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Estimating the Pollution Risks to Urban Groundwater from Industry and Sewers

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Abstract: Urban groundwater continues to be at risk of pollution by organic chemicals and microbiological contaminants despite its potential economic and ecological value. Assessing these risks is hampered by the large number of potential sources and the general lack of detailed site data, and so there is a likelihood of poor decisions being made which would spoil the overall quality of life. However, we have shown that it is possible to build a GIS-based risk analysis tool. The tool, called the Borehole Optimisation System or BOS, has been validated against a variety of field datasets, and has been shown to make reasonable predictions of risks – that is within 2 orders of magnitude. Better predictions are made when there is a multiplicity of potential sources within a borehole catchment. There are a range of types of risk predictions that can be made with BOS, including analysis of a single site, mapping of risk over a city, and generic risk analysis without a site specific component. These risk analyses are probabilistic to take account of the uncertainties and poor characterisation of the environment. The information can be presented in a simple enough way to support decision-making and help to enhance the quality of life by targeting resources in an efficient manner.

Keywords: GIS; BOS; urban groundwater; groundwater pollution; probabilistic risk modelling.

1. URBAN GROUNDWATER POLLUTION

Urban groundwater is frequently considered to be at significant risk of pollution from the urban activities on the land surface above. The major sources of pollution are (a) industry, through spillages of chemicals and the creation of contaminated land, and (b) leaking sewers.

Industrially contaminated land is widespread, although in principle there are regulations preventing it in most countries. There is often legislation requiring assessment of the risks from any pollution and there may be requirements for clean-up of contaminated sites. However, the focus of the regulatory regime is on individual polluting sites, rather than on the cumulative effect of multiple sites on individual receptors.

Much less legislation focuses on the effects of leaking sewers, despite the health impacts of microbiological pollution being much larger than those of industrial chemicals. There is evidence from the UK and elsewhere that sewers do leak and cause pollution of groundwater, and there have been serious consequences for health in some incidents. The most infamous recent case is Walkerton in Ontario, with 2300 people falling ill and seven deaths [Howard, 2007]. Lerner et al. [1994] and others have catalogued cases in the UK and beyond where significant problems have arisen from sewer leakage. A recent exercise found widespread microbiological pollution in shallow groundwater in Nottingham [Barrett...
et al., 1999], and evidence of enteric bacteria and viruses tens of metres below the water table in both Nottingham and Birmingham [Cronin et al., 2003; Powell et al., 2003]. However, there has been no systematic assessment of the risks that such leaks pose to groundwater.

The quality of life can be improved by reducing the risk of pollution affecting human health or ecological quality. However, if money is spent on minor problems of groundwater pollution, it will be diverted from potentially more important investments and it could be argued that the quality of life will be made worse by poor decisions. The urban infrastructure is complex and poorly characterised, and urban hydrogeology is usually poorly characterised as well, due to the costs of investigations. In such circumstances, poor decisions are quite likely to occur due to the lack of good information.

Over a series of projects, we have developed a set of linked tools to estimate the risk of pollution for a potential new user of urban groundwater [Davison et al. 2002; Tait et al. 2004; Chisala et al. 2007; Tait et al. 2008]. The overall package is called BOS (Borehole Optimisation System). The objectives of this paper are to give an overview of BOS and to discuss the validation of risk models. We give some example applications in order to show that it is possible to use information handling to support good decision making in such poorly characterised systems and so enhance the quality of life.

2. BOS: BOREHOLE OPTIMISATION SYSTEM

2.1 Overview of BOS

BOS forecasts water quality at new abstraction borehole locations. The conceptual model is the reverse of the conventional source, pathway and target risk assessment methodology. BOS begins with a user specified borehole (the target), and retraces the flow lines of the capture zone in order to identify the multiple potential contaminant sources situated upstream.

