Using Ground-Water Modeling to Determine Flow Paths and Rates in Fractured Rocks: Implications for Designing and Monitoring Remediation [SERDP ER-1555]

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Abstract

- In fractured-rock aquifers, extreme contrasts in hydraulic conductivity can produce convoluted flow paths and highly variable flow rates. Designing and monitoring effective remediation strategies requires an understanding of these flow paths and rates. For example, for bioaugmentation, the flow regime at an injection well and in the surrounding rock mass are important controls on the distribution of amendments and the efficacy of remediation.

- The U.S. Geological Survey, with the support of SERDP (ER-1555) and the U.S. Navy, is evaluating the remediation of TCE, DCE, and vinyl chloride by pump-and-treat, natural attenuation, and bioaugmentation in fractured mudstones underlying the former Naval Air Warfare Center (NAWC) in West Trenton, NJ. Site-scale groundwater-flow modeling is an important component of this research, because estimated flow paths and rates provide constraints on remediation models and help guide remediation monitoring strategies.

- The NAWC site-scale flow model is developed using results from aquifer tests in combination with a detailed subsurface geologic framework. The model is calibrated to water-level changes during the aquifer tests as well as to hydraulic heads measured during a different time period.

- The model shows that the simulated contribution of flow to a pumping well from an area surrounding a bioaugmentation injection well is much smaller than the contribution from other areas. This indicates that injected amendments and geochemical constituents from the bioaugmented area will be substantially diluted in the pumped water and therefore will be difficult to monitor remediation progress using data from the pumping well.

- The results underscore the importance of using wells between the injection and pumping wells to monitor the effects of the bioaugmentation.

**Aquifer Testing to Identify Hydraulic Connections**

- Short-term aquifer tests were conducted by taking advantage of the pumping & treat system at NAWC. Tests involved temporarily turning off the pumps in individual wells of the system.
- The process of turning a pump off and on again was repeated for each of 7 pumping wells. Water levels were recorded in 40 monitor wells open to a range of depths and mudstone beds.
- Aquifer test data provide information about the presence or absence of hydraulic connections between open intervals of wells. When combined with geologic information, the data show which dipping beds act as flow paths or as flow barriers.
- For example, results show mudstone beds '233' and '301' serve as flow paths, water levels in wells open to bed '233' rise rapidly when the pump is turned off in 15BR or 45BR, and water levels in wells open to bed '301' rise rapidly when the pump is off in 56BR.

**Conclusion**

- The aquifer tests and geologic framework are used to guide the representation of heterogeneity in a MODFLOW model that simulates site-scale ground-water flow.
- Aquifer test data show that 6 fractured mudstone beds have high hydraulic conductivity (K) over distances up to 100 m, and that K decreases with depth in these beds.
- The high-K beds are represented as thin inclined layers surrounded by low-K beds. Overlying horizontal layers represent low-K and weathered rocks.

- The model is calibrated, using inverse methods, to water levels from the aquifer tests and hydraulic heads under conditions of all wells pumping. A low K zone in bed '233' (see below) is needed to produce a good fit; tracer and slug test data support the presence of this zone.

- The model yields a good fit to most calibration data, and parameter estimates are reasonable.

**CONCLUSIONS**

- Powerful combination of aquifer test data and geologic framework's results and calibration of a realistic site-scale flow model.

**Importance of Flow Model to Simulations of Contaminant Transport & Remediation**

- Contaminant transport and biodegradation are being simulated in an area where bioaugmentation has been implemented (see posters by Hsieh et al. and Curtis et al.). Because of their computational requirements, these models cannot simulate transport over the full 3D domain of the flow model.
- The K distribution and ground-water fluxes estimated by the site-scale flow model are used to guide the design of the transport models, so that these models can realistically simulate ground-water flow directions and rates.

**Estimation of Ground-Water Fluxes in Bioaugmented Dipping Mudstone Bed '233'**

- **Estimated K Distribution in Bioaugmented Dipping Mudstone Bed '233'**
  - Bioaugmented Dipping Mudstone Bed '233' has high hydraulic conductivity (K) over distances up to 100 m, and that K decreases with depth in these beds.
  - The high-K beds are represented as thin inclined layers surrounded by low-K beds. Overlying horizontal layers represent low-K and weathered rocks.
  - The model is calibrated, using inverse methods, to water levels from the aquifer tests and hydraulic heads under conditions of all wells pumping. A low K zone in bed '233' (see below) is needed to produce a good fit; tracer and slug test data support the presence of this zone.
  - The model yields a good fit to most calibration data, and parameter estimates are reasonable.

**Implications of Site-Scale Flow Modeling Results for Remediation Monitoring**

- Estimated fluxes in the bioaugmented mudstone bed show that only a small fraction of the water pumped from 15BR comes from the injection well zone. This is consistent with a tracer test from 36BR to 15BR showing very large dilution at 15BR (see poster by Shapiro et al.).
- **Estimation of Ground-Water Fluxes in Bioaugmented Dipping Mudstone Bed '233'**
  - Estimated fluxes in the bioaugmented mudstone bed show that only a small fraction of the water pumped from 15BR comes from the injection well zone. This is consistent with a tracer test from 36BR to 15BR showing very large dilution at 15BR (see poster by Shapiro et al.).
  - Because of this large dilution, changes in VOC concentrations, microbiology, and geochemistry caused by the bioaugmentation might not be detected in water samples from 15BR.
  - To effectively monitor the effects of the bioaugmentation, it is therefore important to sample the three wells that lie between 15BR and 36BR.

**CONCLUSIONS**

- Site-scale ground-water flow modeling provides important constraints on K and fluxes that help guide:
  1. the design of contaminant transport and bioaugmentation models, and (2) remediation monitoring strategies.