Comparing Approaches to Locating Boreholes in Spatially Heterogeneous Aquifers

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Abstract

Limited sampling of an aquifer downgradient of closed environmental sites results in uncertainty in the spatial distribution of aquifer properties. This spatial uncertainty causes uncertainty in the migration pathway of any contaminants that might leak from the closed site. Techniques for locating samples that can provide the greatest reduction in uncertainty with respect to contaminant migration from the closed site must be developed. Two different techniques are examined: a traditional method based on minimizing the kriging variance and a new method based on the sensitivity of simulated contaminant releases from the closed site to the hydraulic conductivity at every location in the aquifer. The second method considers the correlation of different performance measures to the hydraulic conductivity at every location. Those locations with the highest correlation to the transport results are targeted for additional samples. An example problem from a hypothetical aquifer allows for demonstration and comparison of the two techniques. In general, the sensitivity analysis approach produces the greatest reduction in the uncertainty of the performance metrics; however, the differences between the two techniques are minimal for this example.

Introduction

As contaminated sites in the United States are remediated and closed, it is necessary for a long-term stewardship program to predict the future risk that these sites may pose. These risks are framed in terms of regulatory thresholds determined by regulatory and stakeholder organizations. Calculated performance measures can be compared against these thresholds. Any reduction in the uncertainty of the future performance of the remediated site and the geologic environment to meet these performance measures will lend confidence to the long-term stewardship program.

A new approach to locating characterization boreholes is presented herein. This new approach is based on a sensitivity analysis using the Spearman rank-correlation coefficient. This new approach is compared to a traditional method based on minimizing the kriging variance.

Approach

The approach employed in this study considers the $\log_{10}$ hydraulic conductivity (K) of an aquifer to be a multiGaussian spatial random function. At every location, the uncertainty in the K value can be defined by a Gaussian distribution conditional to surrounding data points. Geostatistical simulation is used to create multiple equally probable realizations of the hydraulic conductivity field, each of which is conditioned to the available data. Steady-state groundwater flow and advective transport, from a source to a regulatory boundary, are simulated through each realization of K. Values of the fifth percentile arrival time, the median arrival time and the residence time (defined as the 95^{th} minus the 5^{th} arrival time) are defined as the performance measures and are calculated on each realization.

In the sensitivity-analysis approach, each simulated transmissivity value is considered as a stochastic input parameter to the flow and transport solution. Each simulated value of K at each location in the aquifer is compared to the three transport performance measures to determine the correlation between K and the performance measure. The strength of the correlation for each K value is then mapped and regions of high correlation are targeted for additional characterization boreholes. The calculation of correlation between K and *each* performance metric allows for acquiring additional information in areas that are strongly related to the specific performance metric being addressed. In comparison, the traditional technique of reducing estimation variance does not take into account the transport performance metric and only creates a "one-size-fits-all" sampling pattern.

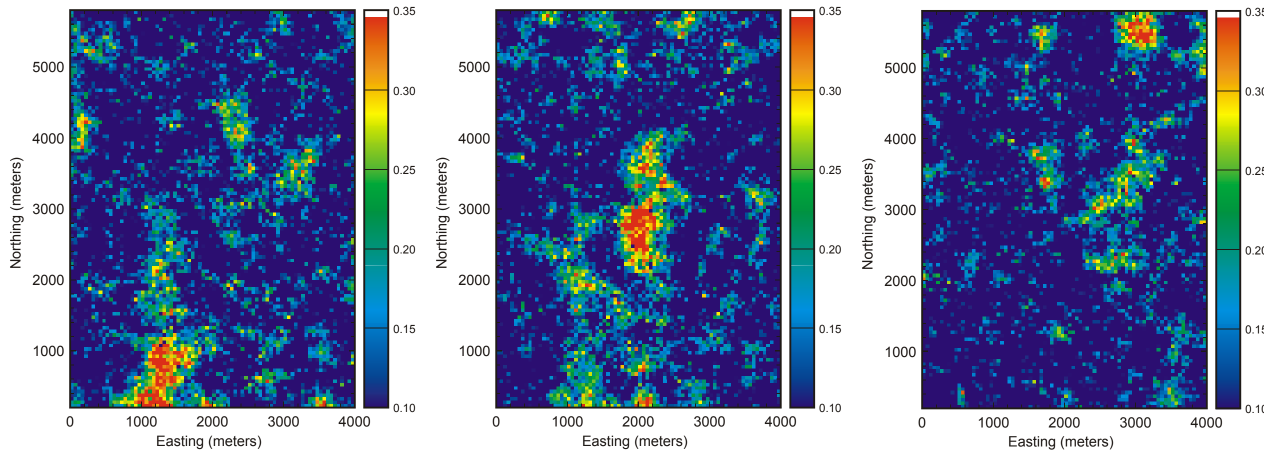
An example problem of a contaminant source in a spatially heterogeneous aquifer is used to demonstrate an approach to optimally locating additional boreholes. For this example problem, 89 hydraulic conductivity measurements are available in the 5.0 x 5.6 km area. The kriging variance and sensitivity-analysis approaches are employed on the example problem to determine the optimal locations for 10 additional monitoring wells. The reduction in the uncertainty of the transport results due to the ten additional monitoring wells is compared across the two approaches.

