Groundwater risk assessment at contaminated sites: a new investigation approach

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Abstract A new investigation approach for the assessment of groundwater contamination based on the inversion of concentration time series measured within pumping wells is presented. Using the inversion approach, it is possible to investigate the mean pollutant concentration and the concentration distribution over a control plane perpendicular to the groundwater flow direction downstream of a pollutant source, as well as the mass flux over this control plane.

INTRODUCTION

At many contaminated sites the presence of pollutant hot spots as well as preferential transport paths and low conductivity zones within the aquifer result in an irregular distribution of contaminants in groundwater. Under such conditions, many costly monitoring wells would be needed to reliably determine the concentration distribution downstream of the pollutant source. Therefore, a new investigation method for groundwater risk assessments is proposed (Teutsch et al., 1998). In the new investigation method one or more groundwater pumping wells are placed and operated simultaneously or sequentially downstream of a pollutant source at a predefined control plane, with positions, pumping rates and pumping times allowing the well capture zones to cover the overall width of the contaminant plume. During pumping, the depth integrated concentration of one or more groundwater contaminants is measured as a function of time at each of the pumping wells. For the interpretation of the concentration time series measured at the pumping wells, an inversion approach was developed and coded into a computer program (Schwarz et al., 1997). The new approach allows the determination of the total contaminant mass flux over a control plane downstream of a pollutant source as well as of the contaminant concentration distribution within the undisturbed groundwater flow field between the wells. Therefore it can be used very efficiently for the detection and quantification of pollutant sources.

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INVERSION APPROACH

It is usually observed that the contaminant concentration measured within a pumping well does not remain constant during pumping. The contaminant concentration fluctuation is a result of the increasing well capture zone during pumping and of the spatial distribution of the contaminant downstream of the pollutant source. Therefore the concentration time series measured within a pumping well provides information on the spatial distribution of the contaminant mass within the capture zone.

The capture zone of a pumping well can be estimated, e.g. numerically by particle back tracking techniques, and it is possible to describe the increase of the capture zone under transient flow conditions. Then, based on a time dependent mass

Fig. 1 Pumping well positioned in a contaminated aquifer and the concentration time series measured at the pumping well.
balance calculation for the increasing capture zone, the contaminant concentration distribution within the undisturbed groundwater flow field can be computed from the contaminant concentration time series measured at the pumping well.

In the simple case of a homogeneous, isotropic, confined and unbounded aquifer with a constant thickness \( h \) and a radially symmetric groundwater flow field resulting from a pumping well with a discharge rate \( Q \) shown in Fig. 1 (i.e. in a situation with a negligible natural groundwater flow velocity), the concentration \( C(r) \) along a streamline at the distance \( r \) from the well within the undisturbed groundwater flow field can be obtained analytically using:

\[
M(n dt) - \sum_{i=1}^{n_e} \left[ \frac{2M(i dt)}{\pi} \arccos \left( \frac{r((i-1)dt)}{r(n dt)} \right) - \arccos \left( \frac{r(i dt)}{r(n dt)} \right) \right] - 2ndtQ \arccos \left( \frac{r((n-1)dt)}{r(n dt)} \right)
\]

with \( M(n dt) = ndt QC(n dt) \) and \( r(n dt) = \sqrt{\frac{ndt Q}{\pi h n_e}} \), \( n, i \in N \).

In equation (1), \( n \) describes the number of an individual concentration measurement within the time series and \( M \) the corresponding mass of the capture zone, \( dt \) is the time increment between the measurements, and \( n_e \) is the effective porosity of the aquifer. For practical reasons, it is assumed that the concentration does not change significantly along a streamline within the undisturbed groundwater flow field at the scale of the well capture zones. The position of a contaminant plume can then be identified from the resulting concentration distribution at the predefined control plane, and the total mass flux representative of the whole contaminant plume can be computed, without the need to regionalize point-scale concentration measurements.

For more complex situations, i.e. non-stationary, non-uniform three-dimensional groundwater flow fields with a significant natural groundwater flow velocity and spatially variable aquifer hydraulic and transport properties, the inversion problem is solved numerically. In general, the inversion solution will not be unique. However, if more than one pumping well is used successively to measure concentration time series, overlapping of the individual capture zones provides additional information for the inversion. Then, the concentration measurements from multiple wells can be used simultaneously to solve the inversion problem.

**TESTING AND APPLICATION OF THE NEW INVERSION APPROACH**

The new inversion approach was first tested by inverting numerically simulated concentration time series at pumping wells within a given contaminant plume. A good agreement between the inversion results and the given plume was observed.

The new investigation method was also applied in the field at an abandoned landfill site near Heidelberg in the Rhine Valley in Germany. At this site, the groundwater within the porous aquifer of 15 m thickness is contaminated mainly with TCE. A total of six pumping wells, each with a pumping rate of 3.0 \( l \) s\(^{-1}\), were
positioned along a control plane of 180 m length. The wells were operated in two consecutive campaigns (each one with three active wells and a duration of 14 days) to cover the whole contaminant plume downstream of the landfill. Groundwater pollutant concentrations were measured at each of the pumping wells with sampling intervals allowing a spatial resolution of about 0.5 m along the control plane.

From the numerical inversion of the concentration time series, the average TCE concentration results to $6.0 \, \mu g \, l^{-1}$, and the total TCE flux is $2.5 \, g \, day^{-1}$. The respective maximum acceptable contamination levels are $10 \, \mu g \, l^{-1}$ and $20 \, g \, day^{-1}$, i.e. at present the site does not need to be cleaned up.

CONCLUSION

The new investigation approach yields a quick and accurate estimation of the average contaminant concentration and of the concentration distribution along a control plane as well as of the total contaminant mass flux downstream of a pollutant source. It is therefore a quick and cost-efficient tool for the investigation of groundwater contamination.

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