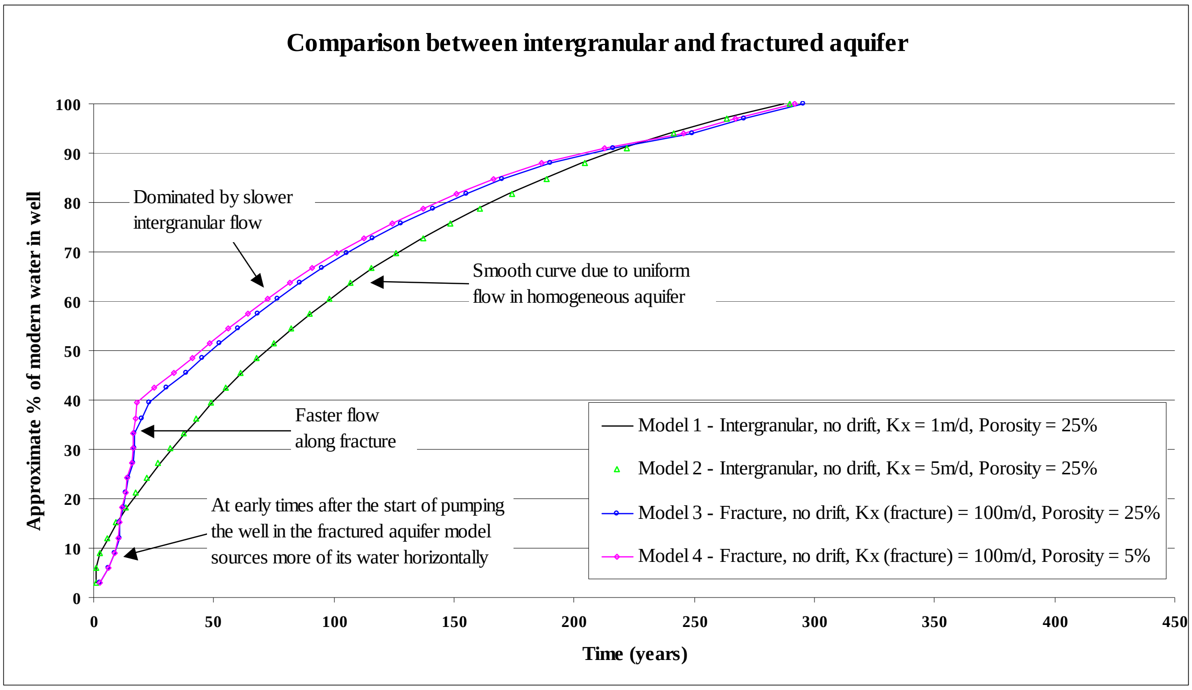

Figure 10. Comparison of percentage of modern water pumped against time between intergranular and fractured aquifer

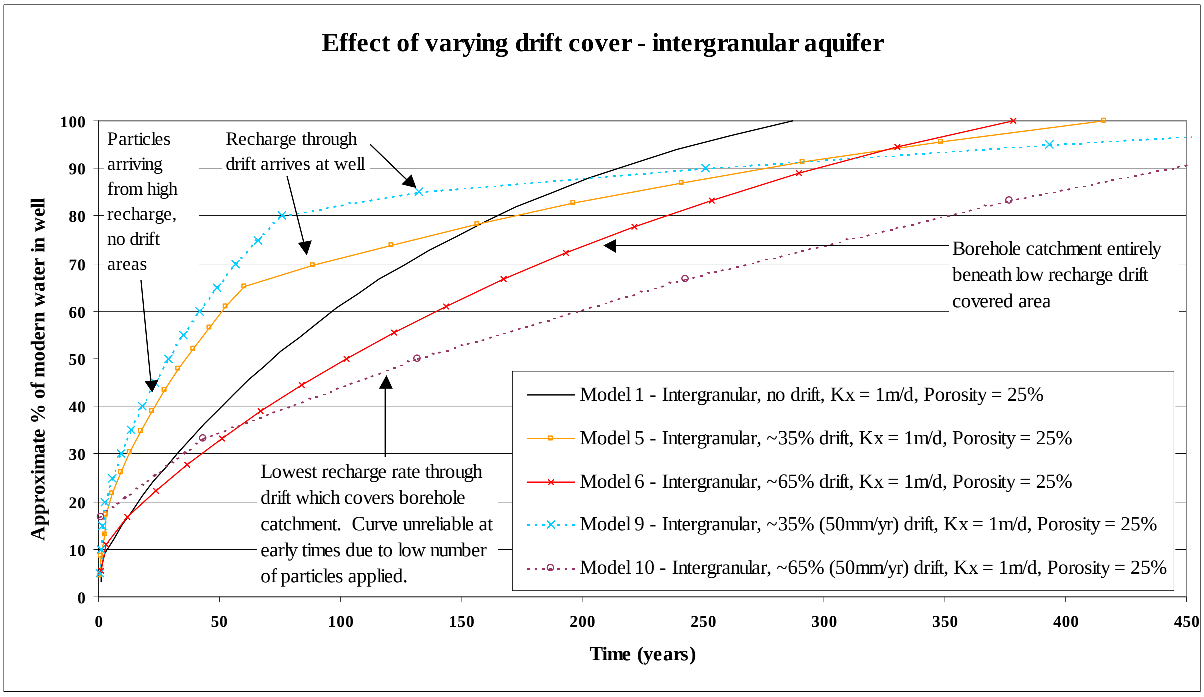

Figure 11 **Comparison of the percentage of modern water pumped against time between different drift cover scenarios**