Results

Maps of the Spearman rank correlation coefficient and the kriging variance are shown in Figure 1. Note that the sensitivity analysis technique only uses the absolute magnitude of the correlation, and therefore only the absolute values of the correlation coefficient are shown. Areas where the K is strongly correlated to the performance metric are targeted for additional sampling. The SA technique produces maps with significantly different areas targeted for additional sampling depending on the performance measure considered. In contrast there is only one kriging variance map.

Ten additional samples of K were obtained from the aquifer based on each of the different maps in Figure 1. For each new sample set, an additional 100 realizations of the K field were created and flow and transport were simulated through each K field. These resulting distributions of the performance metrics are compared to each other and to those simulated on the original set of K fields as well as with the true value of the performance metric.

The distributions of the three performance metrics obtained through sensitivity analysis and kriging-variance-based sampling are compared to the distributions obtained from the original 89 data in Figure 2. Additionally, these results are also compared to the true result for each performance measure. All distributions are accurate, they capture the true value, and with the exception of the residence-time metric, the additional samples, reduce the uncertainty in the estimates of the performance metrics. For this example, there is not a significant difference in the distributions of the performance metrics between the sensitivity-analysis and kriging-variance based sampling schemes.



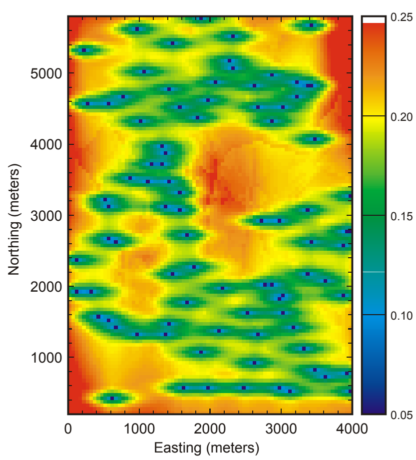


Figure 1. Top images are maps of rank correlation coefficient between K and each performance measure: fifth percentile time (left), median travel time (middle) and residence time (right). Left image is the kriging variance for the same domain.

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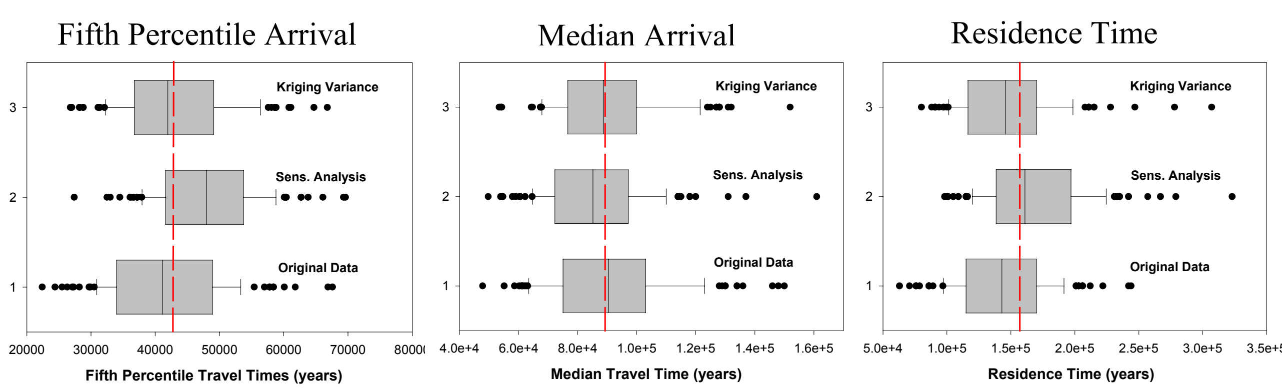

Figure 2. Box and whisker plots of the distributions of the three performance measures as determined from the original sample data, the sample data based on the sensitivity-analysis approach and the sample data based on the kriging variance approach. The boxes show the 25th, 50th and 75th percentile results and the whiskers denote the 5th and 95th percentile results. The vertical red line indicates the actual value of each performance metric.