Groundwater Source Protection Zones – Delineation, Policy and Use

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Implications of vertical hydraulic conductivity variations for SPZ delineation in the Chalk

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In order to accurately delineate Source Protection Zones, knowledge of horizontal variations in hydraulic conductivity is required, and can be obtained from hydraulic (pumping) tests. However, the vertical variations in hydraulic conductivity are also of paramount importance, but unfortunately, much less information about these is usually available. Often SPZ determinations are based on over-simplified or uniform vertical hydraulic conductivity profiles which form the basis of regional groundwater flow models. While such models are adequate for predicting water fluxes, they are inadequate for the estimation of flow velocities upon which SPZ determinations are based.

Investigations of hydraulic conductivity structure of the Chalk aquifer of East Yorkshire are reported including pumping tests, packer tests, impeller flow logging, borehole dilution testing and forced-gradient well-to-well tracer testing. These data are reviewed alongside pumping test data from previous investigations. The confined aquifer has lower overall transmissivity (several hundred m^2/day) compared with the unconfined aquifer (several thousand m^2/day); however, both the unconfined and confined aquifers are characterised by a relatively thin layers of high hydraulic conductivity. Some high-conductivity layers represent individual fractures while others represent zones of highly fractured or weathered chalk several metres thick. In the unconfined aquifer, a large proportion of the transmissivity (50 – 75%) is associated with enhanced dissolution within the zone of water table fluctuation (typically 5 – 20m thick); this can be seen from comparison of transmissivity values measured at maximum and minimum water table levels. Deeper discrete conductive layers, in some cases up to 50m below the water table, are evident from open-well borehole dilution tests. In the confined aquifer, most transmissivity results from the presence of a periglacially weathered chalk layer immediately beneath the glacial cover sediments, typically 5 -10m thick. The solute transport properties of this layer were measured using a well-to-well tracer test. The implications of this hydraulic conductivity structure for the delineation of SPZs in the confined and unconfined parts of the aquifer will be discussed.

Source Protection Zone Delineation on Carboniferous limestone in the Wye Valley, Derbyshire

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During the 1990s SPZs were drawn for licensed abstractions in the Peak District Carboniferous limestone aquifer following standard guidelines set out in the Environment Agency methodology for the definition of SPZs (Environment Agency 1996). With the notable exception of Meerbrook Sough (a lead mine drainage level) the SPZ were defined using the Flowpath equivalent porous media finite difference program or were hand-drawn catchments, the size of which was based on the recharge needed to supply the licence quantities. These methods are unsuitable for the Carboniferous Limestone, as this is a karstic aquifer. In 2006 the SPZs for five boreholes and springs that are licensed to abstract water from the Carboniferous Limestone aquifer in the Wye valley were updated. With one exception (St

Anne's Well) the approach adopted was to review data from 45 natural gradient tracer experiments and from hydrochemical studies. These data, together with geological and topographic information, formed the basis for the definition of the potential catchment area for each source.

It is standard practice that the Inner Zone (Zone I; 50 day travel time from recharge to source) is based on the licensed daily quantity and that the Outer Zone (Zone II, 400 day travel time) and Total Catchment (Zone III) are based on the licensed annual quantity divided by 365.25. However, the tracing experiments provide evidence of high groundwater velocities, as expected for conduit flow in karstic aquifers, making it likely that travel times from point of recharge to point of discharge will be less than 50 days. The tracing experiments also demonstrate that divergent flow is common so that the catchments for individual sources are likely to overlap. Hence, SPZs were not delineated based on protected yields equivalent to the licensed quantities and the normal suite of SPZs have not been delineated for any source. Instead, only one source protection zone, the potential catchment zone, designated as an Inner Zone (Zone I), has been delineated.

The potential catchment zone, which is shown on the EA web site covers all of the following sources: Stanley Moor (Borehole), Staden Lane (Borehole), Rockhead Spring and Buxton Hydro/Eagle Street (Borehole). It also covers St Anne's Well, Buxton which Gunn et al. (2006) have shown is fed by groundwater from both the Carboniferous limestone and the Millstone Grit Group rising from over 1km with limited near-surface mixing. The Millstone Grit Group component is probably derived from strata cropping out in the Goyt Syncline to the west of Buxton. This is not within the SPZ but the long-residence time of the water (an age in the range 3900–6400 years is suggested by dating using ^{14}C isotopic methods and the bulk age for the water is taken as being 5000 years by Barker et al. 2000) makes this unnecessary. However, as St Anne's Well is only 230m from the Buxton Hydro source it cannot be separated from the larger SPZ.