In order to undertake the risk analysis, BOS utilises three discrete component modules. The Catchment Zone Probability Model (CZPM) module identifies the probabilistic surface expression of a borehole catchment. The Land-use Model (LM) module identifies the potential current and historical contaminant sources within the catchment area from either industrial landuses or the sewer network. The Pollution Risk Model (PRM) module is essentially a transport model, and estimates the combined threat posed by the identified potential contaminant sources at the abstraction borehole. The integration of these independent component modules (CZPM, LM and PRM) within a single Graphical User Interface (GUI) was central to the successful development of BOS as a powerful tool for addressing the issues regarding the best use for urban groundwater under conditions of high uncertainty. In this case GIS offers the ideal platform for coupling the diverse components that make up BOS.

BOS seamlessly integrates the CZPM, LM and PRM modules within a GIS based GUI which contains all of the necessary functions with which to undertake the groundwater risk analysis while shielding the user from the complexities of the background process controlling the component modules. The integrated working environment offers either full control to the experienced user or minimal interaction to the novice and creates a powerful decision making tool for establishing the best locations for new boreholes in urban areas.

BOS depends on the user to supply the specific modular datasets for the urban region to be analysed. Thus a MODFLOW groundwater flow model, historical land-use and sewer network shapefiles, land-use and contaminant property databases and surface elevation coverages are essential. Background shapefiles (roads, rivers, railways etc) of the study area are not necessary but can be utilised by BOS, for visualisation purposes, if present. The reliance of BOS on the user to provide these representative datasets means that the application is not restricted to the analysis of a single urban area. Indeed the BOS application can be applied to any region given the appropriate data in the correct format.
2.2 Components of BOS

The CZPM module is based on a three-dimensional finite-difference MODFLOW groundwater flow model. It is described by Davison et al. [2002] and Tait et al. [2004].

The LM module identifies pollution sources within the catchment using spatial land-use information and associated Microsoft Access land-use and contaminant databases. It comes in two versions. The original version handles landuse, and identifies sources of industrial pollution, principally organic contaminants [Tait et al. 2004, 2008]. The newer version has added information on sewer networks in order to estimate loads of microbiological pollutants. Using the limited data that is available on sewer leakage rates, and how these rates are related to sewer age, a model has been developed to estimate leakage rates for each 500x500 m grid square in the city [Chisala and Lerner, 2008a].

The Pollution Risk Model (PRM) module employs a stochastic analytical solute transport model based in a Microsoft Excel spreadsheet with Crystal Ball probabilistic extension [Decisioneering, 1996] and custom PRM add-ins. For organic pollutants, each source term is conceptualised as the dissolution of the contaminant from a non-aqueous phase liquid (NAPL) by recharge, so is represented by the contaminant solubility \( C_s \), mole fraction \( X \), recharge rate \( R \), and the area of the source \( A \), with the latter providing a way of describing and varying the source strength [Chisala et al. 2007].

Calculating potential attenuation requires the total travel time for contaminants through the unsaturated and saturated zones. The unretarded travel time through the unsaturated zone to the water table is a function of soil moisture content \( \theta \), unsaturated zone thickness \( w \) and recharge rate. The unretarded travel time \( t_s \) in the saturated zone is automatically calculated by the groundwater flow model (see above). Biodegradation, treated as a pseudo first order decay process, and sorption are described by the biodegradation rate constant \( \lambda \) and retardation factor \( R_f \) respectively. The resulting pollutant flux at the borehole is summed over all \( m \) sources, and is diluted in all the water pumped from the borehole by use of the pumping rate \( Q \). The predicted concentration at a borehole, \( C_w \), is given by:

\[
C_w = \sum_m C_s X \frac{R A}{Q} \exp \left[ -\lambda R f \left( \frac{\theta w}{R_s} + t_s \right) \right]
\]  

(1)

For microbiological pollutants, this conceptual model of fate and transport was found to be inadequate as it underestimated the concentrations observed in the field [Chisala and Lerner, 2008b]. A revised model which allowed preferential flow of a small fraction of the pollutant load was employed and gave much better results. :

\[
C_w = \sum_m F_u \left[ 0.01 \exp \left( \frac{\lambda R f t_s}{f} \right) \right] + 0.99 \exp \left( \lambda R f t_s \right)
\]  

(2)

where \( F_u \) is the flux of pollutants reaching the water table, 0.01 is the fraction of the load travelling by preferential pathways, and \( f \) is a travel time factor expressing how much faster flow is in the preferential pathway than in the bulk, matrix flow, pathway.

