Measuring groundwater parameters to improve modeling and regulation

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Abstract
Groundwater forms 70% of the world's freshwater supply, and is typically much cleaner than surface water supplies. It is therefore a key water resource that needs to be carefully managed. In urban areas, groundwater can be overexploited by industry, leading to degradation in quality. In order to regulate groundwater use, an understanding of the key parameters that control groundwater flow is required. This paper focuses on methods of measuring some of these parameters, so more accurate groundwater flow models can be created. The results from standard techniques are compared to other, lower technology methods. The Chalk aquifer of East Yorkshire in the UK is used as a case study. It is hoped that the lessons and principals learned by groundwater regulators in the UK and other developed countries can be used to avoid similar problems in the developing world as urban populations increase.

Keywords
water resources; contaminants; pollution; modeling; quality

INTRODUCTION

In the UK, groundwater provides about 40% of the drinking water supplies (UK Groundwater Forum, 1998). By 2002, 10% of aquifers had urbanized land directly above them. Whilst there is an increasing trend for abstracting water in rural areas and pumping it to the cities, (Morris et al, 2007), many public water drinking supplies are still pumped from aquifers in urban areas. In addition many industries are based in the cities, and their private abstraction wells put additional pressure on groundwater. Groundwater is usually considered to be much cleaner than surface water, and often requires little or no treatment before it can be used for drinking. However, overabstraction can lead to deterioration in quality, as low quality water is drawn in from neighboring sources, including other aquifers, rivers or the sea. Urbanization brings additional threats to groundwater quality from sources like petrol filling stations, waste disposal, leaking septic tanks, leaking sewers and the removal of any protective confining aquifer layer during construction works (Aldrick et al 1999). Urban drainage can also decrease soil infiltration rates, so rainfall never enters the aquifer. In the UK, land use and groundwater abstraction rates are now regulated by the Environment Agency in order to maintain high groundwater quality.

In order to be effective regulators, the Environment Agency maintain a series of groundwater flow models which can predict the impact of changes in abstraction rates, and track potential contaminants. Whilst many of the input parameters for these models are well known, some are much harder to measure, including hydraulic conductivity.

Hydraulic conductivity is defined as "the rate at which water flows through a rock", and together with the pressure gradient, controls the speed of groundwater flows, which ultimately controls how much water can be abstracted and the speed and dilution rates of any potential contaminant plumes. Whilst the methods for measuring an average value of hydraulic conductivity over the depth of the aquifer are standard, methods for establishing the variations in hydraulic conductivity with depth are still being developed. It is important to understand these variations. For example, where the horizons with high hydraulic conductivity are all situated near the top of the aquifer, drilling expensive, deep wells is unnecessary. In addition, contaminants can travel faster through a few thin zones of high hydraulic conductivity than a thick zone of low hydraulic conductivity, and are hence the contaminants will be less diluted.

This paper presents several different methods of measuring the vertical distribution of hydraulic conductivity including impeller flow logging and dilution testing under both pumped and ambient conditions.

METHODS

Pumped well methods

The principal of these methods is illustrated in figure 1 and is best described by Molz et al (1989). A pump is set up at the top of the borehole, so that the water flows radially towards the borehole, and then up the borehole towards the pump inlet.

As depth down the borehole increases, fluid speed decreases as each producing zone is passed. If there is no ambient flow, the derivative of this log is proportional to hydraulic conductivity.