It is emphasized that the new SPZ which are shown on the EA web site do not represent the area that is required to supply the sources with the licence quantities. The zone indicates an area where there is a possibility that conduits may exist that could provide water to the sources of the Wye Valley, based on the tracing test data.

Improvements in SPZ delineation for the chalk aquifer taking account of karst

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The Chalk of southern and eastern England forms an important water supply aquifer. The chalk, being a soluble rock, contains large numbers of karstic features. These features influence the way in which water percolates down into the aquifer and how groundwater moves through it. Although the degree of karst development appears less mature than that of other older limestones, with reference to the PBA Natural Cavities Database, it can be demonstrated that the numbers and spatial occurrence is significant. Presently hydrogeological modelling of SPZs on the Chalk does not adequately take account of karst. This is a major shortcoming when considering the travel time for pollutants to reach a source and how best to protect it. European Union funded studies (COST 620, 2003) have reviewed approaches to assessing karst areas, mapping their vulnerability and developing risk-based protection measures. Building on this body of work it is proposed that through geomorphological studies into the development of chalk karst and how it influences the underground flow regime, an improved understanding of karst impacts on SPZs can result. Some case study examples illustrate how SPZs can be influenced by chalk karst and where improvements in source management are required to protect them. The initial results of such studies also have implications for land usage within karstic chalk land areas where groundwater vulnerability is often more sensitive than published maps suggest.

Effect of conduit flow on SPZ delineation and implications for calculations with aquifer parameter

Dr Mike Price

A public water supply was experiencing pollution problems from the soakaway field at the M1/M25 motorway interchange in Hertfordshire. The defined SPZ of the time showed that the soakaways were outside the 400-day travel time for the nearest PWS. Tracer tests eventually showed a connection to the PWS in around 25 days, and travel to a nearby monitoring well in 30 hours. This rapid flow derives from conduit flow. This reveals problems with the treatment of calculations with K, kinematic porosity, etc. Although this work was conducted some time ago it appears that the results are not widely known. This presentation serves to unearth these problems and increase their prominence among active hydrogeologists.

Determination of kinematic porosity for source protection zones in the Chalk

Steve Worthington (Worthington Groundwater)

Source protection zones (SPZs) have been defined for some hundreds of public water supplies in the Chalk. Inner (50 day) and outer (400 day) protection zones have been determined using either manual equations or numerical models. Kinematic porosity is the most difficult parameter to estimate in both cases. It has often been assumed to have a similar value to specific yield and thus be about 0.001 - 0.01. However, more reliable estimates may be derived from borehole geophysics and from tracer testing. Flow meter, conductivity, and televiewer logs show that inflow into boreholes typically comes from just a few horizons, and that flow is from solutionally-enlarged fractures with apertures in the mm to dm range. This implies that kinematic porosity may often be less than 0.001.

There have been some dozens of tracer tests in the Chalk. These often reveal groundwater velocities >100 m/day. The data show that tracer test velocity increases with distance traced. This suggests that the solutionally-enlarged fractures commonly form a network, as theory predicts; this results in long-distance tracer tests having an increasing likelihood of intersecting the network and thus have higher velocities than short-distance tracer tests. Comparison of tracer test travel times with delineated SPZs in Yorkshire, Hertfordshire, and Sussex shows that measured travel times are 10-100 times quicker than would be estimated from the SPZs. This suggests that there may have been a systemic overestimation of kinematic porosity and thus an underestimation of the size of protection zones in the Chalk. Much more tracer testing is needed to determine actual times of travel in the Chalk and thus give more reliable values of kinematic porosity.

Delineating Capture Zones and Thermal Plumes for Well Doublets

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Analytical mathematical techniques utilising the concepts of stream functions and complex number space have historically been the “tools of choice” for analysing capture zones, plumes and flow lines around simple patterns of wells in homogeneous aquifers. They have now been largely superseded by numerical models (which are both expensive and, at best, are only approximations to underlying analytical solutions!). The analytical toolbox has been re-opened to demonstrate that simple and usable solutions to the common “thermal well doublet” (i.e. an abstraction-reinjection pair, used for open-loop ground source heating and cooling) can be readily programmed in two dimensions in a spreadsheet.