3. APPLICATIONS

3.1 Case study area

The City of Nottingham was selected as a study area where BOS could be applied due to its geological character and the numerous studies on groundwater under the city that have been conducted. This urban area is situated in the East Midlands on one of the most important aquifers in the United Kingdom. The Permo-Triassic Sandstone aquifer provides groundwater resources that have been extensively developed for both public and industrial water supply across the country. In areas where they are not affected by human activity the
aquifer produces a high yield of generally good quality groundwater. However previous studies have identified both localised industrial contamination of groundwater in numerous urban areas by organic compounds and more diffuse inorganic contamination.

This city has been a major industrial centre since the 18th century and has a long and varied industrial history largely originating in the textile industry. By the middle of the 19th century Nottingham’s rivers had become too polluted to be used for public water supply. This was a time of growing industry and population contemporaneous with an increased demand for clean water. Thus from 1850 onwards virtually the whole water supply for the region was derived from the Sherwood Sandstones below the city. The impact of the long-term industrialisation in the Nottingham area on the underlying groundwater is indicated in studies by Barrett et al. [2001]. This work revealed the groundwater quality beneath this area to be poorer than nearby rural locations. The deterioration is not great for inorganic species, except for localised pollution incidents, and no trace metals were found. Nitrate concentrations are similar in urban and rural locations, and frequently exceed the drinking water limits. Chlorinated solvent pollution is widespread as are BTEX (benzene, toluene, ethylbenzene and xylenes) compounds originating from fuel and solvent spills. Most water is now withdrawn in the surrounding rural areas. Most of the groundwater abstraction in Nottingham is now used for private industrial use.

The regional hydrogeology and groundwater flow model for the Nottingham area used in this case study has been described by Yang et al. [1999] and Trowsdale and Lerner [2003]. The model is a steady state single layered model covering the urban area and rural locations to the north and east. The landuse component of the LM comprises a series of spatial land-use databases depicting the historical land-use activity in the urban area and a relational database containing the associated industrial and contaminant information. The data inputs for the LM are described in more detail by Davison et al. [2002], and resulted in 6 land-use maps for the years 1901, 1920, 1939, 1954, 1971, and 1991. They contain information on 16 000 landuse polygons for a city of ~250 000 people. The sewer network is represented by the digitised sewer asset map kindly provided by Severn Trent Water, with ages of each area taken from the dates of the housing developments.

### 3.2 Validation

Most environmental risk models are not validated, which should give users some cause for concern. Of course, it is no easy to validate a risk model because its purpose is to forecast the future, which implies that there are not yet any observations available to check the model forecasts against, and to do so in a probabilistic way. Validating a probabilistic forecast would require enough field observations to calculate statistics and frequencies of exceedances. Nevertheless, given the importance of giving confidence to user by validating a model, we have attempted to validate BOS for a number of different pollutants by a range of approaches, as summarised below:

- **Single site, perchloroethene (PCE)** a chlorinated hydrocarbon solvent widely used for dry cleaning. At one borehole in the case study area, average concentrations of PCE were available. BOS was run to predict concentrations at this location, and 91 potential sources of PCE were found in the catchment. The 50%ile concentration predicted (49 µg/l) was within a factor of 2 of the observed concentration (33 µg/l) (Tait et al. 2004).

