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Large-scale spatial trends in hydraulic conductivity

By identifying large-scale spatial trends in hydraulic conductivity, researchers attempt to determine how such trends influence contaminant transport. Some scientists believe that large-scale hydraulic conductivity trends control groundwater and contaminant movement. To test this idea, Eggleston and Rojstaczer (1998) analyzed field data from an aquifer at the Columbus Air Force Base, Mississippi, that had many sediment core samples and extensive flowmeter measurements of hydraulic conductivity. Researchers based their study on more than 2,400 flowmeter measurements.

Hydraulic conductivity is highly variable in most alluvial aquifers, varying at some sites by six orders of magnitude over a distance of less than 10 m. In terms of subsurface modeling, modelers assume "that hydraulic conductivity K variations on a large scale control advective transport and hydraulic conductivity variations on a small spatial scale control dispersive transport. **The exact definitions of 'large scale' and 'small scale' can vary depending on the density of measured data and the amount of natural heterogeneity present.** Although some studies assume that hydraulic conductivity varies on two scales, large and small, others assume that it varies on multiple scales or on a continuous hierarchy of scales. In the terminology of geostatistics, hydraulic conductivity variations that have a spatial scale large enough to be described in at least a roughly deterministic manner are known as 'trends' or 'drift'; smaller-scale variations, which can be described statistically because of limited data, are known as 'residuals.'"

Eggleston and Rojstaczer examined the ability "to accurately describe large-scale spatial variations in hydraulic conductivity found in a heterogeneous alluvial aquifer. . . more importantly, they examined the influence of the inferred large-scale trends on solute transport." Their effort consisted of

- using traditional geostatistics, treating hydraulic conductivity as a correlated random field; they assumed that nonstationary variations or trends followed a continuous function, usually a linear function or low-order polynomial function
- assuming that large-scale spatial variation of subsurface hydrologic variables was controlled by geologic architecture and hydraulic conductivity

Site description

Analysis of sediment cores and of more than 2,400 flow-meter measurements indicated a Pleistocene aquifer with the following characteristics:

- a shallow (<15 m) depth
- composition of sand and gravel
- several meters of silt and clay, the unsaturated zone, overlying the aquifer
- a mean $\ln K$ of -5.4 cm/sec calculated from 2,451 flowmeter measurements
- heterogeneity with textural variations from centimeters to hundreds of meters
- a center field appearing to have a region of higher hydraulic conductivity
- a nonstationary hydraulic conductivity field as suggested by injection of a bromide tracer
- sediment texture varying with depth, suggesting vertical trends in hydraulic conductivity

Defining trends

"Because the true hydraulic conductivity field is unknown, except for scattered local measurements, large-scale trend values must be estimated. In the hydrologic literature, there is **no consensus** on the best approach for identifying large-scale trends. This uncertainty is due perhaps to wide variability in aquifer conditions and the lack of extensive field data for evaluating different methods. More likely, the uncertainty is due to the inherent difficulty of defining the difference between small-scale and large-scale spatial variations" (Eggleston and Rojstaczer, 1998).

Researchers used three methods to define large-scale trends:

- polynomial regression
- distributed parameter Kalman filtering
- hydrofacies delineation

These methods are described in detail in the text of their paper. Each method produces a three-dimensional field of hydraulic conductivity. Researchers then input the derived hydraulic conductivity values into a groundwater model to examine the parameter's effect on groundwater flow and contaminant transport.

Results and conclusions

Eggleston and Rojstaczer found "significant differences between the hydraulic conductivity fields estimated by the three detrending methods, both in spatial variability and effect on transport. These differences underscore the difficulty of identifying hydraulic conductivity trends in heterogeneous aquifers. Even with nearly **2,500 hydraulic conductivity measurements**, it is not possible to unambiguously identify large-scale signals controlling advective transport at the Columbus Air Force site."

"The difficulty in trend identification complicates the use of stochastic equations designed to predict macrodispersion because such equations require a stationary hydraulic conductivity field." If it is not possible to identify and remove major trends, even with a huge quantity of subsurface data, then the equations' assumptions cannot be met. "The results further indicate that even after removing large-scale trends using common methods, hydraulic conductivity variability that remains can produce a non-stationary velocity field. **Small-scale hydraulic conductivity variations that fly under the radar or trend identification methods appear to have significant control over the nonstationary advective plume behavior**" (*Eggleston and Rojstaczer, 1998*).

In addition, the transport simulations do not accurately recreate the bromide plume's (see below) non-Gaussian advection. The difference between simulated and actual advective bromide transport is potentially attributable to several factors:

- failure of the trend estimation methods to capture the aquifer's large-scale trends
- incorrect assignment of model variable to model parameters other than hydraulic conductivity
- local-scale hydraulic conductivity variations exerting significant control over actual plume behavior

Bromide tracer test

The bromide test was performed between October 1986 and June 1988. Samples taken on days 9, 49, 126, 202, 279, 370 and 503 indicated a non-stationary flow field. After 505 days, scientists found that the peak bromide concentration had moved less than 10 m. Dilute bromide concentrations, however, appeared 170 m (over 550 feet) from the injection well. Although the rate of 10 m/yr is slow and predictable, 170 m/yr is neither slow nor predictable in terms of plume delineation and capture. If the chemical under investigation had been a carcinogen such as benzene, even low concentrations would have been a cause for concern.