Comparisons with 2-D numerical models are generally excellent, although 3-D numerical modelling demonstrates that conductive diffusion of heat into overlying and underlying strata can prolong thermal breakthrough times compared with 2-D models. 2-D analytical models nevertheless remain a *conservative* first pass approach to well doublet problems.

The application of analytical and numerical models is demonstrated by a case study of a thermal well-doublet system (which has been running successfully for over 10 years) in north Yorkshire.

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Environmental Issues Associated with the Croydon Cable Tunnel

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National Grid is replacing cable circuits that are coming to the end of their service life in Croydon. Historically cable circuits have been buried beneath roads. Due to the heat generated by electricity transmission, the copper cable is surrounded by oil which absorbs the excess heat. Due to issues with oil leaks from these cables, they are being replaced by a single 400 kilovolt cable circuit which will be housed within a deep bored tunnel within the Chalk aquifer under Croydon. Cooling of this cable will be provided by air blown through the tunnel.

The tunnel alignment passes within 2 km of five public water supply (PWS) boreholes operated by Thames Water Utilities Ltd (TWUL). It passes through the inner Source Protection Zone (SPZ) of one of the sources and within 100 m of the inner SPZ of two others. At the start of the project, the potential risk the tunnel and associated activities posed to these PWS's was a significant concern to both TWUL and the Environment Agency. This case study examines the steps that were taken to minimise risk to these PWS's before, during and after completion of the tunnelling.

Following detailed discussions with the Environment Agency and TWUL a number of mitigating steps were taken.

- The vertical alignment was raised at the eastern end. This ensured that tunnelling adjacent to West Wickham and Addington PWS was undertaken above the watertable. In particular, adits known to extend northwards from Addington were thus protected.
- The selection of an Earth Pressure Balanced tunnelling method. This method balances the water and soil pressures at the head of the Tunnel Boring Machine (TBM) to impart minimal disturbance to the surrounding ground.
- A commitment was made that no soil conditioning agents would be introduced to the head of the TBM.
- Wet and dry caisson sinking methods were employed to sink the access shafts.
- Following leaching tests undertaken on samples of grout, semi-active grouts were selected comprising; limestone, cement, bentonite and water. No gels or additive were added to the grouts.

- An inert material, WR89S, was selected for the TBM tail skin sealant. Leaching tests were undertaken on this material to ensure it contained no List I materials and no List II materials at concentrations that would cause pollution.
- Simple analytical modelling was undertaken to demonstrate that there would be no impact on PWS yields following groundwater abstraction at the shaft sites during construction.
- Modelling was undertaken to investigate the potential for heat pollution from the cable tunnel.
- A detailed groundwater monitoring network was established with water level, electrical conductivity and turbidity monitoring undertaken using data loggers and telemetry of data to the office on a daily basis.

Tunnelling was completed in 2009 with no discernible effect on water quality or levels at any of the PWS's.

Use of Barometric Efficiency to improve SPZ delineation and characterization of aquifer vulnerability

Dr Noelle Odling – University of Leeds

In confined and semi-confined aquifers, boreholes commonly show a significant response to changing barometric pressure, a phenomena that was first quantified in the 1940s. This response is characterized through the barometric efficiency (BE) which depends on the properties of both the aquifer and the overlying variably confining units. For a specific location, barometric efficiency also varies with the frequency of pressure change in the barometric pressure signal. The variation in BE with barometric pressure frequency is characterized by a barometric response function which can be used to estimate the effective hydraulic diffusivity of the confining units. This gives quantitative information which can provide an aid to characterizing groundwater vulnerability and inform the delineation of groundwater source protection zones. In addition, the required data is simple and relatively cheap to collect using programmable pressure transducers placed in boreholes which record water level and barometric pressure as time series. The nature of BE response functions are being investigated for the Chalk Aquifer of East Yorkshire where much of the aquifer is confined or semi-confined by a range of glacial and fluvial sediments. It has traditionally been assumed that these sediments provide good protection to the aquifer against surface contamination but their heterogeneous nature suggests that the degree to which the aquifer is protected may vary considerably. Preliminary analyses of borehole water level records show a range of responses to barometric pressure which supports this. In this presentation, the principles and techniques used to analyze borehole and barometric time series data and some preliminary results and problems encountered in the East Yorkshire Chalk aquifer are described.