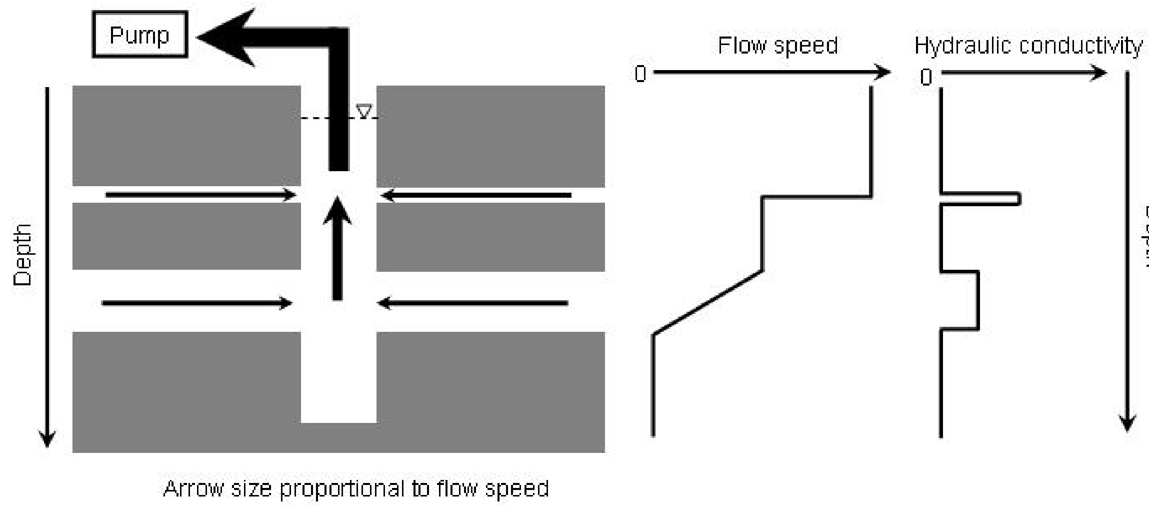

Figure 1: The basic prinicples of a pumped test

Overall transmissivity (product of hydraulic conductivity and thickness summed over the full aquifer thickness) can be measured using a pumping test (detailed in, for example, Kruseman and de Ridder 1990). It is found by measurign the fall in water level in the well induced by pumping. This value is then multiplied by a log of fluid flow speed derivative versus depth to obtain absolute hydraulic conductivity values for each individual layer.

There are several ways of measuring fluid flow speed in a borehole, two of which are described below:

Impeller flow logging. The impeller flowmeter has a spinner whose rotation is proportional to flow speed. As the impeller is lowered down the hole, it measures the sum of the flow speed of the water, plus the speed of the flowmeter (line speed). Line speed is subsequently subtracted during calibration.

Pumped dilution testing. This is described by West and Odling (2007). A hosepipe is lowered down the borehole, and filled with salt solution. The hosepipe is then removed from the borehole, so the borehole is filled with water of a greater conductivity than the surrounding aquifer water. As this water is drawn into the borehole by a pump, the resulting pattern of dilution is observed by measuring the electrical conductivity of the borehole fluid. From this the vertical fluid flow profile can be found.

Ambient methods

Sometimes, it is impossible to pump water from a borehole, perhaps due to time and cost constraints, or very large lifts (i.e. the depth to the rest water level is large). In this case, the ambient well flows can be measured. Ambient flows occur up or down a borehole due to pressure differences between two different conductive horizons intersected by the borehole. The vertical flow velocity between the layers depends on both the pressure difference and the hydraulic conductivity of each layer. As the pressure difference between layers is unknown, a quantitative hydraulic conductivity profile cannot be obtained, but the ambient flows indicate where the layers of high hydraulic conductivity are located and the direction of flow (upwards or downwards) in that part of the aquifer.

RESULTS

The results here are examples from the Chalk aquifer of East Yorkshire, which is a fracture flow aquifer. Fractures are subsequently enlarged by the dissolution of the carbonate rock matrix. Both of these factors mean that hydraulic conductivity varies considerably with depth. The aquifer has both confined and unconfined zones, with glacial clay till acting as the confining layer. Most boreholes in the aquifer are open to the Chalk, but are cased through its uppermost layers, and the till where present. All depths are in metres below ground level. Ordnance Survey National Grid references are given for location.

Pumped methods

Impeller flow logging. A pumped impeller flow log from Wilfholme Landing (TA 062 472) on the confined Chalk is shown in figure 2. The position of the base of the well casing is indicated. The measured data are noisy due principally to turbulence in the borehole set off from rugosities in the borehole wall, and variations in borehole diameter. A regression technique was developed which fits straight lines to the noisy plot. This is described in detail in Parker et al (under review). The modeled flow shows two zones where flow decreases rapidly, an upper zone between 24 and 32m, and a lower zone between 41 and 43m. The hydraulic conductivity profile found from this flow log is shown in figure 3, which also shows the magnitude of the hydraulic conductivity for the two zones described above. The regression technique gives an indication of the confidence of the model fit; 95% confidence limits are shown on this profile.