All of the detrending methods produce fields that, like the measured flowmeter values, have hydraulic conductivity increasing north of the injection well (west to east) and with elevation; thus, it is reasonable to conclude that the methods capture at least the most obvious large-scale patterns of hydraulic conductivity variation. "The question of whether transport model parameters other than hydraulic conductivity are assigned incorrectly is more difficult to answer because of the wide variety of potentially important differences between the actual groundwater system and the model system. The seasonal variability of the natural system is ignored in the transport model, but boundary conditions and recharge were

chosen to reflect average conditions, and the transport time of 503 days is long enough to average some of the seasonal variability. Although the temporal variability in heads may have a significant effect on dispersive transport, its effect on advective transport should not be large compared to the effect of large-scale hydraulic conductivity variability. The porosity and retardation coefficient are best estimate values from Adams and Gelhar and Havey (references can be found in *Eggleston and Rojstaczer, 1998*) and should have spatial variability that is insignificant relative to hydraulic conductivity variability. Although these model parameters may not be assigned correctly, it would be difficult to conceive of reasonable changes to them that would allow the simulated bromide plumes to mimic the strong non-Gaussian behavior seen in the actual plume."

"The differences between simulated and actual plumes are therefore probably caused by hydraulic conductivity variations below the scale of flowmeter measurements ($\sim 10^1$ m) that exert significant control over observed plume behavior. Fine-scale layering (10^{-2} to 10^{-1} m thickness) is present in the aquifer sediments, and evidence of fine-scale hydraulic conductivity variations controlling advective behavior is given by the transport simulation in the kriged field."

"Without identifying the hydraulic conductivity patterns controlling advective transport, it is not possible to make accurate predictions of transport. Our results suggest that at the Columbus site, small-scale (<10 m) hydraulic conductivity structures have significant control over bulk transport. Examination of the sediment facies may provide useful information for improving predictions of transport. In heterogeneous alluvial aquifers, prediction of non-Gaussian transport behavior, if it is predictable at all, will apparently **require knowledge of fine-scale hydraulic conductivity structures**" (*Eggleston and Rojstaczer, 1998*).

Related study of conductivity and porosity

Hassan, Cushman and Delleur (*1998*) explored conductivity and porosity in terms of how the two influence flow and transport processes. They performed "numerical simulations using the Monte Carlo method to solve flow and transport equations . . ." Results indicated that for a plume, a "positive cross-correlation between the porosity and the conductivity decreases dispersion, while a negative correlation tends to increase dispersion in the lateral direction. For transport in heterogeneous media, the geochemical variability alone yields results that are significantly different than when both geochemistry and porosity are random space variables correlated to the conductivity field." These results suggest that a greater examination of porosity variability and its correlation to the conductivity in transport theories is warranted.

Related study of measured hydraulic conductivity

In another study, Silliman and Caswell (1998) subjected two artificial confined aquifers to steady-state pumping tests. Twenty-five observation points provided estimates of hydraulic conductivity, while 87 observation points gave data for numerical experiments. From experiments performed, Silliman and Caswell concluded the following:

- the distribution of hydraulic head and the distribution of estimated conductivities as observed in the laboratory can be reproduced numerically, implying that the experimental error involved in the experiments is relatively insignificant
- the estimated conductivity for the random medium converged, at large distance from the pumping well, to the conductivity predicted from perturbation theory for mean uniform flow in a random porous medium
- in contrast, the estimated conductivity for the structured medium converged at large distance from the pumping well to a conductivity between the geometric and harmonic mean of the medium
- for both types of media (structured and random) the results support work by other authors in illustrating that the **estimated conductivity varies with distance from the well**; estimated conductivity approaches an asymptotic limit when the average distance between the piezometers and the pumping well is of the order of several integral scales

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Land treatment of contaminated soils and sludge

Researchers in Massachusetts who treated contaminated sludge and soils at a Superfund site wanted to determine if the native soil would be a suitable, permeable barrier for land-treated contaminants. Usually a liner/leachate circulation system is used to prevent groundwater contamination.

Site description

Within the Iron Horse Park Superfund Site, Billerica, Massachusetts, is a 15-acre area that contains unlined lagoons and materials dredged from lagoons over the past 80 years. Wastewater containing industrial solvents, lubricating and motor oils, inorganic and organic wastes were pumped into the lagoons. Many of the piles of dredged materials around the lagoons had become overgrown with a mixed hardwood and softwood forest. Results of a site investigation determined that the lagoon sludge and soil piles were contaminated with volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and petroleum hydrocarbons (PHCs). U.S. EPA's Record of Decision stipulated bioremediation in a land treatment cell with an impervious liner. Wiseman and Baker (1992) performed the pre-design evaluation, which included

- delineating the horizontal and vertical extent of contamination in the lagoon sludge and soil piles, and the associated volume of materials requiring treatment
- using bench-scale biotreatability studies to investigate the optimal levels of nutrients and moisture for stimulation of indigenous microbial populations
- identifying suitable locations for land treatment cells

Sampling and modeling

First, researchers conducted a test pit investigation beneath the areas under consideration for treatment cell construction. These wooded areas, formerly farmlands, were adjacent to the lagoons and dredged piles. Workers obtained undisturbed soil cores from distinct soil horizons and submitted them for chemical and physical analyses. These data were then used as input variables for a screening-level analysis to predict contaminant migration potential to groundwater.

Researchers used the model, Chemical Movement in Layered Soils (CMLS), to predict peak concentrations of non-polar organics subject to water movement under natural hydraulic gradients. Applicable to soils with multiple horizons, the model allows different soil properties to be used as input parameters for each horizon. CMLS assumes linear, reversible equilibrium adsorption of non-polar compounds to soil organic matter. It also assumes that any infiltrating water

undergoes instantaneous redistribution to field capacity, which is moisture content at 0.1 bar matric potential. Although this assumption fails for fine-textured soils, it is appropriate for the coarse-textured, sandy soils derived from the glacial outwash found beneath the cells there. A recent field validation indicated that CMLS could provide satisfactory predictions of solute leaching and dissipation of non-polar organics in the unsaturated zone of a similar sandy soil. The soils of that study site and those observed at Iron Horse Park were both classified in the same taxonomic suborder, "Psamments."