- **Multiple sites, PCE.** In a later study, information on PCE concentrations was available for 6 pumped boreholes. Differences between predicted and observed concentrations ranged from <1 to 6 order of magnitude (OM), with 4 cases being within 2 OM. The more accurate predictions were for boreholes with higher numbers of potential PCE sources upstream (Tait et al. 2008).

- **National statistics for methyl tert butyl ether (MTBE)** an additive to petrol to enhance octane ratings and reduce smog-forming emissions. In an attempt to compare BOS against a large dataset, field data from 1100 boreholes in England and Wales was compared with model predictions for 70 sites within the case
study. There is not an exact match between the hydrogeology and pollution scenarios of the two sets, and we expect the field data to show lower concentrations as it includes more rural sites. 96% of the field samples are non-detects, and there were a lot of different detection limits used, which made comparison difficult with the more consistently organised model predictions. Nevertheless, the percentage of exceedances of concentrations from 0.5 to 100 µg/l between the two sets was within a factor of 2 (Chisala et al. 2007).

- Microbiological indicators, 3 sites. Low levels of microbiological pollution were observed at the three locations, two with multi-level samplers which had been sampled on several occasions, while the third had one set of observations from 11 boreholes in a small area. The frequency of field observation of faecal bacteria was compared with model predictions. Provided a preferential flow mechanism was included in the transport model (Eqn 2), there was good agreement for the two multi-level sites, but not for the third location (Chisala and Lerner, 2008b).

These validation exercises gives more understanding of the BOS model and its uncertainties than is usually available for risk models. They show that the model has some predictive power, but that it can only be used as a screening tool. It performs better when there are multiple sources in a catchment, presumably because of the averaging effects.

3.3 Use of BOS to predict risks

The city-wide risk model has four main uses. It can be used to analyse the risks of pollution for a single location, perhaps the site of a proposed supply borehole. In this case, a realistic groundwater flow model can be used, and special attention paid to collecting data about landuses in the probable catchment of the new source. This type of use has been shown in the PCE and MTBE case studies (Tait et al. 2004, Chisala et al. 2007).

A variant on single site analysis is to help interpret the conditions at an existing borehole were pollution is occurring. BOS is able to give a rapid analysis on the potential sources upstream of any site and the probability that they are within the boreholes catchment. This is essentially the type of analysis used in the validation exercises outlined above.

The third use of BOS is to map the risk of pollution across the whole city in order to identify areas of high and low risk. In this case, a standard new borehole is simulated on a grid of positions across the whole city, and the resulting predictions contoured. For the Nottingham case, 1300 locations on a 50 m grid were simulated for the PCE risk map (Tait et al. 2008) and 70 locations for the MTBE map (Chisala et al. 2007).

The final use we have made of BOS is a generic risk analysis, in which broad conclusions on the likelihood and severity of pollution are drawn. This can be done by analysing the statistics of the multiple simulations carried out in a risk-mapping exercise, but can also be done with fewer simulations. For the analysis on the risks of microbiological pollution from sewers, the model was run for a number of randomly selected locations. These showed that there was a significant risk of microbiological pollution in most locations (Chisala and Lerner, 2008b).

4. CONCLUSIONS

Urban groundwater continues to be at risk of pollution by organic chemicals and microbiological contaminants despite its potential economic and ecological value. Assessing these risks is hampered by the large number of potential sources and the general lack of detailed site data. However, we have shown that it is possible to build a GIS-based risk analysis tool. The tool, BOS, has been validated against a variety of field datasets, and has been shown to make reasonable predictions of risks – that is within 2 orders of magnitude. Better predictions are made when there area multiplicity of potential source within a borehole catchment. There are a range of types of risk predictions that can be
made with BOS, including analysis of a single site, mapping of risk over a city, and generic risk analysis without a site specific component.

The case study examples show that a complex and poorly characterised problem such as the risk of urban groundwater pollution can be represented in models. Relatively simple summary outputs can be produced to inform decision makers. These outputs can assist them to make good choices for environmental protection and improvement, and so help improve overall quality of life.

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