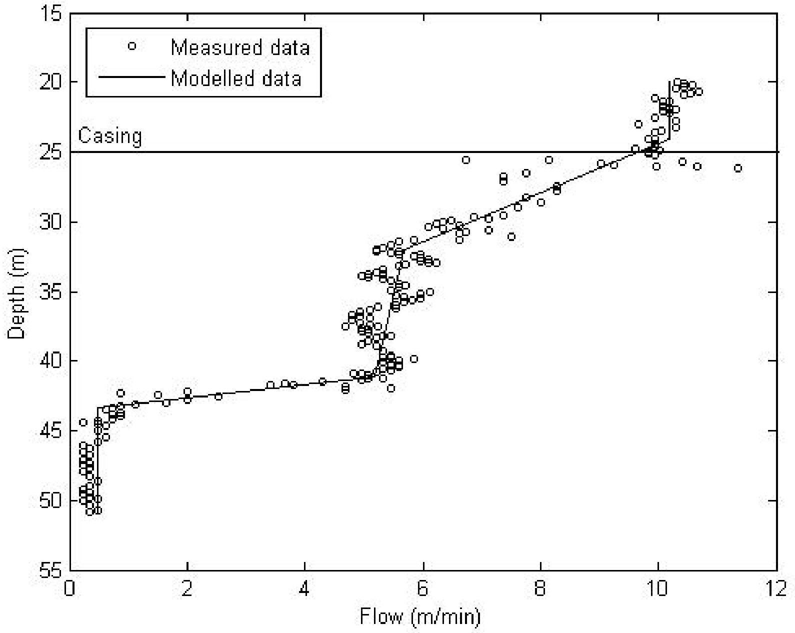

Figure 2: An impeller flow log from Wilfholme Landing, showing the measured data and the regression model fit. The depth of the base of the casing is indicated.

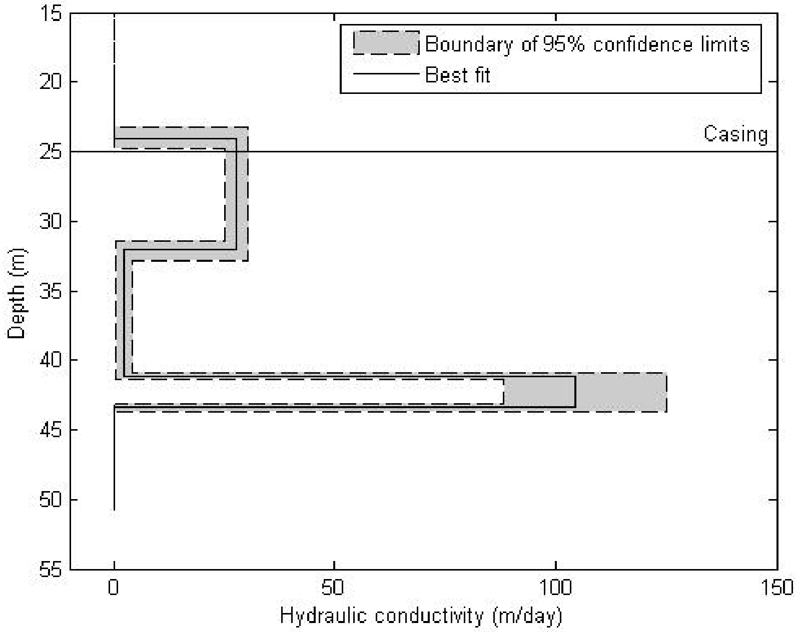

Figure 3: The hydraulic conductivity profile produced from the impeller flow log from Wilfholme Landing. The depth of the base of the casing is indicated.

Dilution testing. The results from a pumped dilution test for the same borehole at Wilfholme Landing are shown in figure 4. The pump inlet was at the bottom of the hole. The salt concentration profiles at several different times are plotted, and the concentration can be seen decreasing with time after injection. Inflows seem to be at 25 and 42m. Modelling of the salt concentration curves (using the technique of West and Odling, 2007) suggests that the well bore flow between 25 and 42m is 3m per hour, and the velocity from 42m to the pump outlet is 6m per hour, suggesting that half the inflow enters at 25m and half at 42m. This corresponds to the hydraulic conductivity profile from the impeller log, shown in figure 2 (i.e. the areas enclosed by the square sections representing the two conductive layers are similar).