Researchers obtained model parameters from the following:

- a local weather station, for climatic data
- the literature, for contaminant properties (see Table 1)
- measured undisturbed soil cores, for treatment cell properties; workers obtained samples from the shallowest soil horizons and the most transmissive soils to use as conservative model inputs; the lowest values of soil organic carbon for each horizon were adopted as input parameters (see Table 2)

Contaminant	K _{oc} (mg/L organic carbon)	T _{1/2} (days)
Bromide (tracer)	0	999999
Benzene	65	6
Fluoroanthene	38019	377

Table 1. Properties of contaminants input to CMLS model. K_{oc} is the organic carbon partitioning coefficient; T_{1/2} is the biodegradation half-life (from Wiseman and Baker, 1992).

Horizon	Depth (in.)	Organic carbon (%)	Bulk density (g/cm ³)	Volumetric Water Content		
				Saturation	-0.01 MPa	-1.5 MPa
Soil/sludge lift	12-0	2.0	0.99	56.2	29.2	21.4
Ap1	0-3	6.5	0.39	80.4	33.0	19.8
Ap2	3-7	1.2	0.98	60.0	17.8	9.0
Bw	7-26	0.5	1.31	54.9	19.0	11.0
C	26-150 ^a	0.0	1.24	57.3	10.1	6.3

^a Depth of water table

Table 2. Input parameters to CMLS model. Measured volumetric water contents at -0.01MPa and -1.5 MPa correspond to the soils' field capacity and wilting point, respectively (from Wiseman and Baker, 1992).

Modelers selected benzene, a relatively mobile and non-refractory aromatic, to represent the site's petroleum hydrocarbons with the greatest potential risk to groundwater; they also selected fluoroanthene to represent the site's immobile

and refractory multi-ring PAHs (see Table 1). Bromide was the conservative solute. Modelers ran simulations:

- assuming the indicator compounds were applied entirely at the bottom of a 12-inch layer of contaminated soil placed upon the treatment cell soil profile
- assuming two successive one-year treatment periods during which the treatment cell remained uncovered, an assumption that would likely maximize vertical contaminant movement
- considering winter precipitation as equivalent to rainfall with no storage as snow and subsequent release as snowmelt
- using the Thornthwaite and Mather water balance method for soil evaporation (see Wiseman and Baker, 1992)

Treatment cell construction and monitoring

After identifying an acceptable treatment area (size, depth to water table and bedrock, suitable soil properties), workers installed monitoring wells and lysimeters, although modeling had predicted that little contamination would migrate beyond the treatment cell.

After workers collected site samples (to determine background pore-water concentrations), the one-acre treatment cell was cleared of trees and brush. Then workers spread a thin layer of clean sand over the topsoil to protect the topsoil from disturbance and ensure a continuous, organic-rich layer beneath the treatment area. Next, workers placed on the treatment cell a layer of contaminated soil, a "lift" approximately 9 inches deep obtained from the contaminated piles. Workers rototilled and fertilized the lift to enhance microbial activity. Soil samples were collected biweekly at random locations and analyzed for total PHCs, PAHs and linear alkane to isoprenoid ratios, which was the stipulated treatment criteria. Workers also monitored soil moisture level.

Modeling results

In the model simulations, bromide, the conservative solute, traveled unimpeded through the soil with the advancing infiltration front. Because fluoroanthene was strongly bound to the organic carbon fractions of the contaminated soil layer, no migration was predicted. Some fluoroanthene degradation was predicted, thereby reducing its concentration within this layer over time. Conversely, the more mobile indicator compound, benzene, migrated downward appreciably but was retarded so strongly within the native soil A horizon (due to a combination of sorption and degradation) that the predicted concentration reaching the water table was approximately one-millionth of 1 µg/L. Thus, the conservative model predicted that the organic-rich topsoil would significantly attenuate contaminant flow from the treatment cell.

Monitoring

Analysis of soil water collected by lysimeters beneath the full-scale treatment cell indicated these contaminants:

- acetone, which was used to cleanse the lysimeters
- esters of dicarboxylic acids, which originated from an epoxy glue on the lysimeters
- elevated nitrate-nitrogen

The nitrate nitrogen fertilizer from the treatment cell reached the lysimeter while the non-polar organic contaminants, as predicted, did not. To prevent leaching of this nitrate-nitrogen, researchers shifted to using a slow-release fertilizer. Comparison between samples prior to and subsequent to cell treatment construction suggests contamination was not reaching groundwater. Thus, researchers were able to use a permeable barrier consisting of native topsoil rather than a liner to contain any potential contamination. Results indicate PAHs were initially below the analytical detection limit (1.0 ppm). PHCs were reduced approximately 20 percent from their initial concentration of 1,450 mg/kg soil. Variability in TPH concentrations in the first sampling round indicated that nearly 20 samples would be required in the second round given the same variability. To reduce the sample variability, researchers considered mixing the soil using a front-end loader prior to placement of the next lift of contaminated soil onto the treatment cell. In addition, designated sample locations could be established to minimize the sample variation from one sampling event to the next.

The three soil/sludge lifts were eventually treated within the land treatment cell and achieved the stipulated remedial goals (*Baker and others, 1993*). Because the PHCs were relatively recalcitrant (although they had undergone some natural attenuation), remediators decided to treat the remaining contaminated soils with asphalt batching.

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UTTU thanks Dr. Ralph Baker, ENSR, <http://www.ensr.com>, for his help on this article.



