Joint Optimization of Groundwater Remediation and Monitoring

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Abstract

We describe the challenge of devising optimization methods which optimize jointly the remediation and monitoring at a contaminated site. We refer to the dual control method as a promising approach to estimate the value of information from measurements in a clean-up project and thus design monitoring in a rational way.

Introduction

It is well known that the cost of cleaning up sites with contaminated soil and groundwater is high. At Superfund sites as well as facilities of the Department of Energy and the Department of Defense, the typical budget is several millions of dollars per site. There is now increasing pressure from the public and the business community to bring these costs under control.

Unquestionably, much of the cost of remediation is administrative overhead and legal fees and these areas should be the first to be targeted for economizing. Furthermore, innovative technologies will likely reduce the total cost. Here, however, we will concern ourselves with the question of how

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to optimize operations to reduce the total engineering costs of remediation and monitoring.

Engineering costs at the site can be divided into two broad categories:

- Clean-up Expenses, i.e., the expenditure associated with eliminating or reducing the presence of pollutants thus restoring the site to other beneficial uses. In the commonly used pump-and-treat method, they consist of the cost of drilling wells, installing pipe systems and treatment facilities, pumping the water to the surface, treating the water, disposing the treated water, and associated operation and maintenance costs. Of course, the types of expenses vary with the method of remediation. For example, in in-situ bioremediation there are costs associated with injecting electron acceptors or substrates.
- Monitoring Expenses, which is the costs associated with site characterization before and during the remediation and with the evaluation of the degree of success of the clean-up project. Monitoring expenses include the drilling of monitoring wells, the collection of water and soil samples, the laboratory analysis of these samples, etc.

Clean-up expenses are high simply because the technical problem of removing common organic pollutants from the soil is very hard. For example, chlorinated organic chemicals are relatively stable (that is to say, they do not degrade readily), sorb strongly on the soil, or accumulate in nonaqueous-phase droplets. The slow rate of mass transfer from the soil or the nonaqueous phase into the groundwater reduces the mobility of the pollutants thus making the pump-and-treat methodology less effective and economical. Other methods, such as in-situ bioremediation or steam injection, hold considerable promise but their application is not inexpensive. The trend now is to recognize de facto and on a site-by-site basis the difficulty and high-cost of complete remediation and to balance the benefits and costs of remediation in setting regulatory goals of remediation.

Monitoring costs are high because geologic formations are complex in structure and variable in properties so that many measurements are needed for an adequate characterization of the site. The source of contamination and the amount that has seeped into the ground are usually not known and, even if they are, transport processes are complex; thus, many measurements are needed to delineate the extent of contaminants plumes in groundwater or contaminated soil. Decontamination may last for long periods, often many years, during which one must collect and analyze samples on a regular basis. Finally, a costly characterization effort is needed to demonstrate that the objectives have been met so that the remediation project may stop.

The Challenge from A Planning Viewpoint

Most of the schemes that have been proposed for optimizing the remediation operation assume that all parameters and costs are known and proceed to find optimal solutions by combining deterministic transport simulation models and optimization techniques. In reality, however, site parameters and pollutant concentrations are not known and cannot be predicted with certainty, which is precisely the reason monitoring is required.

It is useful to review the limitations of the deterministic approach, which uses some estimates of the parameters as if they represented the true values of the parameters. Some of these issues are also discussed in Kitanidis [1987].

First, a completely deterministic methodology is not adaptable to new information, which is obtained from new measurements. One way to circumvent this limitation is to periodically re-optimize the operation with the most up-to-date estimates of the parameters.

Second, a deterministic optimization method does not account for what in optimal-control terminology is known as "caution" or "hedging". Cautious control is one in which the expected costs due to deviations from expected ("best estimate") are minimized. In engineering, the net effect of cautious control is to introduce a safety margin or factor that will reduce the chance of an undesirable or costly outcome. This is an important issue because, although the true values of the system parameters or variables are unknown, it is practically certain that they differ from the best estimates used in the analysis.

Third, a deterministic methodology cannot handle the opportunities presented by "probing". Here is what this term means: The parameters of the groundwater system are unknown but their variances of estimation tend to decrease as new information is extracted from the measurements. However, the reduction in the variance of estimation depends on the conditions in the system. It is often possible to operate the system or to collect additional measurements (monitoring) in such a way that the estimation variance is reduced without significance increase in the cost of operation. By obtaining better estimates of the parameters, the system can be operated more effectively in the future.

There is no satisfactory way for deterministic optimal control methodologies to deal with caution and probing. However, caution and probing are essential effects in determining how to monitor the system. Stochastic optimal control methods are needed which combine simulation transport modeling, optimization, and probabilistic analysis. The difficulty lies in that the application of stochastic control methods to problems of the complexity encountered in groundwater remediation systems can lead to the formulation of computationally formidable problems, which even today's supercomputers could not handle.

The Dual Control Methodology

The dual control methodology is an approximate solution to the stochastic-optimal which accounts for the essential features of stochastic optimal control. The essential advantage of dual control is that it reduces the computational cost of implementation by using a perturbation approximation. This methodology is described in Kitanidis [1987], Andricevic and Kitanidis [1990], Andricevic [1990a and 1990b], and Lee and Kitanidis [1991, 1994].

The basic idea is the following: Our objective is to meet some remediation targets at the most cost-effective way. The total cost consists of remediation and monitoring costs which must be optimized jointly. Minimizing the total cost is sensible because, in practice, the responsible party must pay for the clean-up as well as the site characterization and the demonstration that the targets have been met. Monitoring is expensive but has value in that it allows us to meet the objectives of remediation. A major advantage of this approach is that monitoring is judged not on the basis of some arbitrary or vague accuracy criterion but in terms of the value of information it provides in reducing the cost of remediation.

Appendix: References

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Surface Water Withdrawal Permits Programs for Humid Regions

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Abstract

In humid regions of the U.S., where control of surface water withdrawal is traditionally under the riparian doctrine, there are few strong regulatory programs to restrict water use. In this paper, alternative permit programs for water withdrawal management in riparian regions are discussed and compared qualitatively in the context of six management objectives. Certain alternatives are identified as currently appearing more attractive than others, pending further research and public dialogue.

Introduction

In the humid regions of the eastern United States, rainfalls and streamflows have usually been sufficient to supply nearly all human needs. In those states a set of common-law precedents known as the riparian doctrine has evolved to govern water use. This doctrine is rather imprecise compared to the appropriative doctrine of the western states and many riparian states lack a strong, comprehensive, set of water use regulations (Dixon and Cox, 1985). In recent years, however, problems of concentrated use have become more common and severe in humid regions. Aquifer levels and aquatic stream habitats have been threatened by concentrated withdrawals as cities have expanded, and highly consumptive irrigation has increased in use. While discussion of comprehensive management programs has occurred (e.g., Mack and Peralta, 1987; Walker et al, 1983), implementation has not been widespread. There are a number of options for such programs and a useful precursor to their development is an assessment and comparison of alternatives.

This paper provides such a comparison. Alternative water withdrawal permits programs are compared qualitatively in the context of six management objectives. The first objective is to maximize the ease on the agency's part in setting up the program initially (implementation), operating it routinely (administration), and insuring compliance with it (enforcement). The second

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