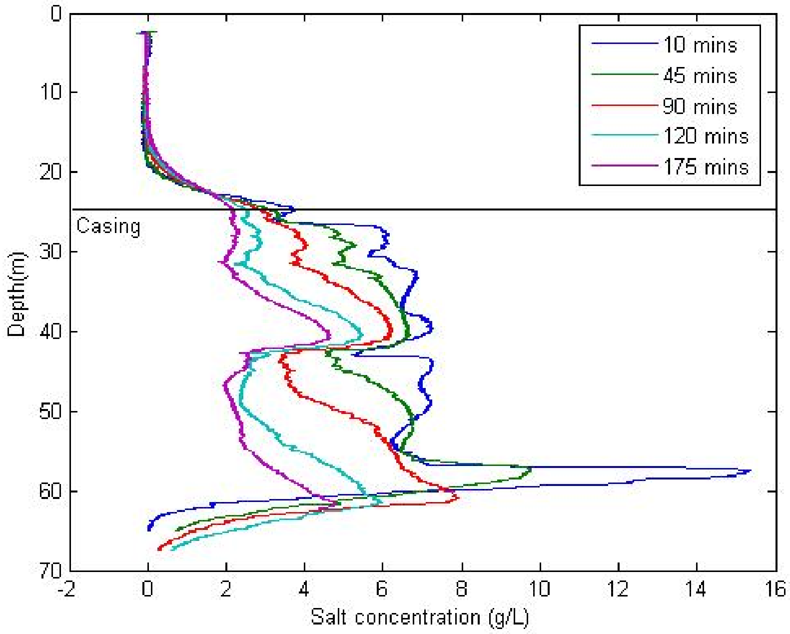

Figure 4: Salt concentration profiles through the duration of a pumped dilution test at Wilfholme Landing. The pump inlet was at the bottom. The base of the casing is indicated.

Ambient methods

Impeller flow logging. Figure 5 shows an ambient impeller flow log from a borehole at Henpit Hole (TA 025 658), on the unconfined Chalk. The resting water level in this borehole is below the casing. This borehole has a blockage at about 30m, below which the impeller cannot pass. However, the flow log indicates that flow is coming from beneath this blockage and leaving the borehole between 21 and 14m depth. It leaves most rapidly at 18m, suggesting this is the location of a high hydraulically conductive layer, possibly even a single conductive fracture.

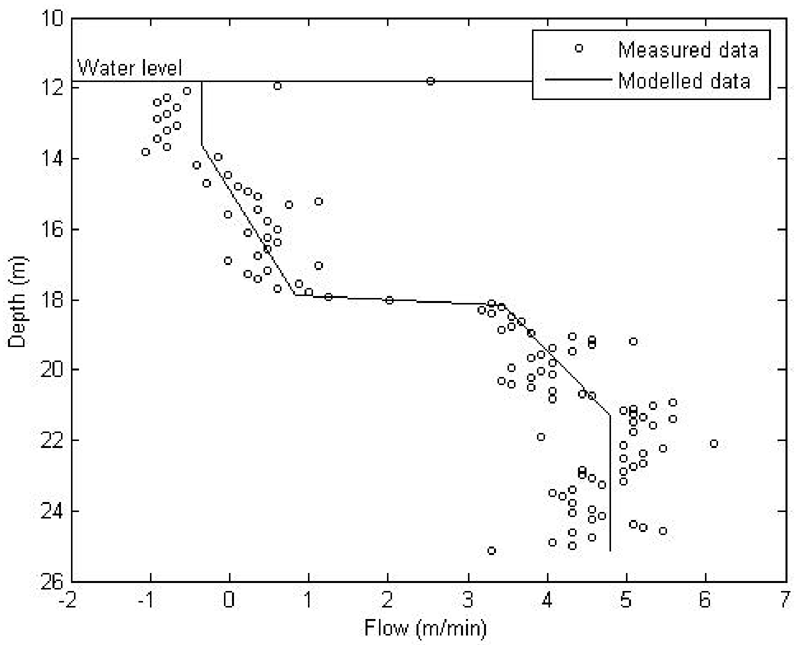

Figure 5: An ambient flow log from Henpit Hole, showing the measured data and the regression model fit.