Petroleum hydrocarbon fingerprinting

Hydrocarbon characterization by fingerprinting can help remediators identify the source or type of petroleum hydrocarbon contaminants at a site. The technique uses a capillary gas chromatograph (GC). Hydrocarbons elute from the GC column at characteristic times and form peaks on a chromatogram. Laboratory workers compare these chromatograms with chromatograms of known hydrocarbon mixtures. The visual process is qualitative and subjective in that it depends on the interpreter's skill. Wigger and others (1998) recently established a more quantitative and less subjective approach to hydrocarbon fingerprinting, which this article describes.

Background

Petroleum hydrocarbons, consisting primarily of hydrogen and carbon, contain a large number of compounds that fall into three major groups:

- alkanes
- alkenes
- aromatics

Alkanes, a major constituent of crude oil, are also found in refined petroleum products such as gasoline, kerosene, diesel fuel and heating oil. The three major classes of alkanes are

- linear alkanes, which have carbon atoms arranged in a line; thus, the molecules have only two ends
- branched alkanes, or isoparaffins, which have carbon atoms branching off the main carbon chain, creating many configurations
- naphthenes, whose carbon atoms are arranged in one or more rings

Alkenes, or olefins, are molecules with one or more carbon-to-carbon double bonds. Double-bonded molecules are more reactive than single-bonded molecules such as alkanes.

Aromatics contain one or more carbon rings (six carbons to a ring) with three of the carbons joined by double bonds. One-ring mononuclear aromatics include benzene, toluene, ethylbenzene and xylene (BTEX). Multiple-ring aromatics—polynuclear compounds—contain multiple six-carbon ring molecules and include naphthalene, anthracene and pyrene.

Refining and distilling crude oil produces hydrocarbon products such as gasoline, diesel fuel and asphalts. "Each product is produced by the combination of multiple individual hydrocarbon compounds, all of which have slightly different vaporization and boiling temperatures. For example, gasoline is the combination of many lower boiling range compounds, including C₄ to C₁₂ alkanes, C₄ to C₇ alkenes, and the

aromatics BTEX. The middle boiling range compounds are used in differing proportions to create products such as kerosene, diesel and heating oil. These products predominantly contain C₁₀ to C₂₄ alkanes and polynuclear aromatics with few to no olefins" (*Wigger and others, 1998*).

Gas chromatography

Workers wishing to identify which hydrocarbons exist in a particular sample can inject a small amount of the sample into the gas chromatograph. The sample is heated, vaporized, and carried by inert gas into a column. An attached flame ionization detector detects the sample's components as they elute. The intensity of the response of the flame ionization detector to each component that elutes depends on the temperature programmed, column length and characteristics, and compound characteristics.

Wigger and others (*1998*) created chromatograms representing the following products:

- gasoline (22 chromatograms)
- distillates (5 chromatograms)
- refinery intermediates (17 chromatograms)
- miscellaneous (2 chromatograms of lubricating oils, mineral spirits, and non-chlorinated solvents)
- crudes and gas condensates (4 chromatograms)

Additional details on the methods and materials used to create the chromatograms are described in their paper. Researchers also established a method to calculate a correlation coefficient between any one of the created chromatograms and a chromatogram from an unknown. A correlation coefficient measures the relationship between two data sets. In this study, researchers examined 89 specific hydrocarbon chromatogram peaks representing compounds such as n-alkanes, olefins, iso-alkanes, naphthenes, isoprenoids, aromatics, polynuclear aromatics and oxygenates. They measured and tabulated integrated peak areas for each of the known hydrocarbon samples. "Once the peak area data were collected and tabulated for all hydrocarbon samples, the data were electronically stored in a database for easy retrieval and rapid numerical comparison to other unknown products that would arrive (*Wigger and others, 1998*)."

Case study

Wigger and others (*1998*) used this chromatogram comparison technique at a refinery process unit to monitor the facility's perimeter. A typical reforming unit at a refinery uses naphtha and converts it to a higher octane stream rich in aromatics. Reformate streams can be split into lighter and heavier fractions, as well as a combined or total reformate stream. Each stream has its own characteristics. Chromatograms were created using samples from the facility and compared to the previously tabulated known chromatograms. "As more samples were collected and analyzed, visual characterization, differentiation and quantification of the degree of difference or similarity of the chromatograms

became difficult. The correlation coefficient data were calculated and used extensively to elucidate subtle differences and similarities in the chromatograms, providing a repeatable, quantifiable measure."

Although the researchers maintained that the correlation coefficient was helpful in quantifying some similarities and differences among samples, other comparisons suggested the technique must be used in conjunction with visual analysis. For instance, a synthetic chromatogram of reformate and naphtha produced a high correlation coefficient, 0.92; however, visual inspection showed several significant differences between the two.

Conclusions

Researchers concluded that for analyses of chromatographic data:

- the standard approach used all 89 peaks in evaluating the data with the correlation coefficient; this worked acceptably, even for samples with few peaks in the heavy end range
- a focused data set, including peaks only in the range of interest, should be chosen
- in this study, correlation coefficients greater than 0.9 indicated a very high degree of fit between two samples; conversely, correlation coefficients less than 0.9 seemed to indicate the need for additional effort in locating a better fitting standard; however, individual interpretation of what constituted a good visual fit could vary
- the numerical techniques provided significant assistance in comparing chromatograms to identify trends in composition and to identify probable sources

Reference

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UTTU thanks John Wigger, Environmental Liability Management Inc., Tulsa, Oklahoma, for his help on this article.

In addition, members of the Groundwater Discussion Group (<http://www.groundwater.com>) discussed limitations and successes of age dating of petroleum releases. See Volume 1, No. 1083, December 1998.



Recommendations concerning California's drinking water

California's Bureau of State Audit recently released a report, "California's Drinking Water: State and Local Agencies Need to Provide Leadership to Address Contamination of Groundwater by Gasoline Components and Additives." The summary of that report, which consists of conclusions, recommendations and agency comments, is presented here. The conclusions and recommendations may have far-reaching effects not only in California but in other states as well.

Conclusions

Although the State of California has ample evidence that gasoline leaking from USTs is jeopardizing the safety of our drinking water supplies, the state has not acted quickly and decisively to address this potential health hazard. The scientific community and the public are particularly concerned about leaking storage tanks and methyl tertiary-butyl ether (MTBE) contaminating numerous groundwater sites and some drinking-water wells. MTBE is a gasoline additive that reduces air pollution from automobile exhaust; at the same time, the federal government has classified MTBE as a possible cancer-causing agent.

State legislation directs various state and local agencies to oversee the safety of California's drinking water. These agencies include the Department of Health Services (Health Services), the State Water Resources Control Board (state board), the California Environmental Protection Agency (California EPA), and nine Regional Water Quality Control Boards (regional boards). As early as 1990, Health Services officials became aware that MTBE was contaminating drinking-water wells within California; however, Health Services did not establish regulations to test for MTBE in drinking water until 1997, nor did it adopt interim emergency regulations although it had the authority to do so. The state board also shares responsibility for not providing leadership to the regional boards and local agencies responsible for alleviating groundwater contamination: the state board has not yet issued specific guidelines or standardized procedures for cleaning up MTBE. Thus, high MTBE levels at some contaminated groundwater sites pose potential threats to nearby drinking-water wells.

Moreover, the state's process for regulating the safety of water sources, and especially for ensuring that gasoline does not contaminate drinking-water sources, has multiple shortcomings:

- the state has been inconsistent in its efforts to identify and clean up releases from LUSTs
- the California EPA's approach for overseeing the local agencies, who are responsible for issuing permits to storage tank operators and for monitoring USTs, has not identified all UST leaks and deficiencies
- Health Services needs to improve its procedures for obtaining sample analyses; public water systems must submit laboratory results promptly so that agencies can identify and quickly alleviate contamination

To further compound the problems concerning MTBE contamination, Health Services and the state/regional boards have failed to ascertain that public water operators, storage tank owners/operators and regulatory agencies are detecting and cleaning up contamination. Not only does the state ineffectively regulate USTs, it has failed in some instances to aggressively enforce the state's Safe Drinking Water Act and the laws governing USTs. Specifically, Health Services, the regional boards, and local agencies have not adequately

- enforced laws that require prompt follow-up monitoring for contamination
- notified the public about contaminants found in drinking water
- managed the complete cleanup of groundwater contamination

Some regulatory problems arise from poor communication among various state and local agencies. For instance, both Health Services and the state board are implementing GIS (geographical information systems), the state's proposed solution for assessing contamination risks to drinking-water sources, as well as for relaying information about these risks to responsible agencies. This duplication of effort could be unnecessarily costly to the state. Health Services should serve as the lead developer for the GIS because it can use the system to evaluate risks to the state's approximately 16,000 drinking-water sources and thus accomplish the goals of the federally mandated Drinking Water Source Assessment and Protection Program. Finally, neither agency can effectively implement a GIS until the state significantly improves the databases containing information on possible contamination sources.

Recommendations

To ensure that California's drinking water is safe from contamination by gasoline leaking from USTs, the California EPA and the Health and Welfare Agency, which oversees Health Services, need to make certain that state, regional, and local agencies fulfill their designated responsibilities and improve their policies and procedures as follows.

The California Environmental Protection Agency

needs to take the following steps to locate leaking USTs:

- ensure that local agencies increase their efforts to identify storage tanks without permits, issue permits as appropriate, monitor storage tank safety and penalize owners or operators who delay reporting leaks
- modify its existing procedures for evaluating local agencies' adherence to program requirements for leaking storage tanks by requiring its own evaluators to review these cases

The Department of Health Services needs to do the following to manage threats to drinking-water systems:

- strengthen its process for promptly obtaining and analyzing laboratory results from all public water systems so it can quickly notify other agencies of threats to drinking water
- ensure that it assess the safety of drinking-water sources for public water systems at least once every three years, as required by state regulations
- consistently enforce the state's water quality laws by following up on corrective actions taken by the district offices and local agencies
- take the lead in establishing a geographical information system (GIS) that will fulfill requirements for the federally mandated Drinking Water Source Assessment Protection Program, help the state monitor risks to drinking-water sources, and allow for state and local agencies to exchange accurate information about these risks

The State Water Resources Control Board should act on the following suggestions to help prevent further contamination of drinking-water wells:

- issue the regional boards and local agencies a set of clear guidelines for investigating and cleaning up MTBE in groundwater
- assist in developing Health Service's GIS by correcting problems with the state board's Leaking Underground Storage Tank Information System (LUSTIS) so that this database is both accurate and compatible with GIS

Furthermore, regional boards and local oversight program agencies directly responsible for managing groundwater sites affected by gasoline should take the following actions:

- notify Health Services promptly about potential contamination
- use their enforcement authority to penalize storage tank owners or operators who do not comply with the law
- continuously follow up on enforcement actions and cleanup efforts

Agency comments

The Department of Health Services generally agrees with the recommendations in the Bureau of State Audits report, with the exception of the recommendation that it should no longer permit its staff to round off the numbers when determining whether a chemical exceeds the maximum contaminant level. Additionally, Health Services still believes that emergency regulations were not justified and that the approach it took to regulate MTBE was prudent. Finally, Health Services states that if it is to expand its role on the state's GIS projects, it will require a substantial increase in resources.