Dilution testing. Figure 6 shows an ambient dilution test from a well at Weaverthorpe (SE 981 702) on the unconfined Chalk. Salt concentration profiles at several different times are plotted, and the concentration can be seen decreasing with time after injection. The profiles show there is an inflow at the top of the water column; this water flows down the borehole and leaves at 35m depth. There is another inflow at 40m. Water from here flows up the borehole and leaves at the same depth of 35m. The salt concentration in the bottom of the borehole remains constant throughout the duration of this test, suggesting that below 40m there are no ambient flows. Analysis of the salt concentration curves suggest that the upper ambient flows are 4 times faster than the lower flows. This suggests there are highly conductive horizons at the level of the water table (22m), and also at 35 and 40m depth.

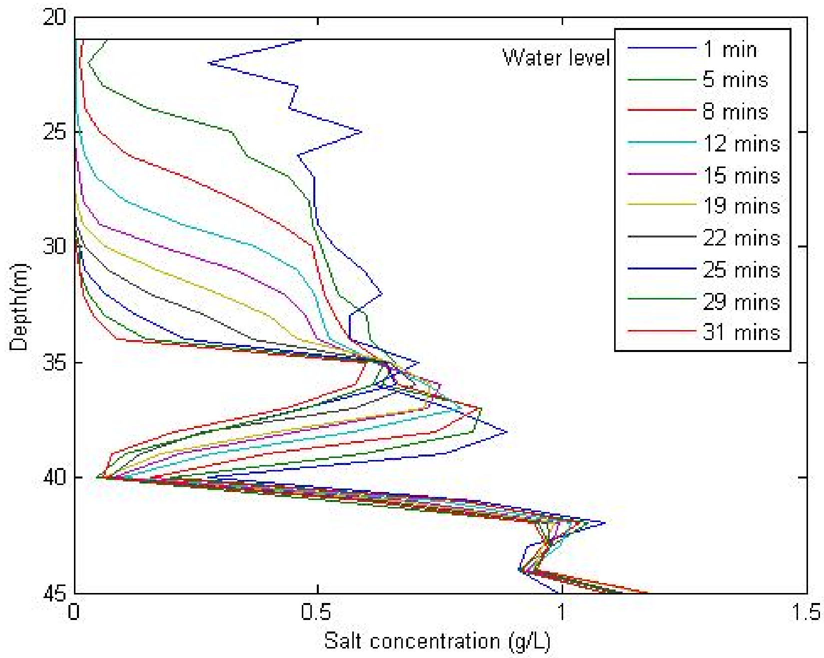

Figure 6: Salt concentration profiles through the duration of an ambient dilution test at Weaverthorpe.

DISCUSSION

Four different methods are presented here for establishing the variation of hydraulic conductivity with depth are presented here. Each has its advantages and disadvantages.

Impeller flow logging under pumped conditions gives the most comprehensive results, giving both the depths and magnitudes of hydraulic conductivity, and also an indication of the certainty of those values from the confidence limits. However, it requires the most complicated and expensive equipment – not only the logging equipment but also a high capacity pump.

Pumped dilution testing provides exact depths of layers of high hydraulic conductivity, with a more approximate estimate of their magnitude. The conductivity can be measured using an inexpensive handheld conductivity probe. A much lower capacity pump can be used (for example a swimming pool pump running from a generator), although as the distance of the resting water level below the ground surface increases, the disturbance induced by pumping will decrease. If large ambient flows are present, they will swamp the efforts of a low capacity pump meaning the data is very hard to interpret; in this situation it would be better to carry out an ambient dilution test.

Ambient tests give a clear indication of the location of the layers of high conductivity, but cannot give any information of their magnitude. Dilution tests are the cheapest to carry out as the only specialist equipment required is the conductivity probe. Their only limitation is in boreholes with high ambient flow, where it becomes necessary to use the impeller to measure flow speed as it can measure much faster flows, but again, the equipment is expensive.

CONCLUSION

Four different methods of characterizing the vertical hydraulic conductivity distribution within an aquifer have been presented. In general as cost decreases, data quality is compromised, although there are some other physical constraints (the magnitude of ambient flows and the distance below the ground surface of the resting water level), and even the lowest cost method provides some very useful information about the aquifer.

The methods presented here can be used to better define groundwater flow model input parameters. The more accurate the model, the better the regulator will be able to predict the effects of changes to the aquifer, for example, the effect of installing a new abstraction well, or the contamination risk presented by a change to industrial land use, as well as the long term effects of increasing urbanization and climate change.

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