Similar to Health Services, the State Water Resources Control Board generally concurs with the recommendations in the Bureau of State Audits report. The state board, however, believes that it would be appropriate for the board to complete the tasks for its existing GIS project, outlined in the 1997 legislation, before Health Services assumes the lead role for ensuring that a GIS provides the necessary information to protect drinking-water wells. The state board indicates that it will work cooperatively with Health Services to ensure that it avoids duplication of efforts and that its efforts are complementary to those of Health Services.

Finally, the California EPA supports the position taken by the state board. In addition, the California EPA provides some supplemental information about its Unified Program.

Reference

California State Auditor, *California's Drinking Water: State and Local Agencies Need to Provide Leadership to Address Contamination of Groundwater by Gasoline Components and Additives*, December 1998, available from California State Auditor, Bureau of State Audits, 555 Capitol Mall, Suite 300, Sacramento, California 95814; 916-445-0255; <http://www.bsa.ca.gov/bsa/>.

Late Note: On March 25, 1999, Governor Davis of California ordered a gradual end to the use of MTBE by late 2002.

UTTU thanks John R. Odermatt, Geologist, San Marcos, California, for contributing this summary to UTTU.



Inspector's guide for impressed current CP systems: checklist, part 4

This is a continuation of the impressed current cathodic protection article that appeared in the March/April 1999 UTU. This section begins with the installation of the components/materials.

1. Were anodes installed at sites within \pm two feet of the site locations identified on the engineering drawings?
 Yes No
2. Were the hole diameter(s) and depth(s) for the anode installation within \pm 10 percent of the dimensions specified on the engineering drawings?
 Yes No
3. How were anodes installed?
 Vertically Horizontally
4. Were the anode cables and their associated header cable(s) installed at a minimum depth of 18 inches below grade, except where they surfaced at a junction box or direct current power source?
 Yes No
5. Did the ancillary cables to the test stations have the proper color coding?
 Yes No
6. Were the ancillary cables to the test stations installed at a minimum depth of 18 inches below grade, except where they surfaced at a test station?
 Yes No
7. Did the anode cables, the header cable(s), and the ancillary cables to the test stations have sufficient "slack" such that they would not be broken during backfilling?
 Yes No
8. If the copper conductors on the anode cables were exothermically welded to the copper conductor on the header cable(s), were the correct weld-metal-part number and mold-part number used?
 Yes No
9. If the copper conductor on the cable to the direct current power source was exothermically welded to the structure(s), were the correct weld-metal-part number and mold-part number used?
 Yes No
10. If the copper conductors on the ancillary cables to the test stations were exothermically welded to the structure(s), were the correct weld-metal-part number and mold-part number used?
 Yes No
11. Did the molds used to make the exothermic welds appear excessively used?
 Yes No
12. Was the exothermic weld tested for integrity?
 Yes No
13. Was the specified material (e.g., fine soil or carbonaceous backfill) properly tamped-in-place in the annulus between each canistered anode and its associated hole?
 Yes No
14. If the carbonaceous backfill was placed around the anodes during their installation (i.e., the anodes were not canistered), was this material properly tamped-in-place and did the backfill columns have the dimensions specified on the engineering drawings?
 Yes No
Backfill-column dimensions _____

15. Were all of the splices between the copper conductors on the anode cables and the copper conductor on the header cable(s) waterproofed in accordance with the specifications?
 Yes No
16. Were the necessary precautions taken to ensure that the soil backfill for the electrical cables was free of any objects that could damage cable insulation?
 Yes No
17. Were all of the electrical connections to the structure(s) coated in accordance with the specifications and/or engineering drawings?
 Yes No
18. If they were required, were weld caps installed at the copper conductor attachment sites on the structure(s)?
 Yes No
19. Were each of the test stations installed within \pm three feet of the sites identified in the engineering drawings?
 Yes No
20. Was the specified type of test station installed at each of the sites identified on the engineering drawings?
 Yes No

- 21. Were the test stations installed in accordance with the specifications?
 Yes No
- 22. Were the electrical connections in the test stations made in accordance with the engineering drawings?
 Yes No
- 23. If any were required, were the permanent reference electrodes installed in strict accordance with the engineering drawings?
 Yes No
- 24. Was the copper conductor on the cable that was connected to the structure secured to the negative output terminal on the direct current power source?
 Yes No
- 25. Was the copper conductor on the header cable(s) (i.e., the conductor to which the anodes were electrically connected) secured to the positive output terminal on the direct current power source?
 Yes No
- 26. Was the direct current power source installed in accordance with the engineering drawings?
 Yes No
- 27. If required, were the anode junction boxes installed in accordance with the engineering drawings?
 Yes No
- 28. If required, were pavement inserts installed at those locations identified on the engineering drawings (e.g., where the structure was located under asphalt or concrete)?
 Yes No
- 29. Was the direct current power source installed in accordance with the applicable electrical codes?
 Yes No
- 30. Were all of the galvanized-steel conduits connected to the direct current power source and the anode-junction boxes installed in accordance with the engineering drawings?
 Yes No
- 31. Was the specified oil added to the proper level if the direct current power source was an oil-immersed rectifier?
 Yes No
- 32. Was a structure-to-environment potential survey conducted for the structure(s) to be cathodically protected before the cathodic protection system was activated?
 Yes No

- 33. Record the results for the structure-to-environment potential survey, if conducted.

- 34. If shunts were required, were the properly sized resistors installed in the anode junction boxes?
 Yes No
- 35. Was the construction area returned to its original status after the cathodic protection system was installed?
 Yes No

With regard to the installation of an impressed-current-type, cathodic protection system where the anodes are to be positioned down a deep hole (i.e., a deep-anode bed), the inspector should record answers to all of the applicable, installation-related questions.

- 1. Was the hole for the deep-anode bed drilled within 10 feet of the site identified on the engineering drawings?
 Yes No
- 2. How was the hole for the deep-anode bed drilled?
 Rotary Other
- 3. Were the diameter and depth of the hole within ± 5 percent of that specified on the engineering drawings?
 Yes No
- 4. Was the hole reamed at least twice after the initial drilling in order to remove sharp edges that could damage the cable insulation?
 Yes No
- 5. Was the hole cleaned after reaming by pumping water into its bottom and allowing it to overflow at the top?
 Yes No
- 6. Was the anode-bed resistance estimated from the drill-stem resistance?
 Yes No
Estimated anode-bed resistance _____
- 7. Was the hole logged with respect to depth vs. resistance?
 Yes No

7. Describe the adjustments for the following:

Output voltage _____

Output current _____

Total circuit resistance _____

8. If resistance bonds were made with any "foreign" structures in the area, were the resistances adjusted such that the natural, structure-to-environment potentials for these "foreign" structures were not significantly changed by the current flow to the cathodically protected structure?

Yes No

9. Were structure-to-environment potentials measured for structures other than those identified as "foreign" that might possibly be affected by stray-current corrosion?

Yes No

10. Was any additional stray-current corrosion identified, and was this effectively mitigated?

Yes No

After at least two months of structure polarization, the inspector should record answers to the following questions.

1. Was a structure-to-environment potential survey conducted for the cathodically protected structure?

Yes No

2. If a survey was conducted, record the results along with the test location.

3. Did the results of the structure-to-environment potential survey reveal that adequate corrosion mitigation had been achieved, according to at least one of the National Association of Corrosion Engineers Criteria for Cathodic Protection? For example, if the protected structure was steel, cast iron, ductile iron, or stainless steel, was it polarized to at least 0.85 volt and no more than 1.3 volts relative to a copper-copper sulfate electrode at all locations?

Yes No

Alternatively, was the ferrous-base material polarized in the negative potential direction at least 100 millivolts and no more than 500 millivolts at all locations with regard to the natural, structure-to-environment potentials at these locations?

Yes No

4. If necessary to adjust the direct current power source, what were the output voltage and current? What was the total circuit resistance?

Output voltage _____

Output current _____

Total circuit resistance _____

5. If shunts existed in an anode-connection box, what were the current outputs for the anodes?

Current output _____

6. Was all of the stray-current corrosion (interference) on "foreign" structures in the area still effectively mitigated?

Yes No

7. If the cathodic protection system involved an underground pipe system where the pipe was cased (e.g., at a road or a railroad crossing), were tests conducted to ensure that the casing was not shorted to the pipe?

Yes No

8. Did any shorted casings exist where an underground pipe system was cased, and were provisions made for clearing these shorts?

Yes No

9. If the direct current power source was a rectifier, was its alternating current power still connected to a circuit dedicated to the CP system?

Yes No

Reference

Myers, J. "Acceptable Criteria for Impressed-Current-Type Cathodic Protection System: an Inspector's Guide/Checklist for Components and Their Installation," 1996, J. Myers, 4198 Merlyn Drive, Franklin, Ohio 45005.

UTTU thanks Dr. James Myers for allowing us to reprint his checklist.



Information sources

Publications available from Lewis Publishers (CRC Press, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431-9868; 800-272-7737, fax, 800-374-3401; <http://www.crcpress.com>; orders@crcpress.com) include the following:

Application of Heat and Chemicals in the Control of Biofouling Events in Wells
Applied Mathematics in Hydrogeology
Designing Groundwater Models with Windows
Design of Remediation Systems
Environmental Engineers' Handbook
Environmental Hydrogeology
Environmental Isotopes in Hydrogeology
Environmental Science and Technology
Fundamentals of Hazardous Waste Site Remediation
Groundwater Chemicals Desk Reference
Groundwater Contamination: Optimal Capture and Containment
Groundwater Geochemistry: Fundamentals and Applications to Contamination
Groundwater Models for Resources Analysis and Management
Groundwater Recharge and Wells
Handbook of Groundwater Engineering
Handbook of Vadose Zone Characterization and Monitoring
In Situ Treatment Technology
Metals in Groundwater
Natural Groundwater Flow
Practical Design Calculations for Groundwater and Soil Remediation
Practical Guide to Borehole Geophysics in Environmental Investigations
Practical Handbook of Groundwater Monitoring
Practical Handbook of Soil, Vadose Zone and Groundwater Contamination
Practical Manual of Groundwater Microbiology
Practical Techniques for Groundwater and Soil Remediation
Principles of Contaminant Hydrogeology
Principles of Groundwater Engineering
Quantitative Solutions in Hydrogeology and Groundwater Modeling
Reactivity and Transport of Heavy Metals in Soils
Remediation Engineering

Remediation of Petroleum Contaminated Soils: Biological, Physical and Chemical Processes

Soil and Ground Water Sampling

Soil Bioventing: Principles and Practice

Subsurface Transport and Fate Processes Water Encyclopedia

Water Well Rehabilitation: A Practical Guide to Understanding Well Problems and Solutions

EPA Publications

Evaluation of Demonstrated and Emerging Technologies for the Treatment and Cleanup of Contaminated Land and Groundwater: Pilot Study Report, 1985-1998 (EPA 542-C-98-004). This CD-ROM contains reports developed over the past 15 years by the Committee on the Challenges of Modern Society. For the CD-ROM, call 800-490-9198 or 513-489-8190 or fax request to 513-891-6685.

Field Applications of In Situ Remediation Technologies: Groundwater Circulation Wells (EPA 542-R-98-009). This report describes completed and ongoing pilot demonstrations and full-scale applications of groundwater circulation wells for remediating saturated soils and groundwater. View or download at <http://clu-in.org/techdrct/techpubs.htm>; printed copies available at 800-490-9198 or 513-489-8190 or fax request to 513-891-6685.

Guide to Documenting and Managing Cost and Performance Information for Remediation Projects (EPA 542-B-98-007). View or download at <http://206.181.65.143/frtr/PDF/guide.pdf>. For hard copies, call 800-490-9198 or 513-489-8190 or fax request to 513-891-6685.

In Situ Treatment of Contaminated Sediments provides a basic summary and current status of in situ treatment technologies for contaminated sediments. View or download at <http://clu-in.org/techdrct/techpubs.htm>.

List of Leak Detection Evaluations for Underground Storage Tank Systems, Fifth Edition (EPA 510-B-98-005). View or download at <http://www.epa.gov/swrust1/ustsystem/nwgolde.htm#ldlist>

National Conference on Management and Treatment of Contaminated Sediments (EPA 625-R-98-001) is a summary of 24 presentations describing treatment options for high- and low-end contaminated sites and future research needs. Obtain printed copies by calling 800-490-9198 or 513-489-8190 or fax request to 513-891-6685.

Site Characterization Library, Vol. 1, Release 2.0 (EPA 600-C-98-001), CD-ROM, contains electronic documents and computer programs related to the hazardous waste site characterization. Call 800-490-9198 or 513-489-8190 or fax request to 513-891-6685.

Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water (EPA 600-R-98-128) provides technical recommendations and outlines steps to understand rate and extent to which natural processes are

reducing chlorinated solvent contaminants. Data collected with this protocol can be used to evaluate natural attenuation through biological processes as part of a protective overall site remedy. View or download at <http://www.epa.gov/ada/report.html>.

Technology Evaluation Report: Technologies for Dense Nonaqueous Phase Source Remediation (TE-98-02). View or download at http://www.gwrtac.org/pdf/e_dnapl.pdf.

Websites

Biodegradation/Biocatalysis Database from the University of Minnesota, <http://www.labmed.umn.edu/umbdb/>

Center for Wave Phenomena, Colorado School of Mines <http://cwp.mines.edu/software.html>

Engineering and Technological List http://www.hwr.arizona.edu/hydro_link.html#hydros <http://terrassa.pnl.gov:2080/hydrology/lists.html>

Environmental Health and Safety Services, ThermoRetec <http://www.ehsgateway.com>

Fenton's Reagent for Cleanup of DNAPLs <http://www.envnet.org/scfa/tech/dnapl/factsheets/fenton.htm>

Geographic Collections Division, <http://www.tec.army.mil/>

Groundwater/Hydrology Links <http://www.us.net.adept/links.html>

Immunochemical Methods, <http://www.epa.gov/crdlvweb/chemistry/immochem/user-guide.htm>

Land Use Study, "Effects of Land Use on Ground Water Quality, St. Cloud, Minnesota—1997 Results," <http://www.pca.state.mn.us/water/groundwater/gwmap/stcloud.pdf>

Plane Failure Analysis for Rock and Soil Slopes with Defined Discontinuity Planes <http://mineral.usfsmc.alaska.edu/bane/kroeger.htm>

Scientific References, <http://library.usask.ca/hywebcat/>

Soil Vision, <http://www.soilvision.com>

U.S. Department of Agriculture, Soil Information: <http://www.nhq.nrcs.usda.gov/WSR/> <http://www.statlab.iastate.edu/soils/soildiv/> <http://www.nhq.nrcs.usda.gov/land/index/publication.html> <http://www/nhq.nrcs.usda.gov/land/us/intro.html>

U.S. Federal Register <http://www.env-sol.com/solutions/FR-V63.HTML>

Discussion groups

Engineering behavior of unsaturated soils, subscribe: mailbase@mailbase.ac.uk; to join: join engineering-geotech [first name] [last name]

Geotechnical earthquake engineering and engineering seismology, subscribe: listproc@usc.edu; to join: subscribe geotech [first name] [last name]

Environmental engineering, subscribe: majordomo@drexel.edu; join: subscribe enveng-l

UTTU obtained many of these sites and other information from the Groundwater Mailing List (<http://groundwater.com>), the Bioremediation Discussion Group (<http://biogroup.gzea.com>) and TechDirect (<http://clu-in.com/techdrct.htm>). UTTU thanks the moderators/editors from these groups—Ken Bannister of Groundwater, Richard Schaffner of Biogroup and Jeff Heimerman from U.S. EPA's TechDirect.

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Correction

In *UTTU* Volume 13, No. 1 in the article "Definitions of some common hydrogeological terms" (page 11), under the term "Darcy's law," the formula given is for specific discharge (or Darcy velocity), normally referred to as q , or $v = Q/A$.

Darcy's law Rate of flow through a porous medium that is proportional to the head loss, inversely proportional to the flow path length, and proportional to a coefficient, k :

$$Q = kiA \text{ or } Q/A = v = ki$$

Where

Q = flow rate (m^3/day)

k = a constant (m/day) that should not be confused with velocity

i = the hydraulic gradient, the loss of head, h , over the distance (dimensionless)

A = the total cross-section perpendicular to the flow (m^2)

v = the flow velocity

The correct average groundwater flow velocity, v , is defined as

$$v = (Ki)/ne$$

K = hydraulic conductivity

i = hydraulic gradient

ne = effective porosity

To calculate groundwater flow velocity, investigators must consider the effective porosity of the porous medium.

UTTU thanks Andrew Zlotnick, Fuss & O'Neill, Manchester, Connecticut, for clearing up this point.